Rail to Digital automated up to autonomous train operation

D32.1 – DATO Business Case

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EXECUTIVE SUMMARY

A good business case method for Digital Automated up to Autonomous Train Operations (DATO) shall be able to achieve efficient and productive results within the context of a project group or research team studying if and how they should implement a DATO concept[1].

However, generalizability of existing business cases for individual DATO implementation projects is low, as effects differ depending on the geographical, economic, financial, and logistical context. Additionally, the benefits and costs of DATO techniques accrue differently across different stakeholders, such as railway policymakers, train operators and infrastructure managers, with different time horizons of investment. It is not surprising, then, that current DATO implementation projects have mixed success rates, often suffering from stakeholder misalignment.

Consequently, the aim of this work package is to develop a productive business case method for DATO with the specific challenges of the railway sector in mind. The method shall be applicable to all DATO techniques across different contextual dimensions.

First, to address the task of being productive within the context of the railway sector, we reviewed the literature from a strategic perspective. This means that we aimed to extract the causes of inefficiencies within large-scale transport projects and find out how one may address them at the business case stage. We also enhanced this literature with own case studies on participatory design and operational change management. Our strategic analysis yielded two main takeaways. First, it emphasized the importance of explicitly addressing the stakeholder dimension within the business case method. Second, it suggested fostering a collaborative project with representation from all stakeholders and continuous alignment among them.

Next, to address the task of being applicable to all DATO techniques across different contextual dimensions, we developed interface matrices that map the theoretical pathways from primary technical and operational measurables to downstream economic and financial impacts. Specifically, we constructed an interface matrix for traffic-change-induced effects, such as decreased delays and increased capacity, that encompasses all DATO techniques considered in this Work Package (see Deliverable 32.5; Koopman – van Welij et al., 2026). In addition, we constructed an interface matrix for human factors, which concerns itself with effects from changed operational tasks for ATO Grade of Automation (GoA) 2, where train drivers are still present while the ATO system applies traction and braking, and its combination with a smarter TMS (see Deliverable 32.4, Lo et al., 2026). Third, we review the literature to construct a matrix of cost categories for all DATO techniques in this deliverable.

The matrices apply our philosophy of emphasizing the stakeholder dimension by categorizing the downstream economic and financial impacts by the stakeholder they accrue to. These matrices represent an important theoretical contribution because they define links between bare research output and all relevant business case outcomes.

Finally, we used our interface matrices and lessons from our strategic review to compose a comprehensive business case methodology that integrates the dimensions of (utilitarian) value

[1] With DATO concepts, we mean those studied and developed within Europe's Rail flagship project (FP) 2 *R2DATO*. These comprise of new track detection technologies such as virtual train detection, Automated Train Operation (ATO) from driver-assisted to fully automatic variants, or the Digital Automatic Coupling (DAC) technique for freight trains, among others.

sizes, stakeholders, and effect categories within and across DATO techniques. Concretely, from the interface matrices, this business case methodology applies Multi-Criteria Analysis (MCA) theory by deriving trees of indicators and assigning them with utilitarian values using semi-quantitative value mapping on constructed attributes. Next, it aggregates the constructed attribute values to generate a semi-quantitative value framework. The final output captures business case effects effectively, concisely and convincingly, with particular emphasis on the relative trade-offs between and across stakeholders, effect sizes, and technologies.

To demonstrate the effectiveness of our methodology, we apply our method to an application scenario of ATO GoA2 on a line in the Netherlands. Specifically, we build on capacity simulations (FP1 Work Package (WP) 9), human factors experiments (FP1-WP16), and rough relative cost size estimations (this deliverable) to demonstrate the way our method works and the output it produces. Note that we lacked resources and mandate to obtain detailed insight into the relative and absolute size of many effects. Nonetheless, the application illustrates the effectiveness and attractiveness of the methodology by highlighting some key stakeholder trade-offs and showcasing the broad scope of potential welfare and financial benefits due to ATO implementation, with benefits especially accruing to society.

In sum, our strategic analysis finds that an efficient and productive business case for a DATO project necessarily emphasizes the stakeholder dimension. Our interface matrices establish all relevant effect categories by stakeholder and tie these effect categories to directly measurable operational effects, ensuring broad applicability. Next, our Business Case methodology shows how to repeatably capture costs and benefits of DATO concepts by means of a business case. The methodology fosters a common understanding of the circumstances under which DATO is attractive. Crucially, the methodology identifies stakeholder trade-offs in an appropriately early stage of a DATO implementation project.

Altogether, a business case that applies our methodology can effectively and comprehensively show the size and scope of potential welfare and financial benefits of DATO, in addition to laying bare stakeholder-level financial trade-offs and risks that may otherwise limit the effectiveness and speed of implementation projects. In such, application of our methodology can accelerate and optimize the implementation of DATO.

Future research may aim to carry out a proper business case for DATO technique(s) for certain applications. For this, one would require more quantitative and more accurate data, a further development of linkages with established cost benefit analysis guidelines, and an understanding of the maturity of the DATO techniques and the time dimensionality of their implementation. Hence, future research can enhance our methodology by introducing such a time dimension, for example by studying and incorporating the life cycle cost path of different DATO techniques regarding which costs accrue to which stakeholders at which points in time. Similarly, future research could enhance our methodology by introducing uncertainty ranges in estimated effect sizes.

ABBREVIATIONS AND ACRONYMS

ATO	Automatic Train Operation
BuCa	Business Case
CAPEX	Capital Expenditures
CBA	Cost Benefit Analysis
C-DAS	Connected Driver Advisory System
CINEA	European Climate, Infrastructure and Environment Executive Agency
DAC	Digital Automatic Coupling
DATO	Digital Automated up to autonomous Train Operation
DSR	Design Science Research
Dxx.y	Deliverable number y of Work Package number xx
EC	European Commission
EIB	European Investment Bank
EMU	Electric Multiple Unit
ERJU	Europe's Rail Joint Undertaking
ERTMS	European Rail Traffic Management System
ESG	Economic Steering Group of the European Union Agency for Railways)
ETCS	European Train Control System
FP1	Flagship Project 1 “MOTIONAL” of Europe’s Rail
FP2	Flagship Project 2 “R2DATO” of Europe’s Rail
GoA	Grade of Automation (for ATO)
HITL	Human-in-the-Loop
HTD	Hybrid Train Detection (for ETCS)
IM	Infrastructure Manager
ISO	International Ogranization for Standardization
LCC	Life Cycle Cost
MAU	Multi-Attribute Utility
MCA	Multi-Criteria Analysis
NG Brake	Next Generation Braking system
OECD	Ogranisation for Economic Co-operation and Development
OPEX	Operational Expenditures
PMI	Project Management Institute

R2DATO	Rail to Digital automated up to autonomous train operation
RSDI	Railway System Data Inventory
RTR	Round Table Rolling Stock
RU	Railway Undertaking (/ Train Operator)
SPAD	Signal Passed at Danger
TCO	Total Cost of Ownership
TMS	Train Management System
WP	Work Package

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2 INTRODUCTION

Digital Automated up to autonomous Train Operation (DATO) concepts have the potential to enhance and transform railway operations as we know them. They can provide various benefits, such as increased capacity, improved service quality, and reducing the need for costly new infrastructure investments. However, their implementation may be challenged by high upfront costs, societal and sector-specific complexities, and diverging interests among key stakeholders. As a result, there is considerable interest from the railway sector and transport policymakers in developing a tailored DATO Business Case (BuCa) methodology to support the adoption of DATO technologies (ERJU, 2022).

The present document constitutes Deliverable 32.1 "DATO Business Case" in the framework of the Work Package 32 "DATO Assessment and Potential identification", part of Technical Enabler 20 "Deployment and Migration" of Flagship Project (FP) 2 "R2DATO". WP32 brings together a diverse consortium including national autorities (NRD), passenger train operators (NS and RENFE), freight train operators (DB Cargo), infrastructure managers (ProRail, ADIF and Trafikverket), and academic partners (NTNU, LTU, KTH, TU Delft, and the University of Twente).

More concretely, the objectives of WP32 are twofold: (i) illustrating the attractiveness of DATO concepts by analyzing them from the perspectives of capacity, energy efficiency, wear, and human factors, and (ii) developing a robust and generalizable methodology for constructing societal BuCa's that support the adoption and implementation of DATO across diverse European contexts. Consequently, this Work Package develops a BuCa methodology that links technological developments to financial and societal outcomes, while being tailored to the needs of the future railway sector and its stakeholders.

To achieve these objectives, we approach the problem in three layers. First, we develop a *strategic framework* to establish the important elements to include in a BuCa methodology to foster fast and effective deployment. This guides how we set up *interface matrices* that link technological effects with BuCa elements, culminating in a *methodology* that ties everything together.

Figure 1 below presents a visual representation of the vision adopted to fulfill the objectives of WP32 including these layers, and to illustrate the contribution of its different deliverables. To clarify these links, we employ a cooking analogy to make the concepts more relatable and easier to understand.

1. *Strategic framework*

The strategic framework serves as the metaphorical kitchen. It is a foundational environment in which the components of the *interface matrices* and *methodology* are prepared and structured. On the "menu" are Business Cases for different (sets of) DATO technologies as "dishes;" prepared by delivery partners ("chefs") for the stakeholders ("dinner guests"). The "chefs" rely on their shared expertise ("culinary education"), literature review ("cooking books") and case studies ("recent relevant cooking experiences") to determine the "cooking" techniques, ingredients and appliances necessary to create an attractive and efficient ("nutritious") final dish.

Specifically, we reviewed the literature on large-scale transport projects, focused on the railway and business case context, especially focused on which elements it emphasizes and where current business cases often fall short. We also enhance this literature with own case studies on co-design methods and operational change management in this deliverable. Deliverable 32.2 (ERJU, 2023) contains an early iteration of our strategic framework.

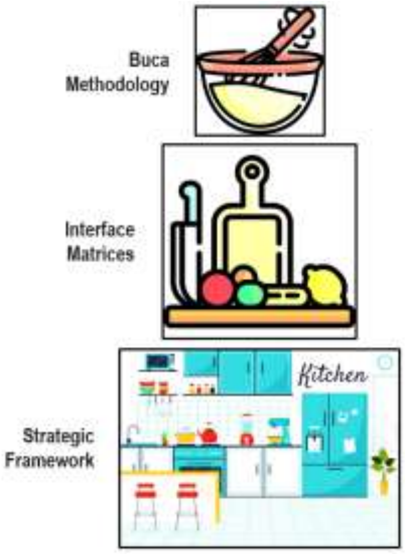

Figure 1: Logical structure of the BuCa work described in this Deliverable

First, we find that cost-benefit methodology is used to assess transport investments in a large number of countries. Since this methodology is grounded in welfare economics and widely established, we conclude that we shall employ the associated data processing principles where possible.

However, secondly, we find that benefits and costs are distributed unevenly across multiple dimensions and stakeholders. Specifically, each stakeholder will prioritize different effects depending on how a given technology impacts their own individual operation and financial bottom line. Indeed, the automation of train operations is inherently a political decision, as it involves multiple stakeholders and requires balancing various dimensions of value.

The consequences of this on constructing a generalizable and efficient BuCa methodology are further exacerbated by the fact that the scope, inclusion, and perception of stakeholder-specific benefits and costs depend heavily on the particular DATO technology, the local geographical and logistical context, intertemporal considerations, and the local spatial-economic, environmental, institutional, and political backgrounds. For example, a policymaker dealing with a heavily congested railway section may be eager to invest in a technology that increases capacity despite high investment costs, whereas a policymaker overseeing low-density railways might prefer to not incur these costs in the absence of those benefits.

To resolve this, we find that the business case methodology should emphasize the stakeholder dimension, a (utilitarian) value dimension and an effect category dimension, with only the latter two being standard in cost-benefit analysis. Secondarily, we conclude that participatory strategies among stakeholders are essential to ensure alignment among all parties. Hence, we deem it worthwhile to study operational change management and participatory strategies among stakeholders in the specific case of the railway sector and DATO techniques. We do this through several case studies, using as cases (i) the diverse multi-stakeholder consortium working on this WP for studies into several co-design interventions, as well as (ii) the Norwegian tram company *Sporveien* to study their conclusions in the sphere of operational change management regarding a shift to ATO.

Chapter 3 extensively describes the literature review and these case studies. Its conclusions form a strategic framework within which we constructed the interface matrices and the BuCa methodology, in the same way one would construct a dish within the framework of a kitchen environment.

2. *Interface Matrices*

As illustrated in Figure 1 above, the interface matrices will function as the link between theory and practice, serving as metaphorical “recipes” to prepare the individual ingredients, and which “kitchen tools” to use for that preparation. This provides methodological support for assessing key technical indicators (“basic ingredients”) impacted by DATO technologies and for converting those indicators into financial and economic outcome categories, or value drivers (“prepared ingredients”) within the BuCa methodology. The matrices define links between bare research output and all relevant BuCa outcomes.

Concretely, we set up interface matrices for the following categories of effects:

- all traffic-change-induced effects for all DATO techniques (Deliverable 32.5; Koopman – van Welij et al., 2026), with a strong connection to FP1-WP9’s capacity simulations. This also includes wear of the rails and wheels when comparing ATO to manual driving (Deliverable 32.3; He et al., 2025).
- human factors for ATO GoA2 and its interaction with TMS (Deliverable 32.4; Lo et al., 2026), with a strong connection to FP1-WP16’s human-in-the-loop simulation of the combination of ATO GoA2 and TMS.
- costs for all DATO techniques (this document, Section 4.2.3).

In accordance with the finding that one should explicitly explore the stakeholder dimension in a BuCa, the interface matrices categorize the outcomes (value indicators) by the stakeholder that incurs the outcome. In addition, the value indicators and intermediate steps in the Traffic-change induced effect matrix contain variables familiar from cost-benefit analysis guidelines, the value drivers for costs correspond to those found in existing cost literature, and the human factors matrix emphasizes that human factors, due to their endogenous character, can be aptly characterized as a risk within the wider BuCa framework.

Indeed, the cited other deliverables in this WP extensively describe the development of these interface matrices, while the present deliverable shortly summarizes them in Section 4.2.

3. *BuCa Methodology*

Finally, as illustrated in Figure 1 above, the *BuCa Methodology* serves as the “integration recipe,” which outlines how to combine the various "prepared ingredients" into the final "dish", while the choices made in the applied cooking techniques, the sourced raw ingredients, and the oven temperature were guided by previously gathered expertise (*strategic framework*). One can create different “recipes” and “dishes” by combining the same ingredients in various ways, reflecting the flexibility in how DATO concepts can be studied and integrated into a Business Case.

Concretely, we adopt a value-based approach to identify the potential impacts of DATO techniques. Barbieri et al. (2024) define (utilitarian) value as a multidimensional construct, with each dimension comprising specific drivers that are measured through relevant indicators (metrics). In this context, we systematically assess the contribution of each DATO concept to these drivers through a process called value mapping.

Using value mapping, we can especially highlight differences between stakeholders for individual effects within or across DATO techniques. Hence, the methodology can fulfil the Strategic Framework's primary requirement of exploring the stakeholder dimension in the final BuCa.

Application and conclusions

We apply the BuCa methodology to one application scenario, which is ATO GoA2 implementation on a railway line in the Netherlands. For this, we used input data from FP1-WP9 capacity simulations and FP1-WP16 human factors experiments. Due to data limitations, we demonstrate a stepwise approach without uncertainty ranges, limiting the analysis to a semi-quantitative assessment (Barbieri et al. 2025) and leaving its extension to a fully quantitative evaluation for future research.

The application demonstrates the potential of our methodology in assessing the effects of DATO implementation. We also show the attractiveness of our methodology in identifying and tackling stakeholder misalignment at an appropriately early project stage.

It is important to note that the objective of this work package was not to condense the impacts of the various DATO concepts into a single outcome or evaluation. This is because DATO concepts can provide diverse types of benefits for various stakeholders and delivery partners, depending on the specific application scenario—such as varying levels of technology maturity and distinctions between logistical contexts. These benefits may be either quantifiable or non-quantifiable, and they can be financial or non-financial. Additionally, implementation costs are still highly uncertain, making it challenging to accurately estimate a single figure for DATO concepts. Indeed, our methodology establishes a foundation for more detailed cost-benefit analyses of DATO concepts.

Further limitations on data availability and data quality stemmed from a lack of expertise on the economic appraisal of capacity and human factors effects, low technical maturity of the studied concepts, and the financial sensitivity of cost data leading to limitations on sharing them within a public document like this.

In sum, the objective of this document is to construct a generalizable outline framework and implementation methodology for developing application-specific business cases for DATO concepts. We approach this in three steps. First, we assess the needs of the sector and review existing methodologies for business case development, constructing a strategic framework and finding that stakeholder misalignment is the key inhibitor of project and business case success. Second, we set up interface matrices that connect direct technological effects in various dimensions to business case output categories. Third, we define a methodology for business case development using a deductive approach. We apply our business case methodology on capacity and human factors results from respective ATO GoA2 studies on a railway line in the Netherlands.

The resulting document structure is as follows. First, Chapter 3 establishes a strategic framework. It explains our strategic analysis of the literature and the sector, describes our case studies on participatory strategies and operational change management, and elaborates on our strategic conclusions. Next, Chapter 4 is the core methodological chapter. It describes the interface matrices and the value-based approach that constitutes our BuCa methodology. Afterwards, Chapter 5 describes our application scenario and its results. Finally, Chapter 6 offers concluding remarks.

3 STRATEGIC FRAMEWORK

3.1 INTRODUCTION

This chapter describes the strategic foundation for our BuCa methodology. Note that Deliverable 32.2 (ERJU, 2023) describes an initial outline of the Business Case, which establishes our tasked BuCa as being located in a multi-stakeholder, technology-shift, and megaproject context. In this chapter, we add to this with a strategically oriented literature review and a set of case studies that members of the WP32 consortium carried out.

The chapter is structured as follows. Section 3.2 reviews the literature in three relevant dimensions – the project management dimension, the operational change management dimension, and the transport economics dimension. We draw conclusions from them that guide and justify the choices we made in our *BuCa Methodology*. Section 3.3 enhances the existing literature with our own case studies that add to the strategic framework, as well as applying the strategic insight to actively involve stakeholders in the process of constructing a BuCa methodology with common understanding. The conclusions of our case studies are in line with the findings from the literature review.

3.2 LITERATURE REVIEW

This section reviews the literature in multiple relevant dimensions. First, Subsection 3.2.1 defines the concept of a BuCa, establishing its position at the project management level. Next, Subsection 3.2.2 synthesizes what the project management literature says about the causal effect of project management strategies on project success. It identifies misalignment between stakeholders as the most salient inhibitor of project success. From this, we conclude that stakeholder effect decomposition shall be emphasized in the BuCa output. Subsection 3.2.3 reinforces this by finding stakeholder misalignment as key challenge in the operational change management literature as well. Afterwards, Subsection 3.2.4 zooms in on the content of existing transport sector business cases, finding strong welfare economics roots and established national appraisal guidelines in the applied methods. Finally, Subsection 3.2.5 summarizes the conclusions from the strategic literature review, with the overarching theme that one shall explore the stakeholder dimension explicitly in business case output.

3.2.1 Business cases and front-end project management literature

From a project management perspective, the concept of a Business Case is subject to varying definitions, as articulated by different authoritative sources such as the Association for Project Management (2025), AXELOS (2017), Kopmann et al. (2015), and the Project Management Institute (PMI, 2025). Despite these divergent interpretations, several consistent attributes characterize the notion of a Business Case (Williams et al., 2019).

A business case is conventionally devised during the design phases of a potential project, constituting a foundational document that sets the evaluation of the project's feasibility. In its essence, a business case serves as a multifaceted instrument that assumes a pivotal role within the realm of project management. It not only justifies the undertaking of a project but also guides its evolution, monitors its advancement, and accommodates shifts in circumstances (Williams et al., 2019). Business cases are dynamic, enabling them to evolve and mirror changes in the project's context or scope. Business cases are typically instigated by high-ranking executives or managers, frequently incorporating input from project managers. They undergo reevaluation upon reaching the culmination of each project phase gate or critical decision juncture and are upheld throughout the project's life cycle. A Business case should also include the delineation of the desired project benefits and outcomes, since it is of cardinal importance for supporting the motivations behind the investment decision (PMI, 2025). However, benefits should not be overstated at the design phase of the project.

3.2.2 Misalignments in megaprojects: Stakeholders and delivery partners

The introduction of DATO techniques can be framed within the category of megaprojects. *Megaprojects* are large-scale, complex undertakings that typically cost more than EUR 1 billion, take many years to develop and build, involve multiple public and private stakeholders, and have significant long-term impacts on the economy, environment, and society (Flyvbjerg, 2014; Hu et al., 2021). They are characterised by their multi-stakeholder governance, high degree of uncertainty and risk, interdependencies across systems, and the necessity for strong strategic alignment to achieve their objectives (Locatelli et al., 2017; Winch, 2017). The scale of investment, transformative potential, and political visibility of these initiatives often make them subject to intense public scrutiny and high expectations for societal value creation (Flyvbjerg, 2023).

The adoption of DATO across European rail networks aligns with these defining characteristics. It represents a continent-wide transformation involving substantial financial resources, the integration of advanced technologies, coordination among national authorities, infrastructure managers, train and freight operators, and industry suppliers, and the adaptation of legal and operational frameworks. Moreover, its long-term societal impacts—ranging from capacity and energy efficiency improvements to enhanced safety and public acceptance—extend well beyond the rail sector, reinforcing its classification as a megaproject.

In megaproject literature, Denicol et al. (2020) identify stakeholder engagement and the capability of delivery coalitions as recurrent determinants of megaproject performance, noting that fragmentation, conflicting priorities, and weak collaboration often lead to cost overruns, delays, and reduced benefits. Similarly, Shenhar and Holzmann (2017) highlight “total alignment” among all parties as a fundamental prerequisite for megaproject success, alongside a clear strategic vision and adaptive management. In the context of DATO deployment—where diverse technical, operational, and institutional actors must work together under uncertainty—these insights support prioritizing the human and relational dimensions of complexity.

In sum, the megaproject literature cites stakeholder misalignment as a key inhibitor for project success, suggesting the mitigation strategy of fostering a collaborative team of delivery partners with representation from all stakeholders and continuous alignment between them. Linking this insight to this WP, we conclude that our DATO Business Case methodology would benefit from being specifically tailored to identify and highlight potential trade-offs among stakeholders regarding the benefits, costs, and risks. In addition, it suggests that our WP consortium, which is also a collaboration of a diverse group of stakeholders, may benefit from continuous and structured alignment.

3.2.3 Stakeholder management in Operational Change literature

Stakeholder management has been an issue in the management sciences, including project management (PMI, 2025; Cleland, 1995), for some time (Freeman, 1984). In the human dimension, shifts in stakeholders’ roles require new expertise, awareness training, and communication. On the organizational side, railway companies must adjust their workflows, structures, and cultures to benefit from digitalization. This process involves ongoing change management efforts. Proper stakeholder communication is crucial in stakeholder management, as noted by Kumaraswamy et al. (2017), Laedre et al. (2015) and Olsson et al. (2008), among others. A distinction can be made between internal and external stakeholders (Cleland, 1995; Gibson, 2000; Atkin and Skitmore, 2008; Winch, 2010). Internal stakeholders are directly involved in a project, whereas the external stakeholders are influenced by a project.

Digital transformation is revolutionizing the railway industry, reshaping how value is created and delivered. This process requires comprehensive change management initiatives, demanding significant expertise and coordination across business units (Huang, Jiang, and Chang, 2023). These initiatives must accommodate operational flexibility to adapt core activities to evolving environments (Vial, 2019; Fletcher and Griffiths, 2020). Flexibility becomes especially critical in projects operating at the intersection of temporary project structures and permanent organizational systems. Railway organizations must therefore continuously align iterative, time-bound development processes with long-term strategic goals (Sun and Tell, 2024).

In the railway sector, the complexity of digital transformation is amplified by its interorganizational nature. Interorganizational projects require collaboration between diverse stakeholders—such as operators, suppliers, and technology partners—leveraging collective expertise and resources to co-create value (Lundin and Söderholm, 1995; Bakker et al., 2011; Sydow and Braun, 2018). Establishing a shared understanding of the project's mission while managing relational and contextual interdependencies between partners is a significant challenge (Engwall, 2003; Bakker, 2010; Sydow and Braun, 2018).

Digital transformation projects in the railway sector thus face several challenges, both internally and interorganizationally. One issue is related to diverse functions and stakeholders, as the involvement of multiple stakeholders and functional units exceeds the scope of traditional project management (Prebanić & Vukomanović, 2021). Reports emphasize unclear goals and several types of uncertainty, including environmental, technological, and organizational uncertainties. These complicate goal-setting (Yeow, Soh, and Hansen, 2018). Also, internal politics and stakeholder misalignment due to competing interests can disrupt coordination and progress (Jiang, 2023). In addition, interconnected activities across boundaries as collaborative projects often face tensions from knowledge-sharing requirements and evolving roles across organizations (Seyedghorban et al., 2020; Yang et al., 2021; Braun et al., 2024).

Nonetheless, literature proposes targeted strategies that railway organisations can use to address these challenges:

1. Flexible Project Integration

- Translate strategic objectives into actionable projects with clear alignment to transformation goals (Olsson and Spelkavik, 2014)
- Develop adaptive frameworks to accommodate changing priorities and environments (Jiang, 2023).
- Ensure seamless integration of temporary projects with permanent organizational structures (Morin, 2025)

2. Dynamic Capability Development

- Actively manage tensions arising from shifting deliverables, participant composition, or technology adoption (Morin, 2025)
- Leverage these tensions as opportunities to innovate and build organizational resilience (Braun et al., 2024).

3. Agile and Hybrid Methodologies

- Adopt agile methodologies for cross-functional collaboration, iterative development, and adaptability (Simard and Aubry, 2024).
- Combine agile and traditional approaches to balance innovation and operational stability through product management frameworks (Leong et al., 2023; Gemino and Reich, 2023).

5. Interorganizational Collaboration Models

- Engage stakeholders early in the project life cycle to align expectations and co-create value (Imran et al., 2021).
- Balance open and closed partnerships to foster collaboration while respecting procurement norms and organizational rules (Hinings, Gegenhuber, and Greenwood, 2018; Korotkova et al., 2023).

6. Framework for Complexity Management

- Develop project management frameworks tailored to the specific operational, technological, and political complexities of railway digital transformation (Badewi, 2022; Sydow and Windeler, 2020).

Railway digital transformation projects thus operate at the confluence of technical complexity, organizational change, and interorganizational interdependence. Addressing these challenges requires robust project management frameworks and continuous stakeholder alignment, ensuring that internal and external actors maintain a shared understanding of objectives as contexts evolve. The stakeholder dimension therefore emerges as a central thread warranting deeper exploration in the sections that follow.

3.2.4 Business Cases in transport policy and economics

If one takes the loosest definition of a business case from Section 3.2.1, then economic welfare estimation does not need to be within scope. However, there are strong methodological roots to methods like Cost-Benefit Analysis (CBA) and Multi-Criteria Analysis (MCA) within the transport sector (Mouter, 2021). Indeed, for large scale public investments into transports, many policymaking contexts explicitly require the application of one of these methods rooted in welfare economics.

Accordingly, we judged the value of our work as much higher if developed a methodology that allows total economic and financial assessment in accordance with existing transport appraisal guidelines and welfare economics. Hence, we include a discussion of these transport appraisal methods here.

Regarding CBA and MCA, a large literature exists that compares the strengths and weaknesses of these methods (e.g., Beria et al., 2012; Mouter, 2020). At a basic philosophical level, though, both approaches aim to obtain one or multiple outcome values, comparing these to outcome values from a null scenario, which either stimulate or discourage the policymaker from implementing the project. Also, they share a methodologically positivist approach to data collection, in the sense that they systematically obtain empirical data to obtain effect size estimates.

A CBA obtains monetary, time-conscious valuations of the studied effects and sums them up using utilitarian welfare functions. By contrast, MCA more easily allows for qualitative valuations of effects beyond a subjective choice of the social welfare function. Specifically, it introduces subjectivity and personal opinions through the choices of criteria and their weights. That this makes results less objective can be a weakness, especially as the choice of criteria and weights are shaped by the expert's background, institutional affiliation, and stakeholder interests (Greco et al., 2016). On the other hand, allowing for subjective criteria and weights may sometimes be a desired feature, as a cost-benefit analysis may not be feasible when many relevant effects are not, or not easily, quantifiable in economic welfare terms.

A large body of literature exists that establishes guidelines on data processing methods and parameters for CBA and MCA. For example, these guidelines establish that one must compare a null alternative to several scenarios, value travel time by a certain number of euros per hour, discount future welfare effects by certain social or financial discount rates, incorporate environmental externalities in certain ways, or set up an analytic hierarchy process to systematically obtain effect weights. Within our context, several European infrastructure/transport ministries as well as European Union level institutions themselves publish official CBA or MCA guidelines that publicly subsidized transport projects must follow to obtain funding.

At the European level, the European Investment Bank (EIB, 2020) provides a guide for the economic appraisal of investment projects, including a rail sector specific chapter that covers CBA, MCA, risk analysis and wider economic impacts measurement methods and parameters. It is applicable to projects co-financed by the EIB. For investments under the Connecting Europe Facility Transport programme, a guideline document (CINEA, 2022) specifies that CBA is mandatory for projects over 10 million euros, although it deliberately excludes projects related to smart and interoperable mobility that DATO techniques fall under. It builds on CBA guidelines published by the Directorate-General for Regional and Urban policy (Sartori et al., 2014).

A notable earlier effort by the European Commission (EC) and EIB sets up common railway project appraisal guidelines (EC & EIB, 2005). Its most interesting theoretical contribution is that it establishes a stakeholder-effect matrix. Although the document does not support this choice with literature, this corresponds to the insights generated in the previous section here. The logic is that redistribution effects and external impacts are especially relevant in the multi-stakeholder context of railway projects. Namely, representing them in the business case can spur ex ante redistribution of resources to account for stakeholder-specific negative effects that would otherwise slow down or prevent project implementation.

At the national level, CBA and MCA guidelines exist as well, also on the topic of how to govern them. For example, in the Netherlands, the Bureau for Economic Policy Analysis publishes a guidance document for CBA (Romijn & Renes, 2013) as well as several handbooks, which use a wide body of economic literature to obtain parameter recommendations. In Norway, a large academic undertaking yielded a so-called Quality Assurance framework, which includes a mandatory conceptual appraisal.

Interestingly, a recent Norwegian study constructs such a conceptual appraisal for ATO (Jernbanedirektoratet, 2023). However, its results are questionable. The KVU report notes that a low technical maturity hindered accurate measurement. In particular, the concept with fully automatic driving (Grade of Automation (GoA) 4) included assumptions with lower fidelity than the concepts with lower GoA levels. For example, the cost for the GoA4 concept includes investments for safety improvements, such as fencing along the entire Norwegian rail network, removing level crossings and installing platform screen doors on all stations. These measures have significant additional costs compared to the other alternatives and are far from a well-established necessity.

Morin, Olsson and Olsson (2026) used the Norwegian CBA and combined it with evaluations of Norwegian rail infrastructure investments, to study cost effectiveness of ATO versus infrastructure expansion. The overarching conclusion is that the two should not be treated as competing concepts but as complementary instruments: infrastructure providing the physical foundation for capacity growth, ATO optimizing reliability and efficiency within the infrastructure. Table 1 below summarizes the findings.

Dimension	Infrastructure investment	ATO	Conclusion
Capacity increase	More cost-effective	Less efficient at scale	Complementary
Punctuality improvement	Often underperforms forecast	Strong efficiency	Complementary
Cost certainty	Higher certainty	Uncertain / immature	Staged approach needed

Table 1: Summary of recent Norwegian MCA into ATO and small infrastructure upgrades (Morin, Olsson and Olsson, 2026).

Note: ATO studies used to arrive at these conclusions were of preliminary quality; effects may strongly differ in other countries and logistical contexts, as well as if the ATO technique matures

The study by Jernbanedirektoratet (2023) is based on the Norwegian Quality Assurance framework, which is mandatory in the country. It clearly is a method rooted in MCA. It is the result of studies (OECD, 2015; Volden & Samset, 2015; Klakegg & Volden, 2016) that signal public projects as a highly political process with conflicting stakeholder interests. In turn, the Quality Assurance framework emphasizes early stakeholder engagement and clear strategic objectives within a governance-oriented institutional setting. Hu et al. (2024) review 34 mega transport projects across the world, also emphasizing the importance of a collaboratively governed institutional framework to aid project success.

Congruously, several studies (e.g. Annema, 2013; Volden, 2019) note that the usefulness of CBA in decision-making depends on decision-makers' understanding of the analyses. Critically, the analyses should be transparent, consistent, and well-communicated to the public and associated stakeholders. Damart and Roy (2009) use experiences from France to illustrate the difficulty of aligning knowledge produced in CBA with knowledge produced by the various stakeholders in the decision-making process. They emphasize that all the actors involved really need to understand the decision-making procedure, as it is only then credible to those involved actors. Hrelja et al. (2020) review the literature and suggest that it is essential to clearly visualize the interaction between technical effects and outcomes in a way that all stakeholders can understand.

Altogether, we obtain the insight that CBA and MCA are well-established, supported by theoretical and empirical literature, and in many cases even legally required for public investment. Hence, our BuCa methodology needs to be compatible with such CBA and MCA guidelines. Practically, this means that our *Interface Matrices* layer uses variables and processing methods that correspond with those used in common CBA and MCA guideline documents.

We also obtain the insight that MCA methods are more suited to cases where many variables are qualitative or unclear. Indeed, we have such a case here, as many data (such as costs) are not available to us, other variables have no economic literature quantifying them yet, some DATO techniques are not mature yet or are not tested in our human factors and capacity simulations, and many variables in especially the context of human factors are qualitative. Hence, our *BuCa Methodology* will apply a technique derived from MCA's analytic hierarchy process, founded in welfare theory.

3.2.5 Conclusion (Literature Review)

From the literature, we obtained four key insights that guide or constrain our choices for a BuCa methodology.

First, we find that we need to explain the stakeholder dimension in our design, to lay bare divergent interests within a sector where individual stakeholders can have a large negative impact on project success if they deem a project undesirable. By contrast, if a business case can show a net positive effect with relative winners and losers, then ex ante redistribution of resources may become more realistic and seem more logical to the involved stakeholder representatives.

Second, a collaborative project team with representation from all stakeholders is essential to ensure alignment across parties. Again, misalignment can lead to individual stakeholders exerting a negative impact on project success. We explore cooperative alignment strategies in the section below.

Third, we find that our business case method benefits strongly from being integrated with standard transport appraisal guidelines. The reason for this is twofold. First, theoretically, strong economic welfare theory foundations allow for welfare-maximizing decision-making. Second, in practice, many guidelines for public investment require adherence to such standard appraisal methods.

Finally, we find that the overall methodology needs to be understandable and highlight the important trade-offs.

3.3 Case Studies

This section presents several case studies that we carried out to enhance the existing literature with (i) insights from the specific context of DATO implementation in the railway sector, as well as (ii) cooperative alignment within a multi-stakeholder project in the railway sector, using the opportunity that this very Work Package consortium offered.

Accordingly, each subsection in this section discusses a different case study. First, Subsection 3.3.1 describes insights from a qualitative study on operational change management experiences in an ATO implementation project at a Norwegian tram operator. Next, Subsection 3.3.2, 3.3.3 and 3.3.4 decribe multiple participatory design workshops applied to our own WP consortium to see the ways these design strategies could identify and resolve various types of misalignment, relating them to the roles of different stakeholders. Finally, Subsection 3.3.5 draws main conclusions from these case studies, which are in line with the conclusions from the literature review.

3.3.1 Operational Change Management (Case: ATO, Sporveien)

We conducted a Sporveien case study to examine how a public transport operator and a technology supplier jointly navigate the organizational and interorganizational dimensions of tramway automation. Specifically, we investigated how collaboration, stakeholder involvement, and governance practices evolve as ATO technology progresses from early experimentation toward operational integration in the Oslo tramway system. A PhD thesis documents and analyzes the case across several publications which address the managerial, interorganizational and business dimensions of digital transformation.

To support the development of the ATO business case within the R2DATO project, this research draws on a longitudinal qualitative case study of tramway digital transformation, conducted with both the public transport operator and the technology supplier involved in the automation initiative. The study is based on two rounds of semi-structured interviews (70 total) complemented by validation and sensemaking workshops with senior managers and project stakeholders. This design enabled an in-depth examination of how interorganizational collaboration, stakeholder involvement, and governance practices evolved over time as automation technologies progressed from early experimentation toward operational integration.

Methodologically, the longitudinal approach was essential to capture the dynamic nature of rail automation projects. Rather than treating collaboration or alignment as static conditions, the study traces how they emerge through repeated interactions, feedback loops, and negotiated adjustments between organizations. The combination of interviews and workshops allowed empirical findings to be iteratively refined, validated, and interpreted in close dialogue with practitioners. This approach ensures that the resulting framework is not only theoretically grounded but also operationally meaningful for large-scale initiatives such as R2DATO.

Empirically, the case highlights that DATO unfolds as a sociotechnical transformation, rather than a linear technology deployment. Early phases of the project were characterized by high uncertainty, incomplete technical maturity, and evolving regulatory interpretations. During this phase, project-based organizing played a critical role by creating a protected environment for experimentation, iterative testing, and joint problem-solving. These project structures enabled both the operator and the supplier to explore DATO functionalities while maintaining safety, managing risk, and engaging key internal stakeholders.

As the initiative matured, the nature of collaboration shifted. The study shows a gradual transition from exploratory, project-oriented practices toward more stable, product- and operations-oriented logics. This transition required the progressive formalization of roles, validation routines, and decision-making structures, as well as stronger integration with operational units, maintenance teams, and long-term planning processes. Importantly, the findings demonstrate that this shift does not occur automatically once technology stabilizes; it must be actively governed through deliberate coordination mechanisms and sustained stakeholder engagement.

Five practical contributions from the thesis are directly relevant for DATO. First, the findings show that organizational readiness is a prerequisite for realizing the benefits of automation. Leadership alignment, workforce adaptation, and early engagement of frontline actors' condition whether technical progress translates into operational value. In the case studied, the involvement of ambassador drivers, tailored training programs, and transparent communication routines were critical in transforming skepticism into constructive participation. For DATO, this suggests that stakeholder involvement should be treated as a core design variable in DATO deployment strategies, not as a secondary change management activity.

Second, the study illustrates the need to actively balance project and product management logic over time. The case shows that initial stages of DATO development require a project-oriented approach emphasizing experimentation, iterative testing, and rapid feedback loops to manage uncertainty and technological immaturity. These project-based practices support learning, risk reduction, and stakeholder alignment during exploration phases. However, as automation technologies stabilize and move closer to operational deployment, organizations must progressively transition toward product management principles. This shift enables long-term ownership, life cycle thinking, operational integration, and continuous improvement. For R2DATO, this insight underscores that DATO should not be treated as a one-off project, but as a productized capability that requires sustained governance, resourcing, and institutional anchoring.

Third, the findings demonstrate that interorganizational collaboration must be deliberately structured, rather than assumed to emerge through contracts or technical specifications alone. The findings show that effective collaboration between operator and supplier depends on reciprocal learning routines, iterative feedback mechanisms, and regular cross-organizational review cycles. These practices enable continuous adaptation of technical solutions to operational realities and evolving regulatory constraints. For R2DATO, this highlights the importance of embedding structured collaboration mechanisms, such as joint validation sessions, shared documentation practices, and synchronized development milestones, into the business case and governance model, ensuring that learning and alignment are sustained throughout the automation life cycle.

A fourth practical contribution concerns cultivating strategic alignment and mutual dependence across organizational boundaries. The case demonstrates that automation initiatives progress when both operator and supplier explicitly recognize their complementary roles and shared responsibilities. Strategic alignment does not emerge automatically but must be actively cultivated through shared problem framing, joint decision-making forums, and transparency regarding constraints and trade-offs. These practices foster joint ownership and accountability, reducing the risk of fragmented decision-making or opportunistic behavior. For R2DATO, this implies that the business case should explicitly articulate mutual dependencies, clarify shared objectives, and support governance arrangements that reinforce long-term partnership rather than transactional delivery.

Finally, the research reinforces the importance of approaching digital transformation as a sociotechnical process, rather than a purely technical upgrade. The case shows that automation success depends on the integration of organizational learning, cultural adaptation, workforce engagement, and change management alongside technical development. Practices such as involving frontline staff in testing, investing in role-specific training, and aligning organizational routines with new technologies proved critical for acceptance and effective use. For R2DATO, this contribution emphasizes that business-case development must go beyond cost–benefit calculations to include organizational readiness, skills development, and stakeholder engagement as core value drivers of DATO implementation.

Taken together, these practical contributions provide R2DATO with suggested operational change management strategies, illustrated in Figure 2 below. By balancing project and product logic, structuring interorganizational collaboration, cultivating strategic alignment, and treating automation as a sociotechnical transformation, railway stakeholders can better manage uncertainty, reduce implementation risks, and build durable automation capabilities. These insights directly inform the

R2DATO business case by clarifying how value is created over time, not only through technology, but through coordinated organizational and interorganizational action. It underscores the conclusion from prior literature review that highlighting continuous and deliberate stakeholder engagement is important for project success, and hence important for the business case methodology to allow for.

The full academic analysis and theoretical grounding of this framework were presented at the European Academy of Management conference (Morin, 2025), while the journal version of the study is currently under review at the Project Management Journal.

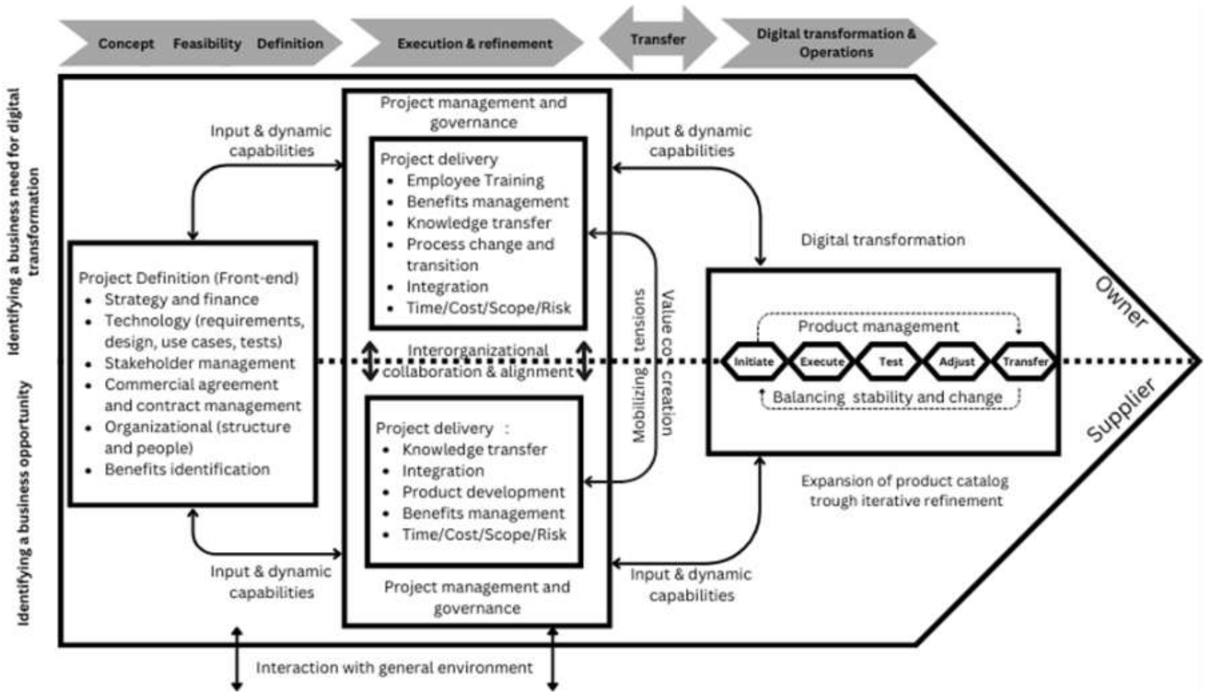

Figure 2: Operational Change framework based on ATO Sporveien case study

Note: Source: Morin, 2025

3.3.2 Collaborative and iterative refinement (Case: within WP32, Delphi)

In the context of developing the business case for DATO, the team conducted a series of structured workshops. These workshops supported the development of the business case elements by exploring the details of the identified components within the initial BuCa outline (Deliverable 32.2, ERJU, 2023). They deepened the conceptual understanding of the subject matter and helped identify and examine relevant impacts and consequences, such as specific business case elements and their effects.

Concretely, the research team designed the first workshop inspired by World Café methodology (Löhr et al., 2020), which encouraged open-ended brainstorming and allowed participants to explore diverse perspectives on the business case elements. Drawing on the findings from this initial session, the team structured the second workshop around the Delphi method (Naisola-Ruiter, 2022), an established technique in both project management and academic research. This method gathers expert judgments on real-world issues through a futures-oriented approach. In the second workshop, the team engaged a panel of experts to further develop and validate the initial insights and identified impacts, aiming to reach a consensus and refine the business case elements.

The research team conducted a pilot Delphi workshop specifically on the theme of “railway capacity,” a core component of the business case, with participants internal to the WP. They conducted the session over three iterative rounds using a structured questionnaire. They invited Work Package members to suggest additional ones, provide concise definitions, and justify each impact’s relevance to “capacity.” In total, participants examined 11 impacts, such as “headway,” “travel time,” and “buffer time”, and reached consensus on the relevance of eight.

The Delphi process did not lead to tangible outcomes used for further development of the inclusion of capacity into the BuCa methodology (see instead D32.5, Koopman - van Welij et al., 2026), as the capacity experts within the WP did not deem the identified list of impacts and their relative valuations of acceptable quality and realism. Indeed, the Delphi process revealed that a team with divergent backgrounds could or might not have the required knowledge to properly judge effect size and scope and might not always reach consensus on conceptual definitions. Participants expressed divergent understandings of certain key concepts, shaped by their disciplinary backgrounds and professional experiences. This divergence highlighted semantic misalignment, which project management literature documents as a potential source of misunderstanding and conflict in complex projects (Scherpereel, 2006).

The research team highlighted the need to investigate alignment and misalignment within the project, examining how these dynamics affect collaboration and how teams might address them to improve coherence in business case development processes. This realization led the research team to define a case study on stakeholder alignment as a foundation for further research, described in Subsection 3.3.3 below.

3.3.3 Design Principles for Stakeholder Alignment (Case: within WP32)

To address the need for a systematic and actionable framework for identifying and resolving stakeholder misalignments, the research team applied a Design Science Research (DSR) methodology. They aimed to diagnose the nature and sources of stakeholder misalignment and to translate empirical insights into design principles that are both theoretically grounded and practically applicable. Through this process, the team developed and validated a set of principles to support the iterative alignment of stakeholder perspectives in complex, multi-actor project environments.

The research team adopted an iterative and participatory approach, incorporating document analysis, semi-structured interviews, and observations from workshops and discussions conducted within WP32. They conducted fourteen interviews with stakeholder representatives from a mix of direct and indirect stakeholder organizations. These included infrastructure managers, operators, and transport authorities (e.g., ProRail, NSR, DB, NRD, RENFE, ADIF), as well as academic institutions (e.g., NTNU, UT, KTH). While the direct stakeholders were affiliated with operational organizations, their involvement in the project was primarily from a research or strategic perspective rather than an operational one. As such, the interviews reflected the views of stakeholder representatives rather than frontline stakeholders themselves. These interviews explored perceptions of challenges in business case development and helped identify key areas of alignment and misalignment, including project goals and scope, stakeholder priorities, interpretation of results, and decision-making processes.

The research team analysed the findings thematically, applying both empirical problem-solving and design theorizing perspectives. They discovered that misalignments arose not only from technical or procedural gaps but also from cognitive and institutional differences among stakeholder groups. Based on these insights, the team conceptualized alignment across three core dimensions: Cognitive alignment, Goal alignment, and Practice alignment.

Cognitive alignment refers to the degree to which stakeholders share or differ in their values, beliefs, and perceptions about a project, its problems, and potential solutions. When stakeholders interpret situations similarly, they achieve high cognitive alignment, which fosters trust and smooth communication by creating a sense of being "on the same page." It also facilitates knowledge sharing and collective learning, as all parties interpret information in comparable ways (Tessitore et al., 2023). For example, when two project partners describe a technical issue in the same terms and both propose upgrading a system as the solution, their aligned perceptions demonstrate cognitive alignment, likely resulting in mutual trust and easy agreement on next steps.

Another key area of investigation focuses on alignment in goals, particularly in coordinating the objectives of various stakeholders (Caldwell et al., 2017). The extent to which stakeholders' goals and objectives for the project are shared, compatible, or in conflict. Goal alignment means stakeholders are working toward compatible or collective objectives, whereas goal misalignment means each is pursuing their own, possibly clashing, goals. In many collaborations, parties start with inherently different objectives (Tessitore et al., 2023).

Practice alignment (Corsaro & Snehota, 2011) refers to the extent to which stakeholders' actions, processes, and ways of working are coordinated. Practice alignment means stakeholders adjust or synchronize their operational practices, procedures, and competencies in pursuit of the project, whereas practice misalignment means their methods clash or remain siloed (Tessitore et al., 2023) In other words, this focuses on how stakeholders work together: Are their processes and decision-making routines in harmony, or do they conflict? Prior research notes that differing institutional or organizational logics can drive practice misalignment, if each party adheres to its own established practices without adaptation, joint work can be driven to misalignment (Besharov & Smith, 2014). Conversely, when stakeholders develop harmonious ways of working, they can create synergistic value beyond what each could do alone (Tessitore et al., 2023). This category of practice alignment captures evidence of stakeholders aligning their work processes and way of working during collaboration.

The research team gained valuable insights during the interview phase into the challenges stakeholders faced throughout various stages of the R2DATO-WP32 project. Participants shared both individual and organizational experiences, revealing misalignments across cognitive, goal-oriented, and practical dimensions. Using a structured coding process, the team identified recurring themes, including divergent interpretations of project goals and scope, difficulties in translating the Grant Agreement into specific work package requirements, conflicting stakeholder objectives and priorities, and coordination gaps in workflows. These findings emphasize the complexity of multi-stakeholder collaboration, especially in cross-sector and cross-country settings.

The analysis revealed that practical misalignments, such as leadership transitions, onboarding/offboarding issues, and inconsistent communication strategies, were the most frequently cited. However, overlaps between cognitive and goal-related misalignments were also common, suggesting that misunderstandings in shared mental models often cascade into misaligned objectives and practices. These insights informed the design of the next workshop, which aims to build stakeholder capacity to recognize, reflect on, and respond to misalignments using co-design and design science principles.

To address the observed misalignments, cognitive, goal-related, and practical, identified through document analysis and interviews with stakeholder representatives, the research team developed five design principles to guide the next phase in developing an integrated alignment framework.

1. Raise Mutual Awareness of Misalignment: Encourage stakeholders to openly recognize and articulate differing perspectives and expectations early in the process.
2. Understand the Nature and Sources of Misalignment: Map divergences in goals, values, processes, and assumptions across stakeholder groups to foster mutual understanding.
3. Foster Openness and Mutual Dependency: Build collaborative environments that promote trust, transparency, and shared ownership of outcomes.
4. Enable Continuous Iteration and Feedback: Treat the business case as a dynamic, evolving artifact that reflects changing project and stakeholder conditions.
5. Coordinate Inputs and Outputs Across Work Packages: Ensure consistency and interdependency between technical components and stakeholder contributions throughout the business case development process.

Insights from the interviews, combined with findings from the alignment workshop and the developed design principles, serve as a practical guide for enhancing stakeholder coordination and alignment. In such, they support the design of governance structures and engagement strategies within broader DATO implementation projects, too.

3.3.4 Cooking Analogy (Case: within WP32)

This section describes how two experiential and analogy-based workshops fostered alignment among WP32 members. We designed the first, framed as a BuCa Chefs Workshop, to stimulate reflection and converge on a shared project vision; and the second, framed as a BuCa Restaurant Workshop, to validate and build ownership of the draft BuCa methodology through a Serious Game application.

We designed the *BuCa Chefs Workshop* (Figure 3 below) around a cooking analogy to foster creative reflection and mid-project alignment (Barbieri et al. 2025). The activity engaged fifteen consortium members in preparing and sharing a three-course meal. In alignment with Kolb's Experiential Learning Cycle (Kolb, 2014), the cooking activity served as the concrete experience, followed by a reflective observation phase in which participants unpacked their culinary experience and mapped these insights onto the context of WP32—identifying analogies between cooking elements (e.g., ingredients, recipes, kitchen tools) and project components (e.g., value dimensions, guidelines, assessment tools). This process helped foster team building and mutual trust.

Figure 3: Participants during the BuCa Chefs Workshop

Consequently, the BuCa Restaurant Workshop (Figure 4 below) focused on validating the BuCa methodology and fostering ownership among WP32 members by applying it in a practical, interactive format. Conducted over three separate sessions, the workshop examined three key perspectives: benefits, costs, and risks of digitalisation. To this end, we developed a serious game and framed it around a fictional BuCa Restaurant case, in which participants assumed the role of applicants to a competitive funding call. In this scenario, we tasked participants with using the BuCa methodology to break down the benefits, costs, and risks of digitalisation—thereby strengthening the business case and increasing the likelihood of securing the grant for the restaurant. The workshop enabled participants to apply the proposed BuCa methodology in practice, and feedback from consortium members informed several refinements, resulting in the final methodology presented in Section 4. Some of these refinements included the presentation of the results and the decision to exclude the time dimension from the assessment due to limited resources and lack of research into roadmaps of required investments.

Figure 4: Context of the BuCa Restaurant Workshop

3.3.5 Conclusion (Case studies)

This section described four case studies comprised of one or several interventions, both with the Norwegian Sporveien tram company as a real-world example of a company that is attempting to transition to ATO, as well as within the Work Package consortium itself to study stakeholder misalignment as well as cooperative strategies to address them.

All case studies will be or are already published in academic literature and are described at length there. For this deliverable, we conclude that they add to the literature review of Section 3.2 with broadly similar conclusions. Specifically, we observed the risk of stakeholder misalignment and observed the positive effect that participatory design strategies and alignment workshops can have on limiting these risks.

Specifically, for our BuCa methodology, we find the following recommendations. First, we reinforce the finding from our literature review that we need to explain the stakeholder dimension in our design. Second, we reinforce the finding from our literature review that a collaborative project team with representation from all stakeholders is essential to ensure alignment across parties. The BuCa methodology should therefore allow for stakeholder input in valuing effects. Finally, we reinforce the finding from our literature review that the overall methodology needs to be understandable and highlight the important trade-offs.

4 BUCA METHODOLOGY

4.1 INTRODUCTION

The BuCa methodology is the primary contribution of this deliverable. It can assess stakeholder trade-offs in the business case for DATO while also being universally applicable. In accordance with Figure 1, we use interface matrices to relate cost types as well as directly measurable effects of DATO in the realm of human factors and traffic-behavioural (or capacity) changes with financial and societal/economic outcomes. Specifically, the interfaces map the theoretical pathways from primary operational measurables to downstream economic and financial impacts. As a result, project teams studying DATO implementation can use them as a benchmark, no matter the technique studied or the local logistical, economic, political, financial, or institutional context. The matrices apply our philosophy of emphasizing the stakeholder dimension by categorizing the downstream values by stakeholder.

Next, the BuCa methodology frames these outcomes as (utilitarian) value indicators and uses them as input in a semi-quantitative assessment. This semi-quantitative assessment produces the final DATO BuCa output format we propose. In doing so, we apply the lessons learned in the strategic foundation.

The structure of this chapter is as follows. First, Section 4.2 outlines the interface matrices produced: Subsection 4.2.1 for traffic-change-induced (or capacity) effects, Subsection 4.2.2 for human factors, and section 4.2.3 for costs. Next, Section 4.3 presents the methodology of semi-quantitative assessment in conceptual form. Finally, Section 4.4 instantiates the semi-quantitative assessment methodology in the context of WP32 through the specification of trees of indicators for the traffic, human factor, and cost dimensions.

4.2 INTERFACE MATRICES

4.2.1 Traffic-change induced effects

On a fundamental level, Digital and Automated up to Autonomous Train Operations (DATO) techniques change the way trains can move through the network. Trains may be able to run faster, closer together, and suffer less delays, allowing for a reduction in timetable margins. Railway capacity simulations can quantify the size of capacity effects of DATO techniques by simulating the way trains move through the network, comparing scenarios with and without the new DATO technique.

The interface matrix captures the links between (i) these direct, measurable changes in the spatio-temporal behaviour of trains and (ii) the financial and economic (potential) effects resulting from these changes. We call these ultimate financial and societal effects “traffic-change induced effects.” Within the context of our BuCa methodology, we refer to them as (utilitarian) “value indicators.”

Deliverable 32.5, “DATO capacity and impact simulations report” (Koopman – van Welij et al., 2026) explains the construction of the interface matrix for traffic-change induced effects extensively. It defines each element, explains the links between them, and offers suggestions for potential quantification methods. D32.5 also constructs versions of the model for the DATO techniques of ATO GoA2, ATO GoA4, ETCS HTD, NG Brake, TMS and DAC in its D32.5 Chapter 4, which highlight subsets of elements of the generic interface matrix that are present for these specific DATO techniques.

Therefore, for an extensive explanation of the interface matrix and for DATO-specific versions, we refer to D32.5. Instead, here, we shortly summarize the logic behind the interface matrix, only presenting its generic form. Figure 5 below shows this interface matrix for traffic-change induced effects.

The list of variables and the relations we find between them resulted from a two-year-long iterative scoping and refinement process within the group of authors, as well as through peer review rounds and an interface workshop session within the broader work package, as well as external reviews with FP1-WP9, FP2-WP17, and FP2-WP37 within Europe's Rail wave 1, as well as an external review by the long-term capacity management department at ProRail. As a result, we believe it comprehensively captures effects.

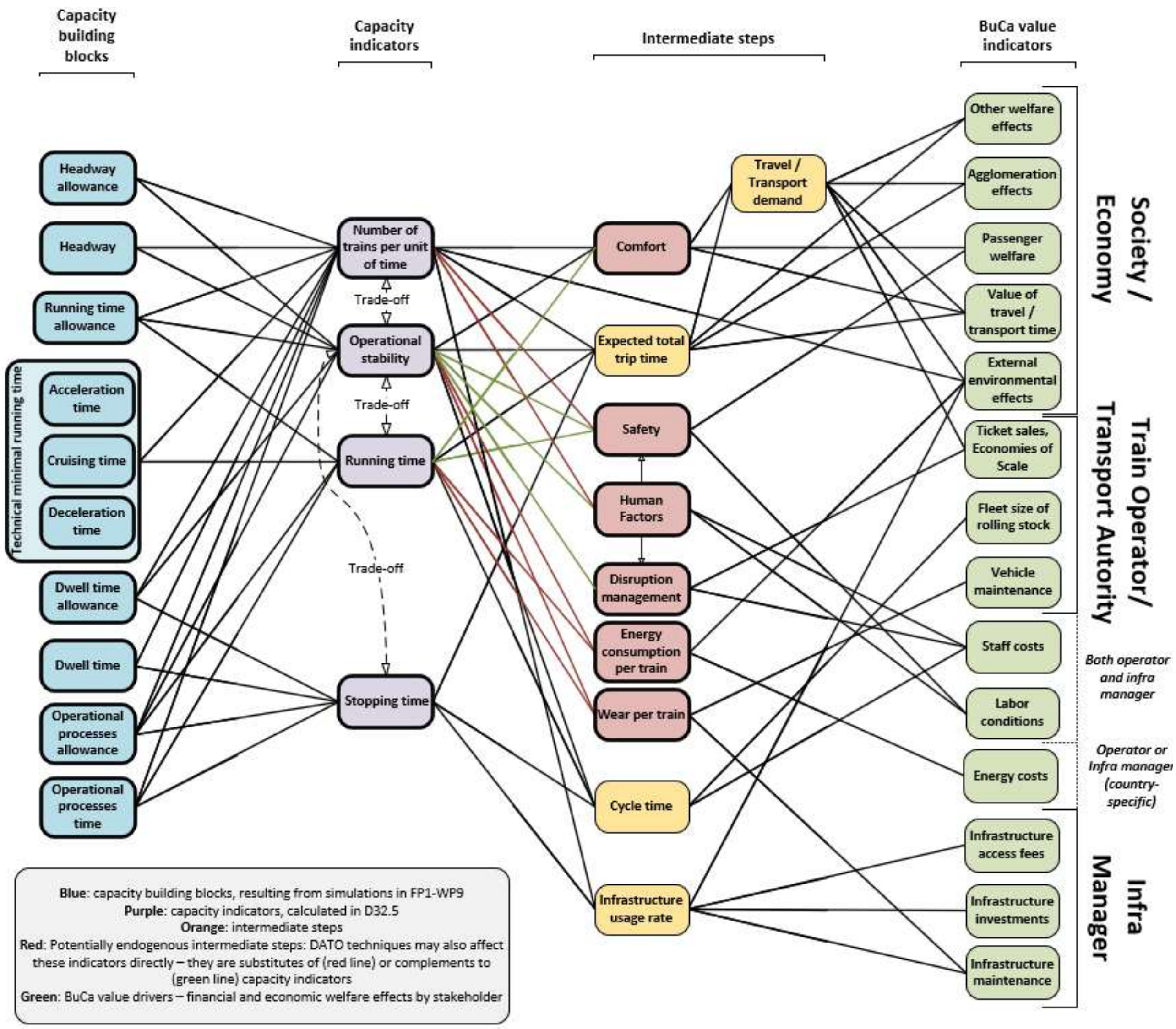

Figure 5: Interface Matrix linking Capacity to Economic and Financial Outcomes (D32.5; Koopman – van Welij et al., 2026)

The interface model follows a three-step approach. First, we categorize the full timetable of a train as a list of *capacity building blocks*, which includes everything from the start-up of trains at the depot or yard up to and including their shutdown at the depot or yard. The sum of these building blocks represents the spatio-temporal behaviour of trains.

Second, we define four *capacity indicators*, which are general constructs that together represent the timetable and performance of a train or line segment. Each is a combination of several capacity building blocks. Microscopic railway simulations usually yield measurements on these capacity indicators (see FP1-D8.3: Pot et al., 2025)

Third, we translate these capacity indicators into *BuCa Value Indicators*, a comprehensive list of economic and financial indicators that (may) change due to changes in railway capacity. Here, we also define *intermediate steps* to clarify the channels through which the relations run, as well as to differentiate effects between the same capacity-to-BuCa-value-indicator pairs that run through different channels.

Additionally, we group the final *business case impacts* into categories of stakeholders affected by them. In our interface model, we identify three main stakeholders: society, representing a policymaker concerned with maximizing societal welfare, thereby also representing the interests of passengers and industry; the train operator, which can be a freight or passenger operator; and the infrastructure manager. This is in line with the Strategic Framework.

4.2.2 Human Factors

Figure 6 below shows the interface matrix for Human Factors pertaining to ATO GoA2 and GoA4 implementation. It summarizes the literature and expert perspective on human factors issues and associated risks that must be considered in decision making when investing in GoA2 or GoA4 levels in combination with HTD. Driven by insights from academic literature followed by expert review, following the risk management model ISO 31000 (Purdy, 2010), analysis on the potential risks (risk identification) and actions to mitigate those risks (risk treatment) is presented below.

4.2.2.1 Risk Identification

Moving to GoA2 and GoA4 levels of train automation could affect several aspects at the operator, organizational, technological/design, and societal levels. The risk analysis was driven by factors identified and measured in the existing literature (Kusumastuti et al., 2025). The most important potential risks were identified and agreed upon by the experts in the consortium (see Deliverable 32.4 for a more detailed analysis).

One of the key consequences of the shift in roles for train operators is the loss of specific job skills, commonly referred to as deskilling. The lesser need for manual operations may cause operators to underutilise their knowledge for tasks such as speed maintenance or having route knowledge (Buksh, 2013; Cogan & Milius, 2022; Emery, 2017). The increasing utilisation of automated operations and decision tools could also degrade operators' decision-making skills in critical situations (Brandenburger et al., 2016; Cogan & Milius, 2022). Transitioning current staff to higher levels of automation also requires them to forego their familiarity with legacy systems and adapt to new modes and interfaces. Additionally, addition of new technologies such as HTD may transform operator's approach to performing their tasks that may require a shift in mental models they have built through accumulated knowledge.

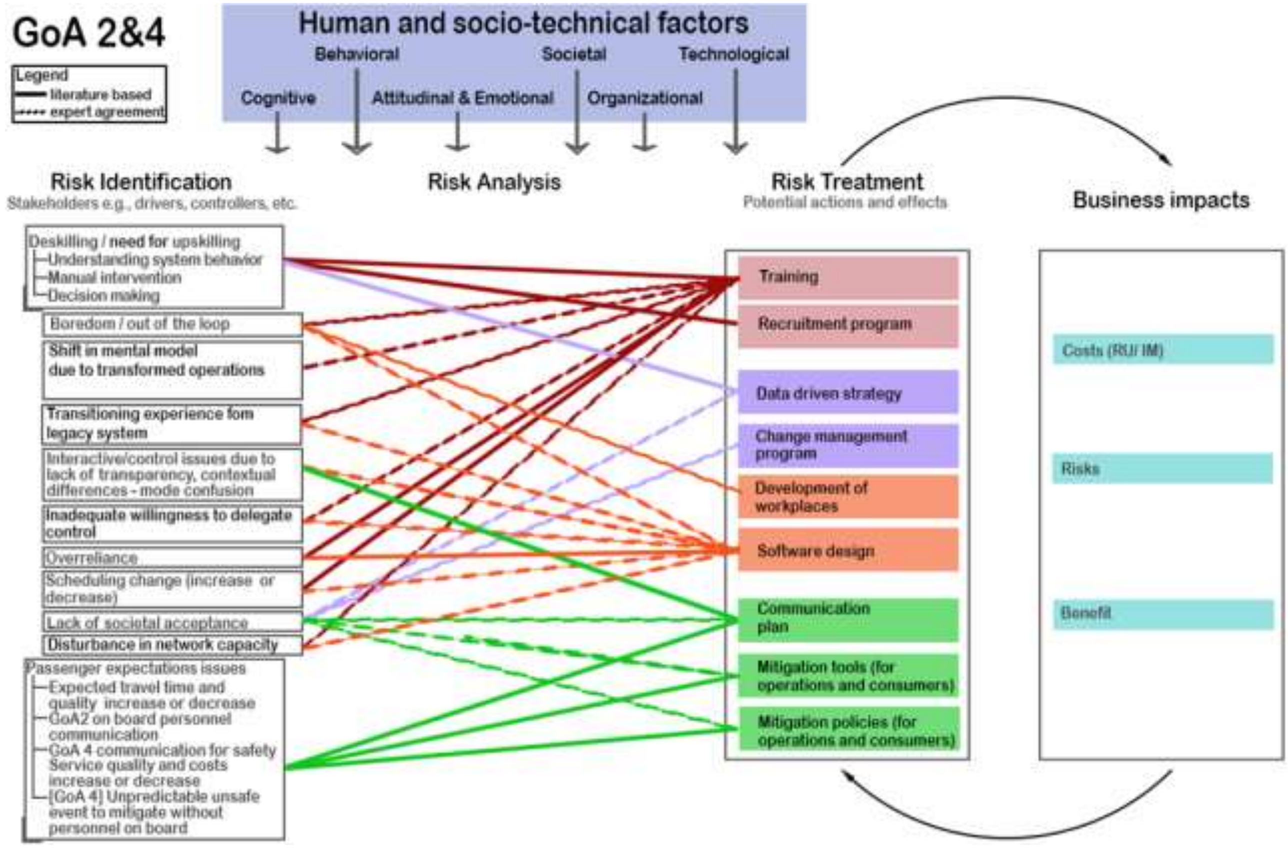

Figure 6: Interface Matrix linking Human Factor induced risks with Risk Treatments and Business Impacts (D32.4; Lo et al., 2026)

Automation reduces the driver's active involvement and changes the work to a passive supervisory role (Vanderhaegen et al., 2021). This change can make the work mundane and routine, leading to boredom and understimulation (Cogan & Milius, 2022), causing operators to be “out of the loop” from the system. Drivers may experience a decrease in vigilance, where their ability to detect anomalies or respond quickly to critical events deteriorate (Ahmadi Rad et al., 2021; Australian Transport Safety Bureau, 2024; Robinson et al., 2015).

Mode confusion occurs when train operators misinterpret or lose awareness of the automation level, e.g. GoA1 to GoA2, leading to errors in role expectations, system monitoring, or interventions (Ahmadi Rad et al., 2021; Stene, 2018). Mode confusion may contribute to accidents, such as signals passed at danger (SPAD) or derailments, for example, when operators misinterpret the signals that indicate movement authority for manually driven trains to run ATO trains in disrupted situations that require more careful driving (Ahmadi Rad et al., 2021).

The lack of transparency in the software and interface design can also contribute to the errors and mistrust towards new technologies related to automated systems. Reliability of the ATO system is a critical factor, because it will influence the train operator’s willingness to delegate control to the ATO system, especially in GoA2 levels of automation (Azevedo Sa, 2021). If the system consistently demonstrates a robust performance across various scenarios, including adverse weather and operational disruptions, operators are more likely to trust and rely on the system (Hoff & Bashir, 2015).

Ultimately, adopting ATO is done to improve the competitiveness of railways compared to other modes of transport. While the potential advantages of automated trains such as reduction in prices, and better availability (through higher capacity and more frequent services) can be easily understood by the passengers, some surveys suggested that passengers would only find it acceptable if it did not compromise safety (Cogan & Milius, 2022; Fraszczyk et al., 2015).

4.2.2.2 Risk Analysis

The process of developing risk treatment from the identified risk involves the analysis of various human and socio-technical factors discovered in the initial literature search and expert input. The cognitive and attitudinal aspects in train operators were assessed through the review of human factors research utilising human in the loop (HITL) simulations. HITL simulations are utilised as an experimental method to test the impact of new technologies such as interfaces and software on train operators. A synthesis of existing HITL studies in the literature compiled a list of aspects that were tested and found to affect train operators. This information is then used to develop a human factors toolkit in rail research. Additionally, the development of the model involves multiple iterations of review with various experts in railway operations and human factors. A more detailed review on the process and development of this method is outlined in Deliverable 32.4 (Lo et al., 2026).

4.2.2.3 Risk Treatment

There are several actions that can be taken to anticipate risks or minimize the consequences of the risk. Training will be a critical part of addressing risks caused by operator role changes. Current staff should be able to be properly retrained, and new staff should be selected based on competencies relevant to the new technology rather than relying on previous hiring requirements (Brandenburger & Naumann, 2018). The adoption of new technologies should always be accompanied by a comprehensive change management program. Strategic alignment between different stakeholders is also critical in facilitating transition of technologies. Collaborative approaches, stakeholder engagement, and incremental deployment can mitigate risks and inhibit limitations on automation technologies (Morin et al., 2025).

Train operators should also be involved in the design process of new automated technologies to understand their needs for the job, whether it is in interfaces or software development. These design choices should be able to anticipate cognitive risks such as boredom and loss of situation awareness. The implementation of new technologies should also be communicated through a sector communication plan that addresses public concerns, as advised by studies on passenger acceptance of automated rail (Detjen et al., 2021; Arzer et al., 2024).

Another component of risk treatment is the development of mitigation tools and procedures. This should be integrated during software and hardware implementation, as well as codifying instructions and procedures, particularly related to safety operation of automated trains. On the passenger acceptance side of ATO GoA2, tools such as visible safety features, information transparency and human-like communication can be used to anticipate societal acceptance of automated rail.

The risk treatment above can also be organised based on the target of treatment, as shown in Figure 7 below. Individual treatments deal with the risk aspects related to the effects of system changes on train operators. As previously outlined, implementing new systems with automated components will most likely result in a shift in roles and changes in job description. This would in turn require a retraining of current employers to fit the new job requirements and an adjustment of what competencies are needed future employees. Addressing these issues fall within the domain of the direct employers of train operators, such as infrastructure managers and train operating companies, particularly the human resources departments. The development of such programs should also involve regulation bodies and worker's unions to ensure equitable processes where all involved parties can cooperate.

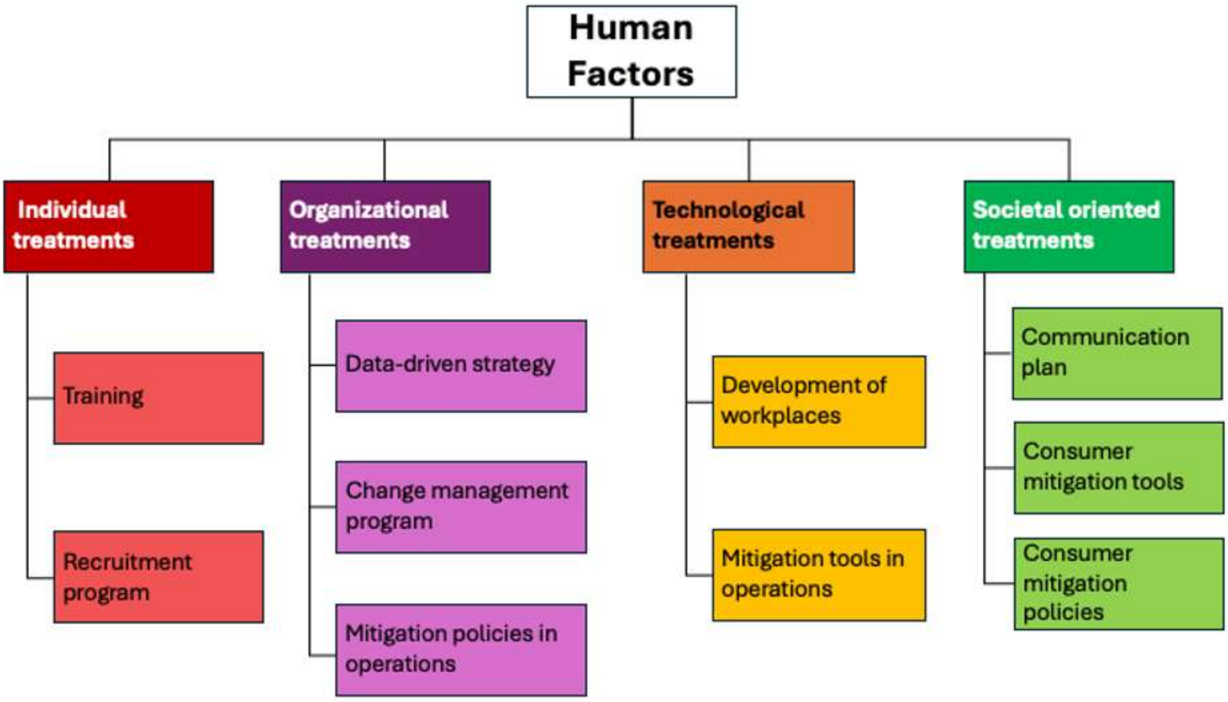

Figure 7: Human Factors Treatment Types

Organisational level treatments involve strategizing change within organisations responsible for conducting train operators. This falls mostly to the leadership of infrastructure managers and railway undertaking with regulatory oversight by train operators and governmental bodies.

As with any technological advancement, risk should also be addressed on the technical side. Here responsibilities lie with parties responsible for software development and implementation, in this case technology suppliers, infrastructure managers, and railway undertaking. It is also important for regulators to provide oversight.

To ensure a smooth adoption of automated train systems, it is also important to examine risk aspects related to end users, i.e., passengers, as well as the societal perception of automated train operations of the public. Communication plans should be co-designed between all stakeholders. The communication plans could be developed to target certain demographic or address specific concerns. A more extensive review of is included in Deliverable 32.4. In addition, there are also mitigation tools and policies as it relates to the experience of passengers, with a particular emphasis in addressing safety concerns.

4.2.2.4 Business Impact

We defer a discussion of business impacts to Section 4.4 below, as we use a Tree of Indicators, a concept introduced in Section 4.3 below, to interpret them for Human Factors.

4.2.3 **Costs**

4.2.3.1 Introduction

In addition to having a clear understanding of the benefits and uncertainties associated with implementing a DATO concept, a business case also requires thorough insight into the cost side of implementation. Here, this work package runs into a strong limitation, because specific cost data for DATO concepts are only available for prototype developments, if at all. Furthermore, they are mostly confidential. Namely, cost structures often reveal strategic information about operations, procurement, and labour and asset management. Sharing this data could expose a stakeholder's future investment or personnel strategy, or compromise their negotiation position relative to competitors, suppliers, or funding authorities.

As a result of the sensitive character of DATO cost data, we are forced to fall back on existing literature that outlines cost structures and rough estimates of aggregated cost categories in the European railway industry. These studies usually rely on anonymized surveys, sometimes employing elaborate statistical methods to derive ballpark cost estimates. Using this, we can still construct a matrix of cost types per stakeholder and DATO concept. This suffices for the goals of this Work Package. The division by stakeholder corresponds to our Strategic Framework.

4.2.3.2 Literature review

A seminal study by Baumgartner (2001) provides a comprehensive overview of various cost types and order-of-magnitude price ranges within the rail sector, focusing on investment, maintenance, and operation costs related to infrastructure, rolling stock, and associated systems. Although it is already 25 years old, it provides a benchmark categorisation of infrastructure investments (e.g., tracks, bridges, stations), rolling stock investments and maintenance costs that subsequent cost literature has built upon. Maintenance costs are expressed as annual expenses linked to infrastructure type and rolling stock, often as a percentage of the investment value. Indeed, the article emphasizes the importance of distinguishing costs over the life cycle and accounting for the economic lifespan and maintenance as key components of a business case.

A next authoritative report by Gatusso and Restuccia (2014) presents a methodological approach to systematically estimate costs in regional rail projects, making a distinction between investment (infrastructure, fixed equipment, rolling stock) and operational costs (traction, depreciation, maintenance, salaries and access charges). Both studies classify costs into categories such as infrastructure, rolling stock, and operational expenses.

Egamberdiev & Lee (2016) offer a life cycle cost (LCC) approach specifically for railway locomotives. The authors underline that a thorough LCC analysis is vital for making optimal decisions concerning purchasing, maintenance, and operation of locomotives, which typically remain in service for over 30 years and represent significant investments. The systematic approach includes three main cost components: (i) Investment costs, including engineering, training, and initial spare parts inventory; (ii) operating costs, covering labour, energy consumption, maintenance (both preventive and corrective), as well as delays caused by maintenance activities; and (iii) disposal costs, such as decommissioning and environmental management.

An interesting observation from the article is that many costs are so-called iceberg costs, hidden below the water until thorough LCC analysis uncovers all expenditures over the system's life. These insights further underline the importance of understanding all cost elements throughout the life cycle when compiling a business case, including those that emerge during operation.

A more recent initiative adopting a similar approach is the Total Cost of Ownership (TCO) framework developed by the Round Table Rolling Stock (RTR) initiative (Round Table Rolling Stock, 2020). This framework provides a hierarchical breakdown of all cost types relevant to the procurement of new rolling stock, defined at a highly detailed level.

Another recent initiative by the European Union Agency for Railways established a task force (ESG) to develop standardized inputs for economic analyses in the railway sector (European Union Agency for Railways, 2025). The ESG aims to close the knowledge gap concerning average reference costs for railway assets and operations, as well as other metrics useful for conducting cost-benefit analyses. Their primary deliverable is the 'Railway System Data Inventory' (RSDI), a repository of detailed indicators showing indicative cost ranges for various railway subsystems at the EU level.

The RSDI mainly provides order-of-magnitude information, as most values/ranges are derived from a combination of literature and anonymous surveys of rail sector stakeholders. While this document is highly useful for obtaining reference data on several cost types, its focus lies mainly on large infrastructure projects and does not yet contain some cost categories relevant to developing business cases for implementing new DATO concepts.

The RSDI provides a recent European-wide study that distinguishes cost indicators related to infrastructure and rolling stock, categorizing investment costs, maintenance costs, economic life, purchase costs related to vehicles, vehicle utilization, and several indicators tied to ERTMS onboard systems. In such, although still partial and evolving, the RSDI offers an authoritative source of reference data for certain cost categories when working on the development of business cases for DATO concepts.

A recent report (European Commission, 2025) highlights that the costs associated with the deployment of ERTMS onboard systems for existing vehicles have increased substantially, particularly in terms of retrofitting and upgrade expenses per vehicle between 2018 and 2022. The study identifies several key cost drivers behind this rise and proposes potential strategies to mitigate them. Notably, authorization-related costs represent a significant factor contributing to the overall increase. Additionally, the presence of missing or inadequately defined interfaces further increases costs, as it limits the possibility of integrating third-party solutions in a plug-and-play manner. This report underscores that cost considerations play a critical role in the implementation and attractiveness of DATO concepts (in this case, ERTMS), with particular emphasis put on retrofitting and update costs.

All these studies highlight the complexity and variability of costs. Most studies call for adopting an integrated life cycle approach when estimating costs in cost-benefit analysis. This approach should encompass not only initial investment costs but also operational and maintenance costs over the entire service life. After implementing a DATO concept, maintenance costs can be lower or higher than before implementation. Our take-away was to use the RSDI and the TCO structure developed by the RTR initiative as a basis to develop some reasonable list of all relevant cost types.

4.2.3.3 List of cost types for DATO business cases

Based on insights from the studies outlined above, including the example of the TCO structure developed by the RTR initiative, we conducted an inventory of cost types potentially relevant for developing a business case for a DATO concept. This inventory also draws on the expertise of the work package participants who have experience in developing business cases within their internal companies.

The inventory aggregates cost categories towards a higher level of abstraction. This approach reduces complexity and enhances applicability, resulting in a more generic list that is suitable for a wide range of DATO use cases. The final list comprises sixteen cost types, divided into two main categories: Capital Expenditures (CAPEX) and Operational Expenditures (OPEX). Table 2 below shows this list of cost types and relates them to the consulted sources explained above.

Cost type		***ESG - Railway System Data Inventory (2025)***	***Round Table Rail - TCO Structure (2020)***	***Baumgartner (2001)***	***Gatusso & Restuccia (2014)***	***Egamberdiev & Lee (2016)***
Project Management			Project management cost, tender costs,	Project costs including feasibility study, preliminary study, project management	Feasibility study, preliminary study and project	
Technology Procurement	**On-board systems**		Material cost	Investment in rolling stock	Rolling stock investment cost	Equipment and material procurement cost, initial spares cost
	Trackside systems	ETCS trackside upgrade/deployment	Material cost	Investments in signalling, cables, telecommunications		
Integration and installation	**On-board systems**	Certification, ESC/RSC type certification, prototype/series deployment and retrofit, upgrade time	Engineering & development, homologation			Engineering cost, installation cost
	Trackside systems		IT integration cost, special tools equipment & assets			
	Infrastructure		Infrastructure integration cost	Investments in infrastructure such as tracks, platforms and noise barriers		
	Maintenance		Maintenance integration cost	Rolling stock life cycle maintenance costs including preventive and corrective maintenance, spare parts, and overhaul		
Training			Training cost			Initial training cost
Maintenance	**On-board systems**	Trainset/wagon service unavailability	Preventive and corrective maintenance, revision cost, repair cost, repair cost	Maintenance costs of rolling stock	Rolling stock maintenance	Corrective and preventive maintenance cost

	Trackside systems	ETCS trackside maintenance	Preventive and corrective maintenance, revision cost, repair cost, repair cost	Maintenance on signalling, telecom and automated signalling		
	Infrastructure	Signalling equipment, track, catenary, telecom, platforms, safety device, noise barrier, substations maintenance cost	Maintenance infrastructure cost	Track and infrastructure maintenance costs		
Staff			Train driving cost		Operating personnel costs including drivers, on-board crew	
Energy consumption		Energy consumption: intercity train, regional/intercity EMU, suburban EMU, high speed EMU	Energy consumption cost	Traction power consumption: electricity and diesel consumption	Traction cost	Energy consumption cost

Table 2: Cost types and examples traced to literature

Table 2 shows that each source provides a list of cost items tailored to different objectives and scopes. It shows that certain cost types are not explicitly named in every source, either because they are embedded within other categories or because the scope or objective of categorization differs. Still, these sources and their examples remain valuable references and can be used, where appropriate, to support cost estimations with quantitative benchmark data. For instance, when a cost item is included in the Railway System Data Inventory (RSDI), this resource can be consulted to obtain relevant benchmark figures. This mapping thereby provides transparency on the alignment and distinctions between our cost framework and the underlying academic and industry cost classifications.

We define CAPEX as one-time investment costs required to implement a new DATO concept, and we define OPEX as recurring costs related to the operation and maintenance of the DATO concept over its life cycle. We list short descriptions of the sixteen cost types divided into CAPEX and OPEX below.

1. CAPEX
    a. *Project management*: All costs related to project management during the migration phase of implementing the new DATO concept. This includes expenses incurred for adapting existing business processes, change management, and efforts by the entire project team.
    b. *Technology procurement*

I. *On-board systems*: All one-time costs of the equipment introduced on the train. Examples, depending on the concept, include an ATO onboard system and perception systems. The cost category *on-board integration* covers additional hardware costs for retrofitting existing trains.

II. *Trackside systems:* All one-time costs of the equipment introduced on the shore side. Examples include ATO trackside systems or remote-control centers.

c. *(System) integration and installation*

I. *On-board integration:* All one-time costs for integrating the required hardware and software into new or existing trains. This includes costs related to homologation with authorities, required consultants, and necessary tests for authorization. Furthermore, it includes costs related to the engineering and development of the rolling stock product.

II. *Trackside integration and installation*: All costs related to the integration of onboard IT interfaces with track-side systems. This also includes one-time costs required to modify existing IT systems to support the migration to a new DATO concept. Examples include changes to planning systems for rolling stock, personnel, and timetable design.

III. *Infrastructure integration*: All one-time costs required for investment in or modification of infrastructure, such as changes to tracks or platforms.

IV. *Maintenance integration*: All one-time costs required for the investment in or modification of maintenance locations and processes, such as changes to depots or workshops due to new rolling stock and adaptations of documentation.

d. *Training*: All costs related to training and instructions, including preparation and execution. This covers training for all impacted staff such as train drivers and maintenance personnel. Training expenses are twofold: the preparation of training content and tools, and the temporary unavailability of staff from their regular commercial services (personnel detachment).

2. OPEX

a. *Maintenance*: All changes in costs related to activities required to preserve the original condition of an asset or resource for as long as possible while compensating for normal wear. This includes preventive maintenance, corrective maintenance, revisions, and software updates. Maintenance costs can occur in three main areas: onboard systems, trackside systems, and infrastructure – and can be higher or lower compared to the situation before implementing the DATO concept.

I. *On-board*: Maintenance and licensing costs resulting from new or extended capabilities on the train.

II. *Trackside*: Maintenance and licensing costs resulting from new or extended capabilities on the trackside, including higher requirements for system availability for infrastructure, trackside systems, and remote operation centers.

III. *Infrastructure*: Maintenance costs that change due to new or modified capabilities in the infrastructure, such as tracks, platforms, and related supporting systems.

b. *Staff:* All recurring costs resulting from changes in operational roles, including both the introduction of new roles and the elimination of existing ones. Examples include additional costs for providing on-site technical support, which train drivers currently perform, or a reduction of train drivers due to the introduction of ATO GoA4.

c. *Energy consumption:* All costs related to changes in energy usage and the resulting expenses or savings. This includes for example, cost reductions due to energy-efficient driving with ATO or increased energy costs due to an increase in capacity.

4.2.3.4 Cost interface matrix

We can map the identified cost types to the stakeholders involved in the implementation of DATO concepts, as well as to the concepts themselves. Figure 8 below shows this interface matrix. It provides an indication of which stakeholder we expect to bear the cost for each cost type. It also indicates the DATO concepts for which we expect the cost type to be relevant.

Cost type		**Operator**	**Infrastructure manager**	ATO GoA2	ATO GoA4	NG-Brake	HTD	Remote Operation
Project management								
Technology procurement	On-board systems							
	Trackside systems							
Integration and installation	On-board systems							
	Trackside systems							
	Infrastructure							
	Maintenance							
Training								
Maintenance	On-board systems							
	Trackside systems							
	Infrastructure							
Staff								
Energy consumption								

Figure 8: Interface Matrix for Costs: overview of cost types, stakeholders incurring the costs, and existence across different DATO concepts. Box filled = cost incurred.

Indeed, the costs incurred vary per stakeholder and depend on the implementation agreements made, particularly regarding who is responsible for which part of the system and who bears the cost. This supports our earlier claim of diverging stakeholder interests and the need for clarity on redistribution of resources at the early project stage.

For example, in an ATO GoA2 implementation, the operator may incur costs for equipping the rolling stock with the required new systems (e.g., on-board system costs and on-board integration and installation costs). At the same time, the infrastructure manager might bear the costs related to setting up the necessary trackside applications (e.g., trackside systems and trackside integration), depending on where the demarcation of responsibilities lies between the operator and the infrastructure manager.

4.3 The BuCa Methodology

Having constructed a strategic framework outlining essential elements of an effective and attractive BuCa methodology, as well as having constructed interface matrices that outline economic and financial indicators for the realms of capacity, human factors, and costs, we now proceed with an explanation of our BuCa methodology. Figure 9 below depicts the internal logic of the methodology. The following subsections explain the steps in detail.

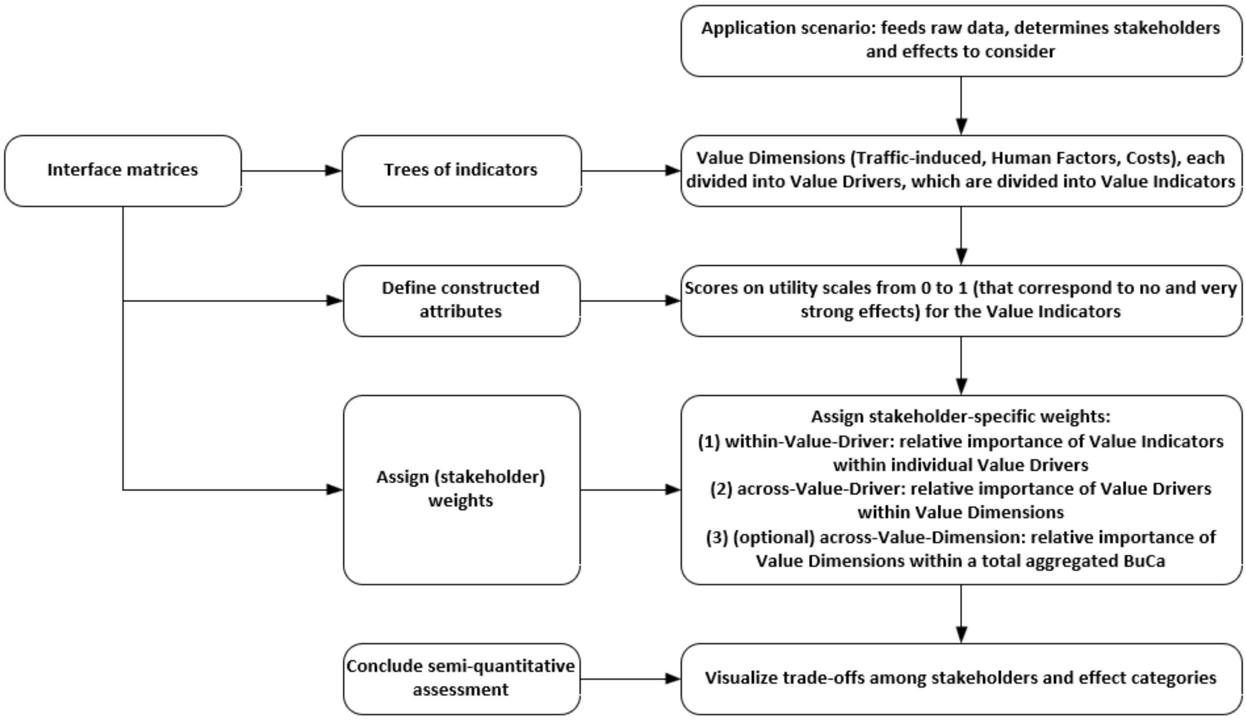

Figure 9: Representation of the several steps of our proposed BuCa methodology

4.3.1 Application Scenario

The first step of the methodology consists of defining the application scenario, which establishes the contextual basis for the assessment. This involves specifying both the DATO concepts to be studied and the network characteristics in which they will be applied. The network characteristics define the logistical and operational environment the project takes place in. The combination of these two dimensions allows the creation of representative scenarios that capture the diversity of operational contexts across Europe and supports a meaningful evaluation of the potential value and trade-offs associated with the considered DATO concepts.

4.3.2 Interested Stakeholders

The second step consists of identifying the interested stakeholders involved in or affected by the implementation of DATO concepts. This list of stakeholders is up to the one performing the analysis. It may include the generic train operator (or Railway Undertaking (RU)), infrastructure manager and societal policymaker, but it may also be specified at a more detailed level. For example, one may emphasize passengers, train drivers, unions, and regulators.

4.3.3 Trees of Indicators

Given the context of a major technological shift with high presence of qualitative or uncertain data, we aligned the BuCa methodology with value-based approaches. This adheres to MCA philosophy. As Figure 10 illustrates below, value is generated across multiple dimensions (Barbieri et al., 2024), each capturing different facets of value and represented as tuples of value drivers and value indicators. In this context, value drivers (or enablers) are factors that significantly influence the realization of value, while value indicators (metrics) are the performance measures used to assess these drivers. For the purposes of this work, in line with the interface matrices described above, we consider traffic-induced effects, human factors, and costs as the primary value dimensions.

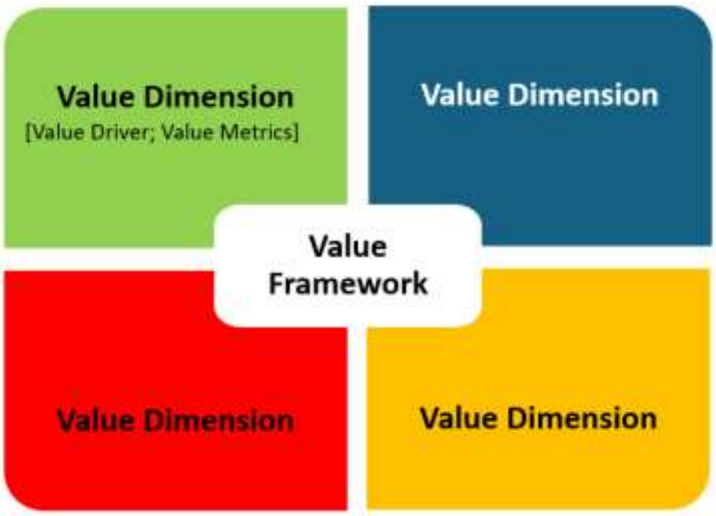

Figure 10: Conceptual representation of DATO Value as the aggregation of multiple value dimensions, each defined by specific value drivers and value indicators

Building on the conceptualization of value shown in Figure 10, one can represent each dimension as a hierarchical structure of value drivers and their associated indicators, as shown by Figure 11 below. This hierarchical breakdown, referred to as a *Tree of Indicators*, enables a systematic and transparent assessment of how DATO concepts contribute to the overall value dimension for the considered stakeholder or delivery partner.

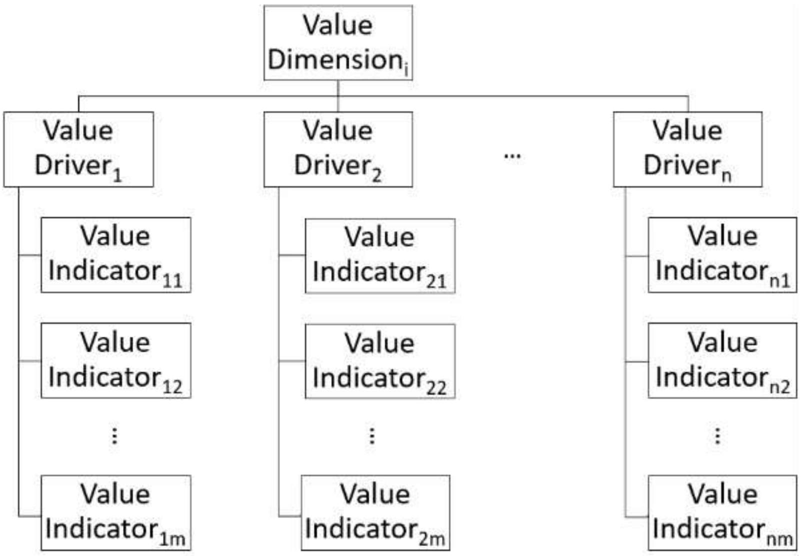

Figure 11: Tree of indicators for the i-th value dimension

4.3.4 Constructed Attributes

Building on the tree of indicators, we selected a *Semi-Quantitative Approach* for the assessment for two main reasons. First, the value elements considered span multiple dimensions that are not easily or reliably convertible into monetary terms without introducing significant assumptions, such as the effects on human factors. Second, uncertainty remains high for DATO concepts that are still at low-to-medium Technology Readiness Levels (TRLs), which limits the availability of precise, validated data.

The semi-quantitative method (Barbieri et al., 2025) enables a structured yet flexible evaluation while avoiding the false precision that purely quantitative monetary assessments might imply at this stage. In this regard, to account for uncertainty, constructed attributes are utilized (as illustrated later). These constructed attributes allow variables to be assessed through ranges. Hence, the approach can provide a practical way of addressing uncertainty while maintaining comparability across indicators.

Among MCA-based decision making, the *Multi-Attribute Utility* (MAU) method is an extension of conventional utility theory (Wallenius et al., 2008). In MAU, the attribute scale provides a means to measure the achievement of a specific objective, with the attribute referring to the quantity measured on the attribute scale (Clemen and Reilly, 2013). For instance, if minimizing cost is one of the objectives in a decision, then measuring cost in monetary units is an appropriate attribute scale, and the cost value represents the attribute for this objective.

According to Edwards et al. (2007), *Constructed Attributes* use scales with two or more distinct qualitative levels of objective achievement, each accompanied by a corresponding verbal judgment. Table 3 below shows a template for this match between scales and objective achievements. This approach converts an uncertain attribute into a deterministic one by introducing ranges or qualitative descriptions, thereby enabling the assessment of how DATO concepts contribute to each value indicator.

Constructed scale	Objective achievement
1	Description of the first attribute level
2	Description of the second attribute level
...	...
n	Description of the n-th attribute level

Table 3: Template for a constructed attribute with *n* constructed levels

Then, one can transform each constructed attribute into a *Utility* using the proportional score method (Keeney & Raiffa, 1993). In this approach, one assigns a score of 0 to the lowest level on the constructed scale and a score of 1 to the highest level, with all intermediate levels rated between 0 and 1 to reflect their relative preference with respect to these two extremes. This transformation converts each value indicator into a constructed attribute expressed as a normalized utility value, enabling the semi-quantitative summation and comparison of different DATO concepts.

4.3.5. Weights

Weights are assigned to reflect the relative importance of the different indicators within drivers, drivers within dimensions, and/or dimensions relative to each other, in the aggregation of overall value. This establishes the relative importance of the effects to be established.

4.3.6 Assessment

For the semi-quantitative assessment, we use Interface Matrices to link technical indicators to the corresponding value indicators. This linkage enables us to assign a specific attribute level and the corresponding utility value to each indicator. We then aggregate the results through weighted sums, combining the utility values with the weights defined in the previous step. Since the value generated by a DATO concept may vary across stakeholders and delivery partners, one can perform the assessment separately for each stakeholder or delivery partner, for each DATO concept, and for each considered application scenario (e.g., geographic location).

4.3.7 Trade-Offs

Once one completes the assessment, one can visualize the overall results as shown in Figure 12 below. This representation highlights trade-offs among stakeholders, facilitating the identification of potential alignments or conflicts in perceived value. It becomes clear why we proposed this methodology here. Namely, not only can the method handle qualitative variables and uncertainty, but it can also explicitly highlight trade-offs between stakeholders, value drivers, and across DATO concepts. In addition, the methodology allows for perceived values based on weights within and across value indicators, per stakeholder. This allows for a representation of which stakeholders value which metrics more.

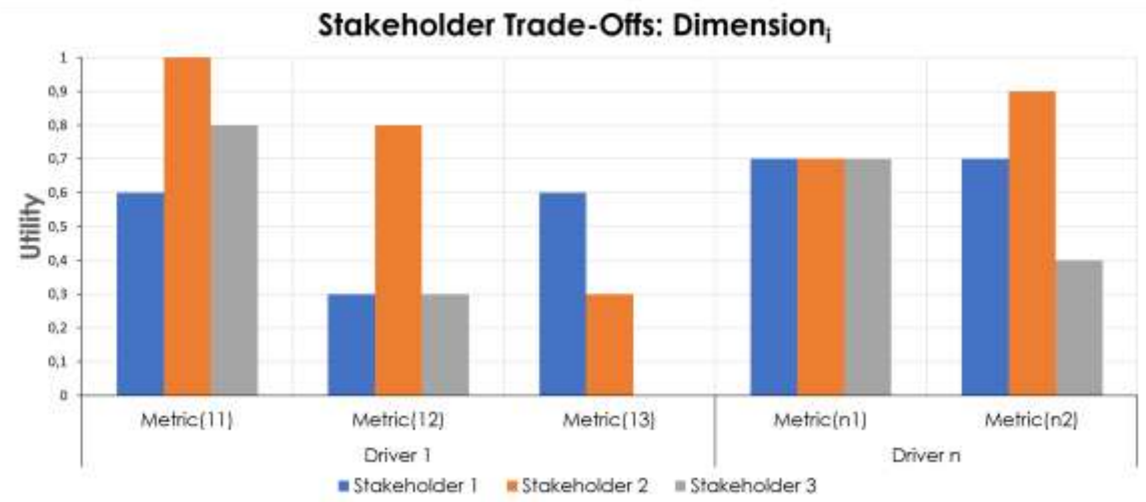

Figure 12: Example of stakeholder trade-offs for a given value dimension, highlighting potential misalignments in the perceived value of a DATO concept

4.4 Trees of Indicators

One key step in our BuCa methodology is to establish trees of indicators. This section describes the trees of indicators we defined for traffic-change induced (capacity) effects, Human Factors, and Costs, with the value indicators resulting from their respective interface matrices as input.

4.4.1 Traffic change induced effects

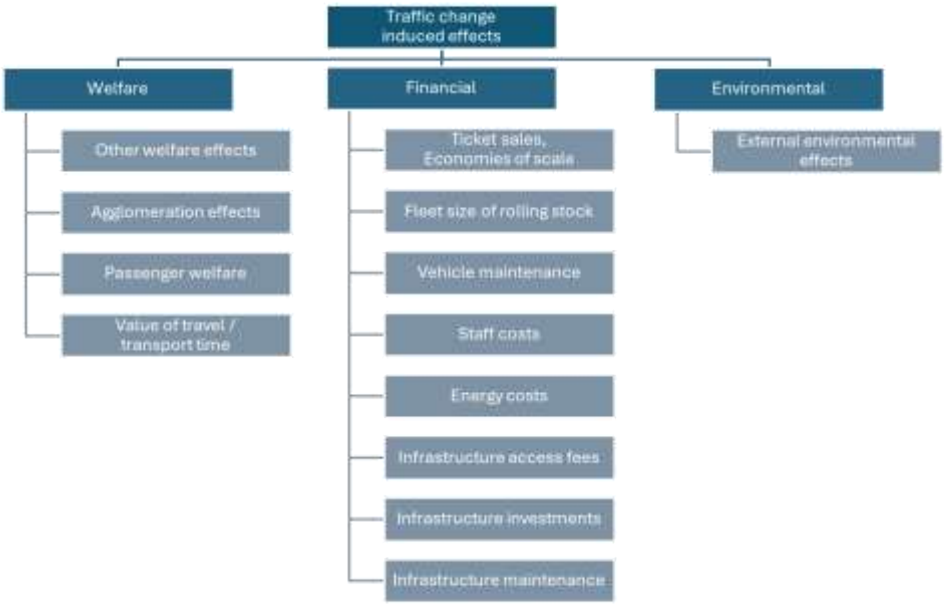

Figure 13: Tree of indicators for traffic change induced effects, following from the interface matrix of traffic change induced effects

In the interface matrix, we defined groups of effects by the stakeholder they accrue to. However, as the section above explains, stakeholders may also care about effects on indicators whose effects do not directly accrue to them. In addition, we signal that grouping metrics based on their type – societal welfare, environmental welfare and financial – feels more attractive. Hence, the tree of indicators for traffic-change induced effects sorts the value indicators into value dimensions of welfare, financial, and environmental effects. Figure 13 above presents the tree of indicators for traffic-change induced effects.

4.4.2 Human Factors

In contrast to the traffic change induced effects interface matrix or to costs, Human Factors do not really have a well-established economic or financial interpretation to refer to from existing transport appraisal guidelines or literature. A collaboration between human factors and business case experts within the Work Package yielded the insight that an untreated risk has a negative welfare effect (higher user errors lead to more incidents and lower job wellbeing), while a treated risk has both costs (treatment implementation) and benefits (abated risk of higher user errors and lower wellbeing). To avoid double-counting, we settle on the characterization that costs are measured as treatment costs, benefits are measured as positive wellbeing effects relative to the untreated scenario, and risks are measured as the potential consequences of usage errors. Figure 14 below presents the Human Factors tree of indicators in accordance with this.

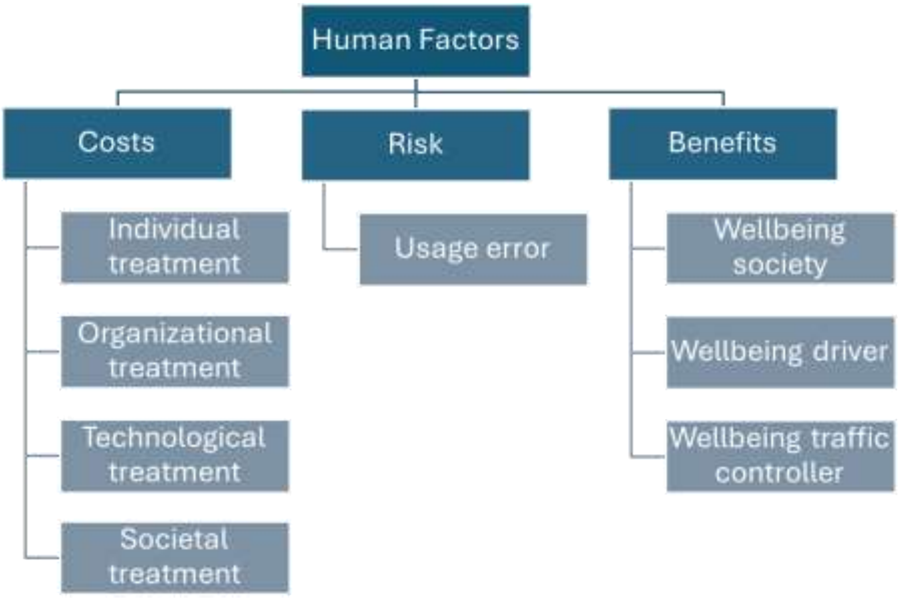

Figure 14: Human Factors Costs, Risks, Benefits, following from the interface matrix of human factors effects

More specifically, *Costs* in the human factors issues as it relates to value indicators generally refers to resources allocated to implement different risk treatment costs. Essentially, in accompanying upgrades in technical systems, investment in financial capital is necessary in addressing human factors risk through risk treatment, both through CAPEX and OPEX. Ensuring that systems comply with human factors requirement could require implementation of additional software and hardware, as well as associated maintenance costs.

In addition to capital costs, the implementation of software and change management programs, training and shift in recruitment materials, development of mitigation tools and procedures, etc. will also require human resource investment. Proper implementation of risk treatments will require involving experts with specialised knowledge and training, who may also need to facilitate knowledge transfer for management and operators.

In terms of *risks* introduced in human factors, one of the key goals of identifying human factors risk and developing risk treatments is to address potential safety issues. Not accounting for human factors risks and appropriately applying risk treatments could lead to avoidable errors and incidents that may cost money, capacity, and/or endanger the safety of train drivers/passengers. Safety failure incurs massive economic consequences not only in financial loss but also reputational damage and loss in trust. Errors in a human factors sense are often conceptualised as “human error.” However, the term human error is often interpreted as an error that is caused by a mistake of an operator interacting with the system, attributing fault to the human. Human factors error can also arise from the system not properly accommodating user needs and way of working. Thus, we encourage the use of the term “usage error” as the potential consequence of human factors risk.

Attending to human factors issues may also provide a *benefit* of improving the well-being of rail workers, as well as society at large by enabling the implementation of ATO. A survey of train drivers determined that major issues in their work include work hour and schedule, work-life balance, driving on the similar route in the same locomotives, behaviours of passengers and fallback strategies of the automatic systems (Qiu et al., 2011). Even in higher levels of automation, there is still some level of human-in-the-loop in rail operations, such as remote train drivers and train traffic controllers to supervise automated train traffic. Adjusting job descriptions and balancing employee workload would lead to more effective and satisfied workers and higher retention rates.

Additionally, well-being of society, particularly train passengers, is also an important component. When society can trust automated technologies in rail and feel safe using it, then the potential benefits in ATO usage can be reached. This is relevant as well to society as large, as public sentiment, which includes non-rail users, also shape automated rail’s acceptance in society.

While this model was initially developed for the context of GoA level 2, the concepts and relations outlined in this model also apply to transition to GoA level 4, the main difference being the elimination of onboard staff. So far, the most advanced shift to GoA 4 in the railway domain has been achieved for a freight use case in Australia (Smith, 2026), and application of GoA4 for passenger has been limited. Aspects related to in cab performance of train drivers are no longer significant, but remote driving may still be needed on occasion, so competencies regarding driving performance may still be relevant in contexts where the ATO system is degraded.

4.4.3 Costs

The tree of indicators for costs straightforwardly follows from the interface matrix for costs, which already contained the exact grouping of cost types (value indicators) into more aggregated cost categories (value dimensions), with emphasis on the difference between CAPEX and OPEX. Figure 15 below shows the resulting tree of indicators for costs.

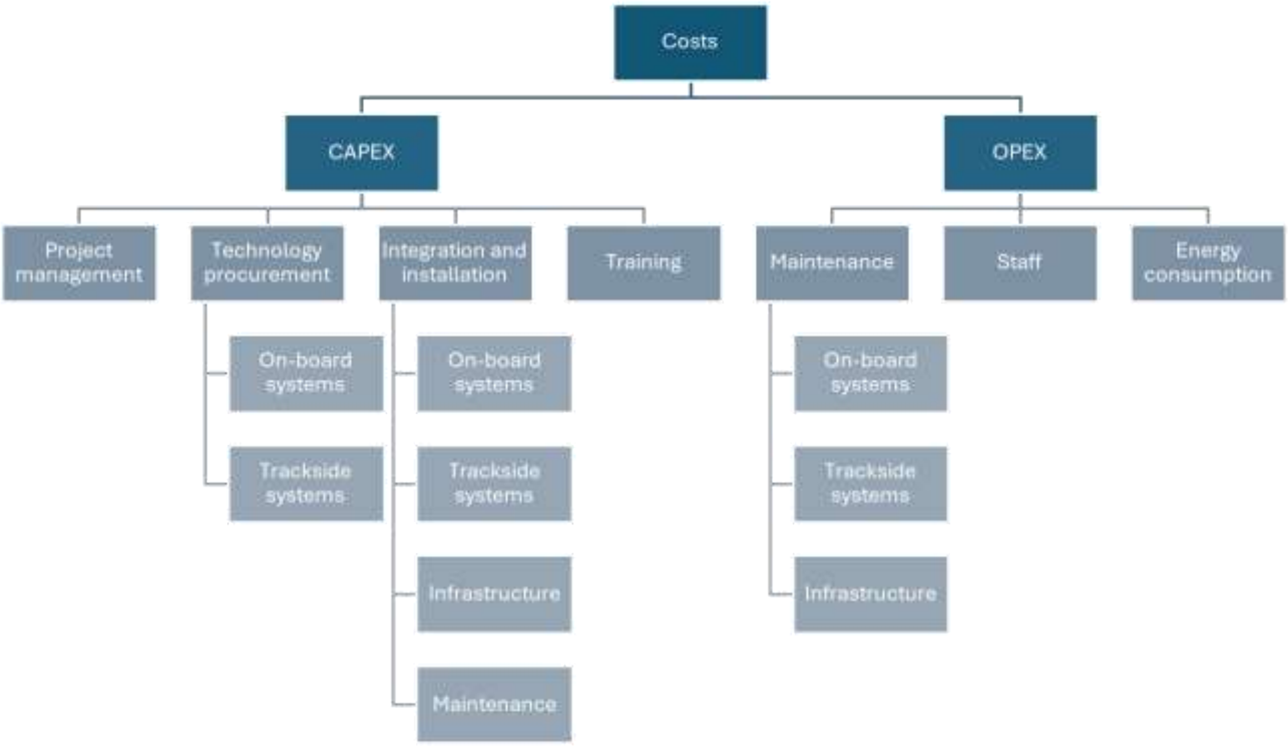

Figure 15: Costs tree of indicators, following from the interface matrix of cost effects

5 APPLICATION SCENARIO: NETHERLANDS, ATO GOA2

This chapter applies the methodology on a case study from the Netherlands, for ATO GoA2. For this geography and DATO concept, we use real input from capacity simulations (see Deliverable 32.5; Koopman - van Welij et al., 2026) and human factors experiments (see Deliverable 32.4; Lo et al., 2026). In addition, we draw from expert insights working in companies that have experience with ATO GoA2 testing and/or business case development.

Nonetheless, we lacked expertise in the valuation of many indicators within our project team. Hence, results should strictly be taken as illustrative only.

The chapter is structured as follows. First, Section 5.1 describes the workshop in which respective experts performed semi-quantitative value mapping by constructing attributes for the value indicators defined by the trees of indicators, using their knowledge as well as measurements stemming from the capacity simulations and human factors experiments. Next, Section 5.2 describes results, first per tree of indicator, then across trees of indicators, focused on relative trade-offs between stakeholders. Finally, Section 5.3 draws conclusions from this application of our BuCa methodology.

5.1 BuCa Workshop

The BuCa methodology was applied to the selected application scenario through a structured workshop. The workshop involved participants from the WP32 consortium, including infrastructure managers, train operators, and academic partners. Participants applied the methodology to evaluate DATO concepts within a defined application scenario. A Miro board (see Figure 16 below) was used to guide participants through the methodological steps. Excel was used for the assessment, with separate sheets defined per stakeholder. The exercise focused on demonstrating applicability rather than conducting a full quantitative business case. Detailed cost estimation and long-term modelling were therefore excluded. The scope is limited to semi-quantitative evaluation and methodological validation.

The BuCa workshop centred around a representative DATO application scenario, in which participants assessed the impacts of automation technology (GoA2) in the Netherlands. This scenario simulated early-stage decision-making conditions where uncertainty is high and multiple stakeholders must evaluate trade-offs. Participants were asked to assess value across three value drivers: Traffic (Welfare–Financial–Environmental), costs (CAPEX–OPEX), and human factors (Benefits–Costs–Risks). Figure 17 below illustrates this.

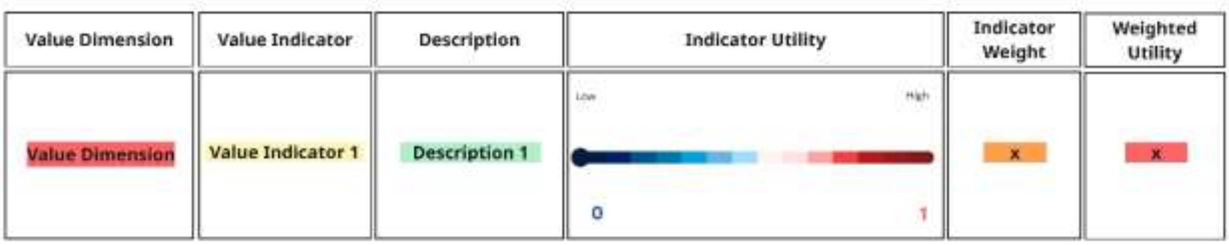

Figure 16: Example of the Miro board used to guide participants through the BuCa methodology

The workshop session began by presenting the conceptual framework, including the role of application scenarios, stakeholders, and value dimensions. This step emphasized that the objective of the methodology is not to produce a single aggregated value but to reveal stakeholder-specific trade-offs. It is important because it aligns participants on the purpose and logic of the method, ensuring consistent interpretation.

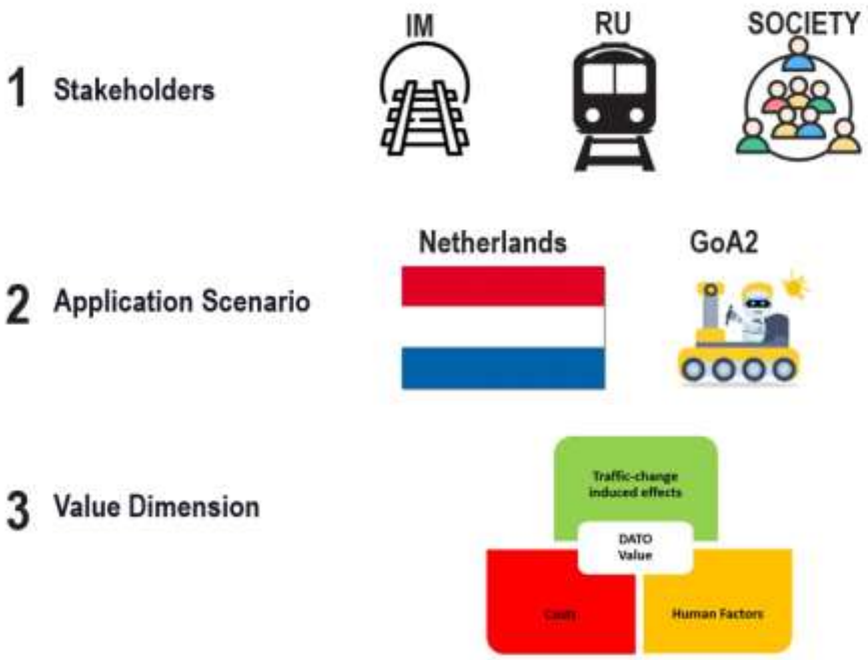

Figure 17: Boundary conditions of the assessment, showing the selected stakeholders (Infra Manager, Train Operator, Society), the application scenario (Netherlands, GoA2), and the selected value dimensions.

1. Application Scenario: participants were introduced to the selected DATO scenario, including the technologies (GoA2) considered and the operational context. This step ensured that all evaluations were grounded in a common reference frame. It is important because it defines the boundary conditions for the assessment.
2. Interested Stakeholders: participants identified and worked from the perspectives of railway undertakings, infrastructure managers, and society. This enabled parallel evaluation of impacts across actors. This allows the methodology to capture divergent priorities and potential misalignments.
3. Trees of Indicators development: participants worked with structured trees of indicators for each value dimension (Traffic, Costs, Human Factors), which correspond to the ones presented in Chapter 4. In such, we ensured a complete and non-overlapping decomposition of value drivers. This step translated abstract concepts into measurable elements. This structures complexity and prevents double-counting.
4. Constructed Attributes: participants defined indicators using a 0–1 scale with qualitative anchors, ensuring a consistent evaluation of both qualitative and quantitative effects. These constructed attributes were developed in alignment with the Interface Matrices, as illustrated in Figure 18 below.

Indicator	Description
C1. Project management	All costs related to project management during the migration phase of implementing the new DATO concept. This includes expenses incurred for adapting existing business processes, change management, and efforts by the entire project team.
C2. Tech procurement: On-board systems	All one-time costs of the equipment introduced on the train. Examples, depending on the concept, include an ATO onboard system and perception systems. Additional hardware costs for retrofitting existing trains are covered by the cost category on-board integration.
C3. Tech procurement: Trackside systems	All one-time costs of the equipment introduced on the shore side. Examples include ATO trackside systems or remote control centers
C4: Integration/Installation: On-board systems	*On-board integration:* All one-time costs for integrating the required hardware and software into new or existing trains. This includes costs related to homologation with authorities, required consultants, and necessary tests for authorization. Furthermore, it includes costs related to the engineering and development of the rolling stock product.
C5: Integration/Installation: Trackside systems	*Trackside integration and installation* : All costs related to the integration of onboard IT interfaces with track-side systems. This also includes one-time costs required to modify existing IT systems to support the migration to a new DATO concept. Examples include changes to planning systems for rolling stock, personnel, and timetable design.

Figure 18: Example of descriptions for value indicators

5. Weights: the weighting procedure consists of two steps. Participants first assigned weights to each metric expressing relative importance across indicators within a value driver ($w_{indicator}$). These values sum to one for representing proportional importance. Then, participants assigned weights to the drivers (a_{driver}). Figure 19 below shows an example.
6. Assessment: Final scores are calculated by combining both components per stakeholder. In this way, a weighted utility is first computed for each indicator:

$$WeightedUtility_{indicator} = w_{indicator}U_{indicator}$$

Then, a utility is assessed for each driver:

$$U_{driver} = a_{driver}\sum WeightedUtility_{indicator}$$

CAPEX (Train operator)			
Topic	Indicator Weight	Indicator Utility	Weighted Utility
C1. Project management	0,185	0,25	0,046
C2. Tech procurement: On-board systems	0,185	0,5	0,093
C3. Tech procurement: Trackside systems	0,037	0,1	0,004
C4: Integration/Installation: On-board systems	0,185	1	0,185
C5: Integration/Installation: Trackside systems	0,037	0,1	0,004
C6: Integration/Installation: Infrastructure	0,000	0	0,000
C7: Integration/Installation: Maintenance	0,185	0,05	0,009
C8: Training	0,185	0,6	0,111
CAPEX Total	1,000		**0,452**

Figure 19: Example of assessment of the weighted utility per indicator. To be taken as illustrative only.

7. Trade-off analysis: Stakeholders assessed the trade-offs associated with each value driver, identifying key influences and possible stakeholder misalignments. The objective is to facilitate informed decision-making. This involved comparing value drivers within the following dimensions:
   a. Traffic: Welfare vs Financial vs Environmental
   b. Costs: CAPEX vs OPEX
   c. Human Factors: Benefits vs Costs vs Risks

At the end of the workshop session, participants shared their results and reflected on the methodology, including its clarity, applicability, and limitations. The next section describes the results of this exercise.

5.2 Assessment Results

5.2.1 Traffic-induced effects

For traffic-change induced effects, we were able to include quite some quantitative data. For example, we were able to estimate a capacity benefit of around 26 million Euros per year of travel time welfare gains for the line segment that we executed capacity simulations on, which comprises roughly 9 percent of the passenger kilometres in the Netherlands. We refer the interested reader to Deliverable 32.5 (Koopman – van Welij et al., 2026) for this analysis, in which we also include a semi-quantitative assessment of the DATO techniques ATO GoA4, HTD and NG Brake.

After going through the exercise of defining constructed attributes and scoring them, we end up with distribution of welfare, financial and environmental effect size estimates across stakeholders presented in Figure 20 below. In the exercise, we assumed the highest weight based on value of travel time gains, as this was the largest quantitative effect. We were able to quantify agglomeration effects, ticket revenues, fleet size of rolling stock and staff costs, too. For the other value indicators, we made an estimate based on our expertise. As this expertise was severely lacking in certain areas, results are to be taken as illustrative only.

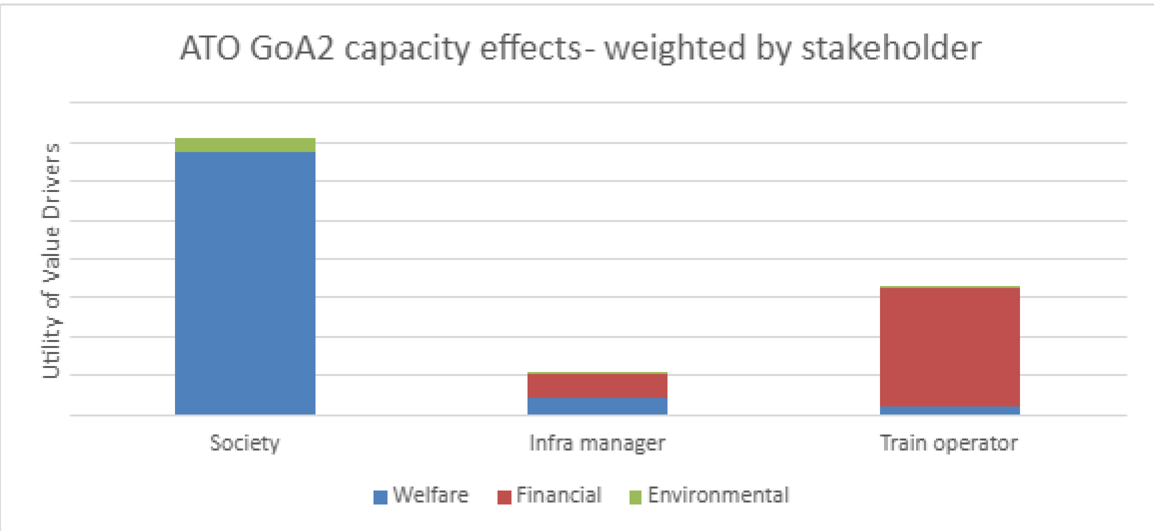

Figure 20: Semi-quantitative value mapping for traffic change induced effects, ATO GoA2, Netherlands, effects per stakeholder. To be taken as illustrative only.

For example, we assumed that the infra manager values labour conditions effects much more strongly than the other welfare indicators combined, and that the train operator or railway undertaking values labour conditions four times as much as passenger welfare, while not caring about welfare effects aside from that. We assumed that the societal policymaker does not value financial effects directly outside infrastructure investment changes, and we assumed that the introduction of ATO GoA2 on this line segment does not come with significant avoided infrastructure investment to satisfy the required line capacity, even though this might be the case in reality. We assumed that passenger welfare and other welfare effects have a size of roughly one tenth of the effect of abated travel time. Finally, we assumed that there is no effect on vehicle maintenance, energy costs and infrastructure maintenance due to traffic changes, as there are counteracting effects from faster running and harder braking versus higher operational stability leading to less unplanned braking and acceleration actions.

Despite our low fidelity, results suggest that society receives the bulk of the benefits from traffic changes, and that welfare effects are larger than financial or environmental effects. In addition, results suggest that no stakeholder has a net negative effect stemming from traffic (or capacity) changes. The total size of the effects shown in Figure 20 correspond to a monetary value of roughly 50 million Euros per year for the line segment that was studied, which comprises roughly 9 percent of the passenger kilometres in the Netherlands. We do not have similar monetary values for Human Factors and Costs below, so the informed reader may perform their own comparison if they do have an idea of the relative value of these. This is also why we exclude units on the vertical axes and exclude a final aggregation of all value dimensions.

5.2.2 Human factors

The human factors result indicates a differentiated distribution of costs, risks, and benefits across stakeholders (see Figure 21 below). Costs are highest for the Train Operator, driven by rolling stock modifications and individual-level interventions such as training. These measures directly reduce usage error and improve well-being, which explains their prioritisation despite higher costs. In contrast, the Infrastructure Manager incurs lower costs due to existing infrastructure investments (e.g., ERTMS), while society bears minimal direct financial burden.

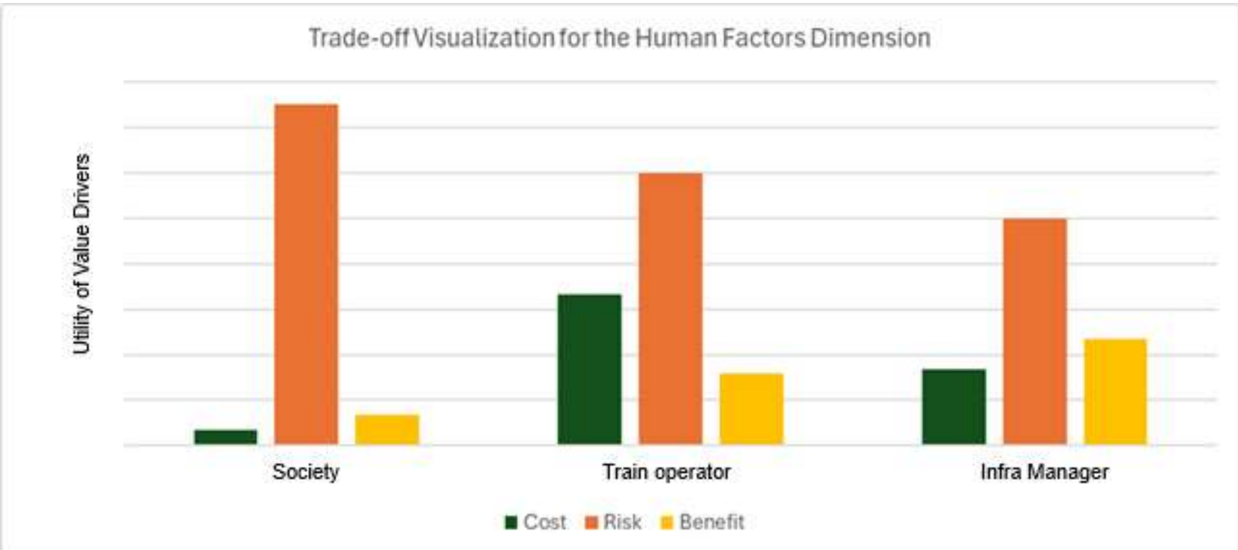

Figure 21: Semi-quantitative value mapping for Human Factors, effects per stakeholder. To be taken as illustrative only.

Value mapping confirms this distribution, with the train operator showing the highest cost value, followed by the infra manager and society. Note that these values are not comparable to the values for traffic induced effects or costs. Note also that these valuations were based on limited expertise and should again strictly be taken as illustrative only.

This demonstrates that implementation costs are concentrated within operational actors. Similar cost distributions have been observed in automation transitions, where system operators carry most adaptation costs while societal actors remain indirect beneficiaries.

Risks are dominated by usage error, where human factors experts in our exercise gave these risks a very high weighted value across all stakeholders. Note, however, that participants indicated that these judgements stemmed from very limited expertise, particularly regarding the valuation of safety outcomes. Since these are politically contentious to discuss, we err on the safe side by assigning huge values to them, which would always justify a treatment of a human factors risk rather than an acceptance, even at very high costs. Of course, a proper assessment needs to be done to confirm this rationale.

Benefits of the risk treatments, which result in higher well-being, are comparable for the train operator and infra manager, indicating moderate yet consistent gains in operational conditions. Technological interventions, particularly software development, play a key role by reducing usage error and improving system interaction.

Overall, the results indicate an interesting imbalance between cost allocation and risk exposure. The train operator bears the highest implementation costs for the human factors risk treatments, while society faces the greatest risk without treatment. Benefits are more evenly distributed between train operator and infra manager, whereas societal benefits take on greater importance when linked to perceptions of acceptance and safety. This distribution highlights the need to align investments, risk exposure, and expected benefits, particularly by addressing usage error as the central factor in implementation feasibility.

5.2.3 Costs

The cost results, too, are to be taken as illustrative only. We relied on expertise about the relative size of effects with respect to each other, which was limited for some cost types. One important thing to note is that costs heavily depend on economies of scale. That is, some costs are marginally decreasing in their implementation size. This is an important nuance in an analysis that aggregates the cost dimension with the capacity and human factors dimensions. It may be that a roll-out is not on aggregate beneficial at the individual railway line level but is on aggregate beneficial at the country or cross-country level.

Figure 22 below shows our semi-quantitative assessment of costs for ATO GoA2 in the Netherlands. They imply a differentiated distribution of CAPEX and OPEX across stakeholders. This is relevant because it clarifies how investment and operational burdens are allocated within the BuCa framework. First, the CAPEX distribution is analysed. Second, OPEX effects are examined. Third, combined cost implications are interpreted. The scope is limited to the cost dimension.

CAPEX is highest for the train operator, driven by project management costs, integration and installation of on-board systems, and training. This reflects the operator’s responsibility for rolling stock adaptation and implementation activities. In contrast, the infrastructure manager shows a significantly lower CAPEX, with contributions mainly from trackside system investments and training.

OPEX results show a contrasting pattern. For the train operator, OPEX also increase somewhat, mainly due to maintenance of on-board systems. Other operational categories (staff, energy consumption) remain negligible, reflecting uncertainty or limited short-term variation. Indeed, any staff benefit from lower running times or an energy consumption benefit from higher operational stability is not part of the cost value dimension, but of the traffic-induced / capacity dimension in our analysis. For the infra manager, OPEX is negative (−0.011), primarily due to reduced infrastructure maintenance costs (−0.014). Indeed, a negative cost, which is beneficial, is possible within the confines of our methodology too. The estimate suggests that automation and system optimisation may generate operational savings over time for the infra manager.

When combining CAPEX and OPEX, the results indicate that the train operator bears the highest overall cost burden, dominated by upfront investment requirements, while the infra manager experiences a lower capital burden and potential operational benefits. The scope is limited to the interpretation of aggregated costs.

Hence, the results show an asymmetrical cost distribution. This imbalance highlights the need to align cost allocation mechanisms, particularly in early-stage deployment, where upfront investments and long-term operational savings are distributed unevenly across stakeholders.

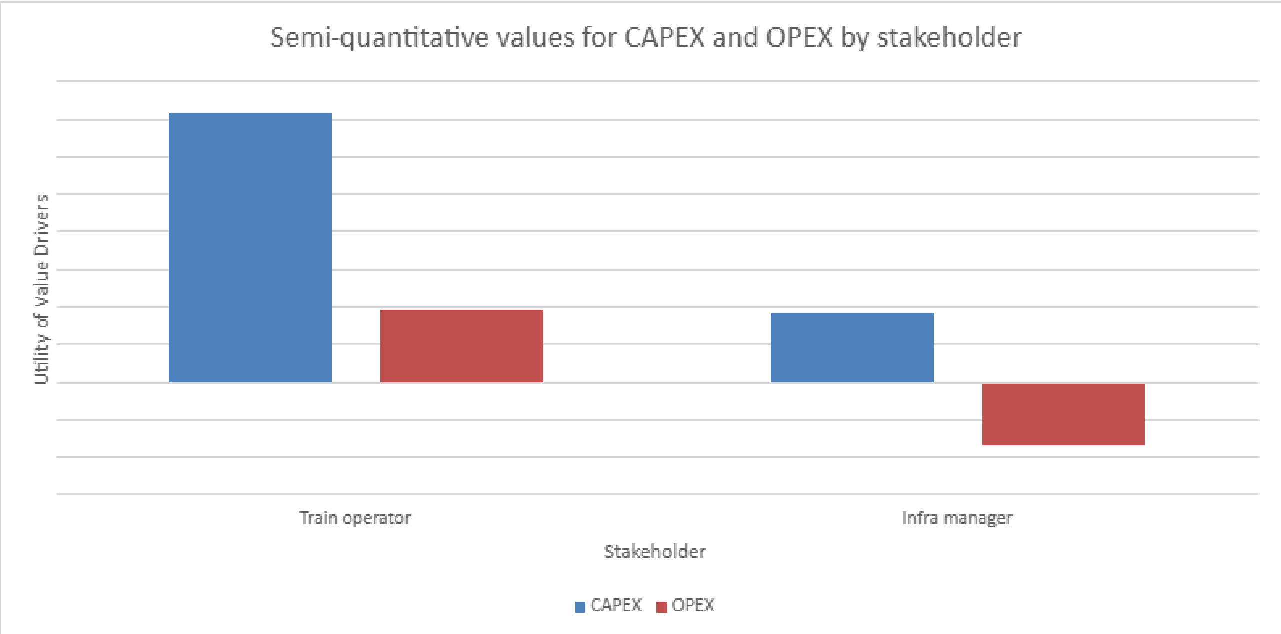

Figure 22: Semi-quantitative value mapping for Costs, effects per stakeholder. To be taken as illustrative only.

5.2.4 Stakeholder Trade-off

Note that we refrain from an exercise that aggregates the effects for traffic changes, human factors and costs into a final figure. While this would be insightful, we cannot justify it due to finding it too difficult to guess the size of the human factors effect – it may be factor or two lower than the size of the other categories from an economic and financial point of view – and as we do not have internal mandate at our companies to represent the size of the cost effect in this report.

Nonetheless, we can offer some qualitative conclusions. Value mapping builds on the weighted results by structuring and interpreting outcomes per value dimension and per stakeholder. Indeed, each dimension retains its own aggregation logic – traffic (Welfare vs Financial vs Environmental), cost (CAPEX vs OPEX), and human factors (Benefits vs Costs vs Risks). Results are not aggregated into a single metric, but mapped across stakeholders (Society, RU, IM) to show how benefits, costs, and risks are distributed. This enables the identification of patterns, asymmetries, and trade-offs while preserving the multi-dimensional structure of the assessment.

The presented results illustrate how the BuCa methodology differentiates value across stakeholders under a defined scenario. The scenario operates as a methodological test case. Taken together, the results show that value is unevenly distributed across stakeholders. Financial and human factors treatment costs are concentrated at the train operator or railway undertaking, while benefits are concentrated at society.

5.3 Discussion of Results

We applied the BuCa methodology to assess DATO concepts and to evaluate its suitability for early-stage decision-making. The results show that the methodology structures multi-dimensional value into clear and interpretable components. Value dimensions (traffic, economic, and human factors) are inherently difficult to integrate within a single framework. The use of dimension-specific aggregation preserves the internal logic of each domain, while the tree of indicators ensures a non-overlapping and traceable decomposition of effects. The semi-quantitative assessment enables consistent comparison across indicators without requiring full monetisation. In contrast to purely financial approaches, the methodology captures the multi-dimensional nature of DATO by explicitly representing the value drivers.

The results show that this structure enables the identification of stakeholder differences at the metric level. Value is assessed per indicator using constructed attributes, and weights for each stakeholder. This allows the detection of misalignments, defined as differences in how stakeholders experience benefits, costs, and risks. First, some stakeholders obtain high benefits with limited exposure to costs or risks (e.g., society in Traffic). Second, others carry disproportionate burdens, such as high CAPEX or operational responsibility (e.g., the train operator in Cost).

These misalignments indicate potential trade-offs between stakeholders. When one stakeholder captures limited benefits while bearing high costs or risks, resistance to implementation is likely. Conversely, balanced or positively distributed value supports alignment. The framework enables the explicit identification of these misalignments, supporting structured negotiation and decision-making.

The semi-quantitative approach supports evaluation under conditions of limited data availability. Note, however, that the methodology also supports iterative refinement as additional data becomes available.

Finally, the methodology also reveals limitations. Fully informed analysis requires significant expertise, and aggregation requires expert interpretation. Weighting introduces subjectivity, and limited data reduces the precision of estimates. The assignment of weighting should ideally be done by a broad consortium of affected stakeholders. In addition, interdependencies between indicators are sometimes assumed as accruing to one indicator instead of the other, which may simplify complex system interactions.

Future methodological development could focus on addressing these limitations in a future application. In addition, future methodological development should reflect advances in knowledge and maturity of the techniques by potential alterations of the interface matrices and subsequent systemic BuCa methodology.

Most importantly, however, future methodological development could incorporate uncertainty on the value indicator estimates, especially over time – that is, to incorporate which stakeholder incurs which cost or cashes in which benefit at which point in time. This should be the focus of further development in next phases of research.

6 CONCLUSION

This deliverable set out to develop and demonstrate an effective and generalizable Business Case (BuCa) methodology for DATO. Its primary objectives were twofold: first, to clarify how DATO technologies may generate value across multiple dimensions such as capacity, human factors and costs; and second, to provide a methodology that can foster fast and effective roll-out of DATO across Europe.

In response, the deliverable provides a coherent methodological framework that links technological effects to financial, economic, and societal outcomes, explicitly addressing stakeholder trade-offs and misalignment while remaining compatible with established European transport appraisal practices.

The methodology resulted from integrating insights from project management, operational change, and transport economics literature, as well as contributing to this literature with own case studies. These insights established that stakeholder misalignment is a key risk in DATO implementation programmes and why business cases must explicitly surface trade-offs rather than obscure them through aggregation. The interface matrices operationalise this insight by linking direct technical effects – in the realm of capacity, human factors and costs – to downstream value indicators familiar from transport appraisal practice. Finally, the BuCa methodology itself integrates these elements into a systematic assessment process.

We applied the methodology to an ATO GoA2 use case in the Netherlands. While the empirical results are strictly to be taken as illustrative (although in some places supported by concrete data and evidence), the exercise shows that the methodology can accommodate heterogeneous data sources and distinguish clearly between welfare and financial effects across different dimensions and stakeholders. Importantly, the application illustrates one of the core premises of this deliverable: that value from DATO is unevenly distributed across stakeholders. In the illustrated scenario, benefits from traffic-change-induced effects accrue predominantly to society, while costs and human factors risk treatment efforts are concentrated at train operators, with infrastructure managers positioned in between. By making such distributions explicit, the methodology supports redistribution of resources at an early project phase and may prevent project delays or cancellations later.

Our proposed methodology and application as presented in this Deliverable do have several limitations. Data and expertise availability constrained the scope and fidelity of the application, particularly for cost estimation and the valuation of safety-related effects for human factors. Weighting remains inherently subjective and sensitive to stakeholder perspectives. This requires careful governance in real-world applications. Most importantly, temporal aspects and uncertainty, that is, when costs are incurred and when benefits materialise, and to whom these costs and benefits accrue, are not yet explicitly modelled. These limitations do not undermine the methodology but indicate where further development is needed.

Several open points therefore remain. Most notably, the integration of uncertainty and time dynamics into the BuCa methodology requires further methodological work. Future extensions should explore how DATO costs, risks, and benefits evolve over time and how these trajectories differ across stakeholders. In addition, further validation on additional or over time further-matured DATO concepts, geographies, and operational contexts is needed to refine the interface matrices and strengthen empirical grounding. Access to more detailed and shareable cost data would also significantly improve the attractiveness of the outcome by providing the opportunity to potentially truly show a positive business case for DATO.

Looking forward, the BuCa methodology can support subsequent waves of DATO research by enabling more consistent comparison across technologies and contexts, and by serving as a common language between technical development and economic appraisal. As DATO concepts mature and empirical evidence accumulates, the methodology can be progressively extended toward more quantitative cost–benefit analysis, while preserving its core strength, which is the explicit representation of stakeholder trade-offs.

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