CLUG Demonstration of Readiness for Rail – CLUG 2.0

D6.5 - ARCHITECTURE TRADE-OFF ANALYSIS AND PROPOSED LOCALISATION ON-BOARD SYSTEM

Due date of deliverable: 31/01/2025

Actual submission date: 12/03/2025

Leader of this Deliverable: Andreas Staudte, DB InfraGO

Reviewed: Y

Document status		
Revision	Date	Description
0.1	01.06.2024	Initial version
0.2	30.08.2024	Final document structure
0.3	05.11.2024	Stable version – authors review
0.4	29.11.2024	Stable version – technical review
0.5	28.01.2025	Final version for EUSPA review
1.0	05.02.2025	Final approved version after quality check
1.1	28.02.2025	EUSPA review comments included
2.0	12.03.2025	Final version officially submitted to EUSPA

Project funded from the European Union's Horizon 2020 research and innovation programme		
Dissemination Level		
PU	Public	X
SEN	Sensitive, limited under the conditions of the Grant Agreement	
Classified R-UE/EU-R	EU RESTRICTED under the Commission Decision No2015/444	
Classified C-UE/EU-C	EU CONFIDENTIAL under the Commission Decision No2015/444	
Classified S-UE/EU-S	EU SECRET under the Commission Decision No2015/444	

Start date of project: 01/02/2023 Duration: 30 months

CLUG 2.0 has received funding from the European Union's Horizon research and innovation programme under grant agreement **No 101082624**

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EXECUTIVE SUMMARY

This document is part of the "Work package 6 - Communication, Dissemination, Exploitation and Business Case" with the sub task "T6.6 - Definition of Modular and Interoperable LOC-OB System for future Standardisation" of the CLUG 2.0 project which stands for Certifiable Localisation Unit using Global Navigation Satellite System (GNSS) in the railway environment. The project is one more milestone in transforming the way of train localisation using technologies such as GNSS and European Geostationary Navigation Overlay Service (EGNOS) which are among the "game-changing" technologies for future digital and automated railway operations.

This document is the deliverable "D6.5 Architecture Trade-off Analysis and Proposed Localisation On-Board System" of the European project "CLUG Demonstration of Readiness for Rail" (hereinafter also referred to as "CLUG 2.0").

The previous work packages of CLUG 2.0 did not deliver comparable system architectures suitable for a system architecture trade-off study. Consequently, this document adopts a qualitative approach to identify potential architecture options, trade factors and evaluation measures, which are organized into a Pugh matrix[1] to facilitate a comprehensive trade-off analysis.

The final system architecture trade-off study identified the system architecture that best addresses the underlying system requirements. This architecture is composed by two independent constituents as CCS-OB and LOC-OB. Based on the functional allocation, components are allocated to these constituents, and external interfaces with defined exchange items are identified as shown below.

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[1] Method to assess several solution options based on defined and weighted criteria to identify best fit option.

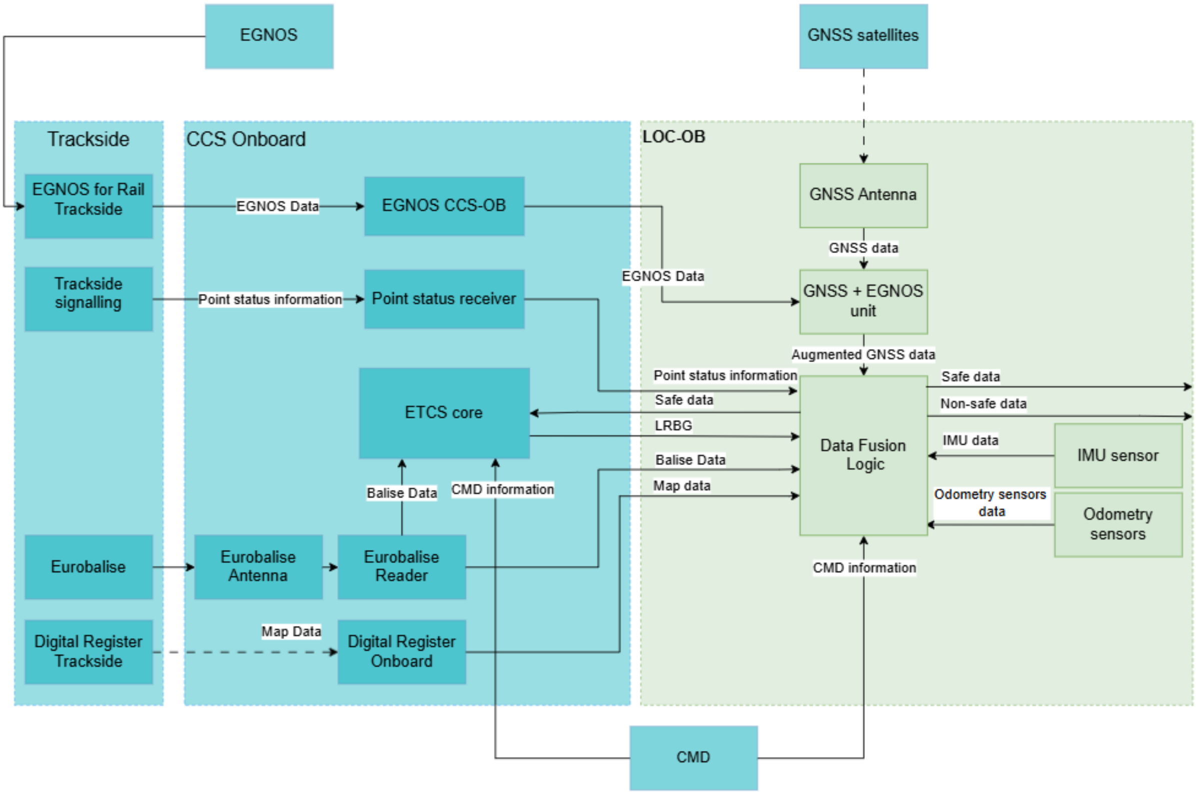

Figure 1: Final system architecture

For future initiatives it would be recommended to do an analysis on ALL functional interfaces which are relevant for the entire CCS context and perform an architecture trade off on system boundaries and function allocation to identify potential modules based on that. The result may differ from the current result in CLUG 2.0.

LIST OF ACRONYMS

ACRONYM	CONCEPTS
BTM	Balise Transmission Module
CMD	Cold Movement Detector
CCN	CCS Communication Network
CCS	Command, Control and Signalling
CCS-OB	Command, Control and Signalling Onboard
DM	Digital Map
DR	Digital Register
EGNOS	European Geostationary Navigation Overlay Service
ETCS	European Train Control System
FFFIS	Fit, Form and Functional Interface Specification
GNSS	Global Navigation Satellite System
IMU	Inertial Measurement Unit
LOC-OB	Localisation Onboard
MTBF	Meantime between Failure
RAMS	Reliability, Availability, Maintainability, Safety
RBC	Radio Block Centre
SiS	Signal in Space
STIP	Standardisation and TSI Input Plan
TSI	Technical Specification of Interoperability
WP	Work Package

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Applicable Documents

The following documents define the contractual requirements that all project partners are required to comply with:

- Grant Agreement N°101082624 (which includes Description of Work, Grant Preparation Forms and annexes): This is the contract with the European Commission which defines what must be done, how and the relevant efforts.
- Consortium Agreement: This defines our obligations towards each other.

Each of the above documents was established at the start of the project, and copies were supplied to each partner. Each document could potentially be updated independently of the others during the project following a prescribed process. In the event of any such update, the latest formal issued version shall apply.

In the event of a conflict between this document and any of the contractual documents referenced above, the contractual document(s) shall take precedence.

1 Introduction

1.1 Purpose/ Objective of the document

The purpose of this document is the re-evaluation of alternative system boundary options against trade-off criteria and constraints from collaboration projects and standards. Initial system boundaries, defined in WP2, D2.3 [2] as well as the functional architectures described in D4.1 [6] shall be considered and an appropriate architecture trade-off analysis shall be performed.

The final decision and consolidation of any architecture depend on the definition of the Control Command and Signalling On-Board (CCS-OB), which is beyond the scope of CLUG 2.0. Today, there is no final onboard system architecture agreed in the railway community. As a result, CLUG 2.0 made assumptions about the overall system which is currently being specified within the System Pillar of EU-Rail Joint Undertaking. CLUG 2.0 will be an input for these activities.

An architecture trade-off analysis is usually performed on system level and based on several different architecture options, addressing the underlying system requirements, as a result of a system design process. Based on CLUG (1) [9], CLUG 2.0 fosters a LOC-OB functional architecture (D4.1, [6]), focusing on the internal architecture of the data fusion logic, based on a specific sensor coupling architecture.

The previous work packages of CLUG 2.0 did not deliver comparable system architectures suitable for a system architecture trade-off study, but several functional architectures of the data fusion logic as input for suitable system architectures. Consequently, this document adopts a qualitative approach to identify potential architecture options, trade factors and evaluation measures, which are organized into a Pugh matrix to facilitate a comprehensive trade-off analysis.

As an initial step, various architecture variants were identified, taking into account the current state of railway technology development and relevant initiatives as result of a project partners effort and final agreement. For each architecture variant, pros and cons were identified and consolidated in a matrix to find similar arguments with different metrics, indicating there is a quantifiable difference for those arguments between the architecture options, which can be used as potential trade factors.

As second step, a qualitative analysis of the different interface configurations, based on the identified architecture options, is performed, and delivers robust arguments to decide on the final ranking of the proposed architecture options.

Finally, the identified architecture options are ranked in a Pugh matrix by trading them against the identified trade factors and supported by qualitative arguments from the interface analysis in the second step.

The result is a recommendation for a final system architecture based on the current technology understanding. Also, some findings out of the analytical steps and discussions, which are not reflected in the results, are finally discussed and passed to some recommendations for future initiatives.

1.2 Assumptions

1.2.1 General Assumptions

The target of the CLUG 2.0 project is to develop an independent constituent for onboard localisation functions, referred to as LOC-OB. This leads to a modular system architecture in which LOC-OB consolidates all identified localisation functions into a distinct constituent. The identification of the relevant functions to be assigned to LOC-OB falls within the scope of the CLUG 2.0 project.

For completeness, also a fully integrated system architecture will be shown but not considered in the final system architecture trade-off study. This architecture option is based on today's technology and system architecture with fully integrated odometry functions to CCS-OB but extended by new localisation functions as GNSS/EGNOS data receiver and IMU sensor. All sensor inputs are fused in a new data fusion logic. This architecture is composed by all functions which are also considered for the modular architectures and can be used as benchmark for future activities.

All questions with regards to decide on modularity are not considered in this document and are left to the initiatives at the System Pillar of EU-Rail Joint Undertaking under consideration of the results of the OCORA project [10], [11] . The outcomes of CLUG 2.0 will serve as input for these activities.

This document focuses on a trade-off study for potential modular architectures only. The final CCS system architecture is not in scope of CLUG 2.0, its future definition could influence the interpretation of the results presented in this document. There is still the option on fully integrated system architectures being more advantageous beyond the scope of CLUG 2.0, especially as system requirements and migration strategies become more refined in the future.

1.2.2 Architecture Constraints

(1) The communication between the trackside and train onboard is assumed to be realized through mobile communication via the RBC and CCS-OB. Data that is required by the LOC-OB from the trackside like EGNOS augmentation data, Digital Map (DM) and potentially the point status for track selectivity is assumed to be forwarded by the RBC to the CCS-OB which in turn provides the data to the LOC-OB.

(2) It is assumed that the EGNOS augmentation data for GNSS will be received by the trackside directly from the EGNOS ground segment, avoiding any additional delay of the information which is then distributed to the CCS onboard via radio, which then forwards it to the LOC-OB. This is applicable to all architecture options, with one exception that includes direct EGNOS data reception from geostationary satellites additionally. This means as well that the architecture options must consider the GNSS+EGNOS data delays from time-of-validity in their solution.

(3) GNSS data is received by a GNSS antenna directly from space whereby the GNSS antenna is part of LOC-OB. This applies to all architecture options of this study.

(4) All architecture options feature a CMD which is a separate constituent supporting both, CCS-OB and LOC-OB.

(5) It is assumed that LOC-OB will get ETCS relevant safe data inputs via the CCN. It is also assumed that all systems of the wider system of interest, given in D2.1 [1] , will be provided with safe and non-safe data outputs from LOC-OB via the CCN. Because the definition of the CCS-OB is still under development and it is beyond the scope of CLUG 2.0, the data outputs from LOC-OB via the CCN are represented in the architecture figures (Figure 3, Figure 4, Figure 5, Figure 5) with arrows pointing to LOC-OB's boundary. Additionally, the interface between the LOC-OB and ETCS core for providing position and speed safe data is depicted with a direct arrow connecting the two entities.

1.2.3 LOC-OB Sensor Configuration

(1) GNSS receivers, odometry sensors and IMU sensors are an integral part of the LOC-OB and are incorporated in all architecture variants.

(2) Redundant multi-sensor set configurations for safety and availability reasons will not be considered in this analysis and are assumed to be considered as part of the final system definition in accordance with the results of WP3, D3.5 [5] and of WP4, D4.1 [6]. The redundancy scheme is not considered as a critical aspect of feasibility, so it must be addressed at the time of LOC-OB product industrialization.

1.2.4 Future strategy constraints

(1) It is assumed that for this architecture trade-off analysis, the existing ETCS functionality (D2.3 [3] , chapter 2.1.1) will be the main consumer for the safe data outputs of the LOC-OB.

(2) The CLUG 2.0 project's target description assumes a separate functional module for LOC-OB functions. The resulting target for future architectures is to reallocate localisation functions from CCS-OB to LOC-OB and to extend the data inputs to LOC-OB to GNSS, EGNOS, trackside signalling and CMD. Depending on the final functional allocation between CCS-OB and LOC-OB and the resulting modularisation, new external interfaces will be established and need to be standardised.

1.3 Hypothesis

WP2 has provided 4 deliverables:

- D2.1 [1] Operational Needs and System Capabilities, identifying customer operational needs, derived system capabilities and derived high-level user requirements.
- D2.2 [2] Start of Mission and Track Selectivity, describing specifically challenges to LOC-OB from the operational scenarios "Start of mission" and "track selectivity".
- D2.3 [3] Localisation On-board System Definition and Operational Context, defining the high-level system architecture and operational context of a LOC-OB as well as the resulting system interfaces.
- D2.4 [4] LOC-OB System Requirements, delivering the derived system requirements from D2.1 [1] , D2.2 [2] and D2.3 [3] .

The LOC-OB system requirements (D2.4 [4]) are used to support WP3 – RAMS Analysis, WP4 Functional Architecture & Design and WP5 – Integration & Testing of a demonstrator which is based on the functional architecture, defined in WP4 D4.1 [6].

Deliverable 6.6 [8] aims to consolidate the LOC-OB system requirements from D2.4 [4] by considering the results of these three work packages and perform a gap analysis of the functional context of the wider system of interest, based on that.

This document, the deliverable 6.5, aims to use all this information to formulate trade factors and constraints to be used in a trade-off analysis of several identified architecture options. The result of this architecture trade-off analysis is the rationale for the argumentation of the final architecture proposal and the corresponding system boundaries for CLUG 2.0. Also, associated recommendations for future initiatives can be formulated by the result of the architecture trade-off study.

2 Method

A Pugh matrix[2] is intended be used to perform the final system trade-off analysis. Initially, a systematic approach has been foreseen to identify the architecture options to be traded, along with the trade factors and the metrics, in accordance with system design methods, as these are necessary inputs for the Pugh matrix. Such an approach is usually used to take a design decision at the end of a system design process, delivering two or more architectural solution options to address the initial system requirements.

Based on CLUG (1) [9], CLUG 2.0 fosters a LOC-OB functional architecture (D4.1, [6]), focusing on the internal architecture of the data fusion logic, based on a specific sensor coupling architecture. No different system architectures have been developed by the system design process to enable a system architecture trade-off study, but several functional architectures of the data fusion logic have been considered. That means there are no sufficient architecture options with a comparable maturity level in place to perform an architecture trade-off analysis as described.

It has been decided within the working group to change the method to an alternative approach by doing a qualitative analysis based on four steps as below:

1. Identify potential variants of the architecture,
2. Describe advantages and disadvantages of the architecture variants,
3. Perform a qualitative analysis of the functional interfaces for the architecture variants,
4. Identify measures to compare and evaluate the architecture variants.

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[2] Method to assess several solution options based on defined and weighted criteria to identify best fit option.

Step 1 is intended to deliver a set of potential and feasible architecture options, addressing the system requirement, in a team effort.

Step 2 is intended to write down qualitative arguments for each of the architecture options in a pro`s and con`s matrix. The expectation is to identify similar arguments with different metrics, indicating there is a quantifiably difference for those arguments between the architecture options, which can be used as a potential trade factors.

Step 3 is intended to analyse the qualitative impact of different interface definitions as described by the architecture options. The focus here is to find differences by implementing the interface as an internal one to CCS-OB or LOC-OB, or as an external one between CCS-OB and LOC-OB. Also, it can be used to support ranking decisions of the Pugh matrix.

Step 4 is intended to consolidate the arguments out of step 1 to 3 and identify most powerful trade factors, offering the biggest potential for clear different metrics to the architecture options. The quality of the trade factors is very much important to rationalise the result of the Pugh matrix. With this data, a Pugh matrix will be established to run the architecture trade-off analysis, to identify the best option for a CLUG 2.0 system architecture and its system boundaries. Also, further recommendations for future initiatives and development can be given and rationalised based on that. As the consolidation of the CCS-OB architecture is still ongoing within the System Pillar of the EU-Rail Joint Undertaking and lies beyond the scope of CLUG 2.0, the wide variety of possible component and interface combinations allows only for a qualitative analysis at this stage.

3 Consolidated System Requirements

In D6.6 [8], the system requirements, identified in D2.4 [4] , have been reviewed under the consideration of the functional architecture D4.1 [6] as well as the outputs from other initiatives. Consolidated system requirements are taken into consideration as underlying system requirements for the architecture trade-off study in this document.

4 System Architecture Options & Descriptions

4.1 Non-modular Architecture

4.1.1 Architecture with LOC-OB included in CCS-OB

The Figure 2 shows a hypothetical CCS onboard architecture where localisation functions are not separated into a modularized and independent LOC-OB constituent but extended by functions, supporting GNSS, EGNOS, track selectivity and start of mission. As stated in the general assumptions, this architecture is included in this document for reference. However, since the CLUG 2.0 project focuses on modular architectures, with LOC-OB as a separate constituent, this architecture variant is not traded in the Pugh matrix.

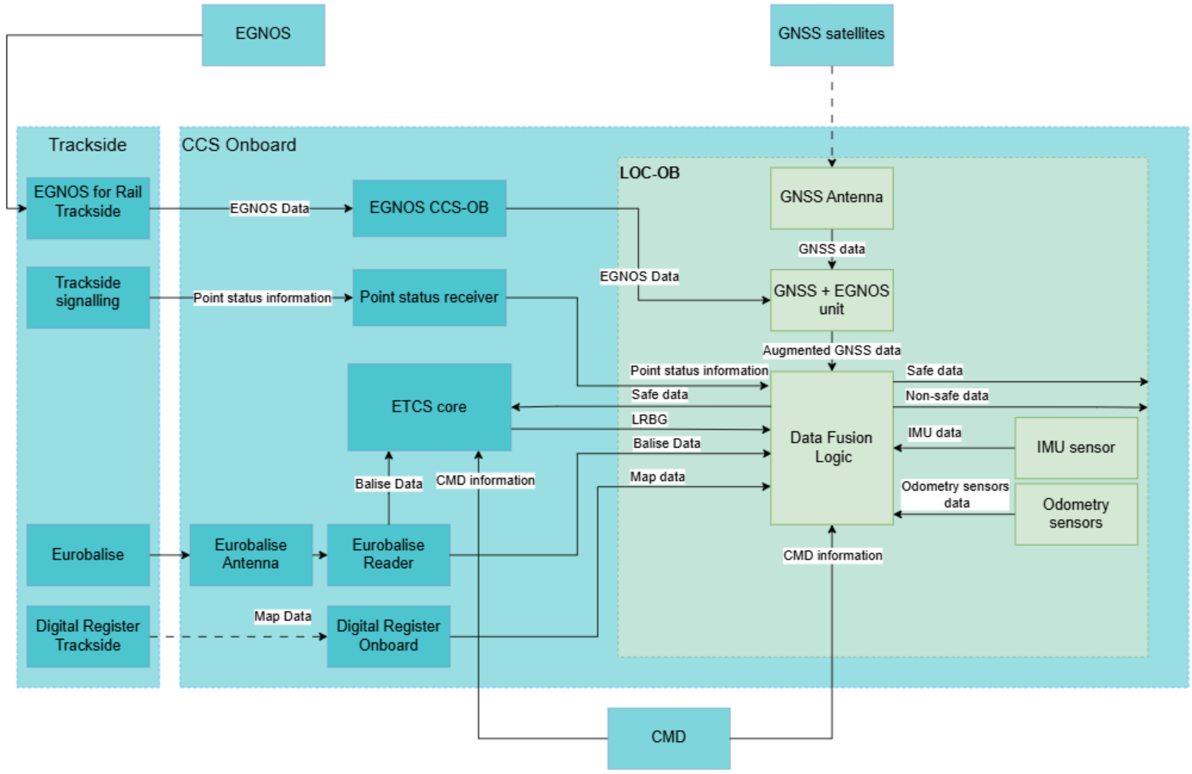

Figure 2: Architecture with LOC-OB as part of CCS-OB

Pros	Cons
Simplicity in development and deployment since there is only one deployable unit and only one supplier is responsible for it.	Scaling a monolithic system like adding new technology, is a significant challenge, it requires scaling the entire system rather than individual components. Monolithic systems can become more costly when they have a shorter lifecycle, as frequent replacements are needed to keep up with evolving requirements and new technology. A tightly coupled system often requires a significant effort for updates, leading to higher maintenance and development costs compared to systems designed for modularity and scalability.
The framework from the CCS-OB is re-used, existing products will be updated.	Achieving backwards compatibility would be difficult, the system might not be designed as efficient.
Communication between the functional entities is simplified by having direct internal communication interfaces instead of external standardised communication interfaces.	While there may be potential single points of failures which affects the entire system with all functional entities, the assumption is that the CCS-OB will be designed with built-in redundancy to mitigate such risks.
Simplified end-to-end testing because the entire application is within one context. No pre-testing of subcomponents and following integrated end-to-end testing of the entire system necessary. Safety demonstration and certification is also easier since already existing products are extended and re-validated.	Maintenance of a monolithic system in terms of maintaining individual functional entities is more difficult.
Market acceptance might be higher since industrial companies may prefer extending their existing system.	

Table 1: Pros & Cons of architecture with LOC-OB included in CCS-OB

4.2 Modular Architectures

4.2.1 Option 1 – Architecture, reflecting functional architecture, presented in D4.1 [6]

The Figure 3 illustrates the architecture with the Eurobalise reader and antenna as part of CCS-OB but a separate constituent for LOC-OB.

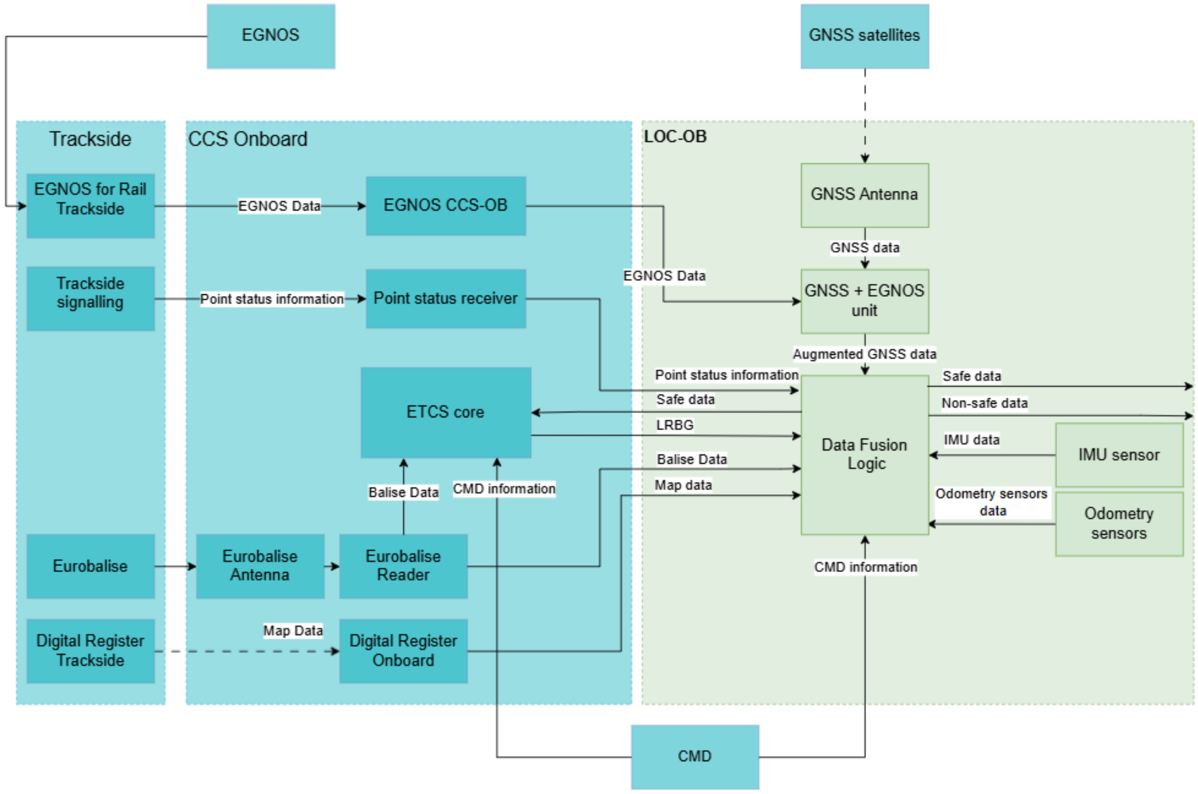

Figure 3: Architecture, reflecting functional architecture, presented in D4.1 [6]

Pros	Cons
Scaling is easier for example in adding additional sensors or use different technologies.	Deployment is more challenging, sub-systems of different suppliers need to be integrated and end-to-end tested. The safety analysis must incorporate the safety case of the LOC-OB into the overall safety case to ensure comprehensive safety assessment.
Any update or upgrade in the LOC-OB doesn't directly affect the functionality of the CCS on-board.	The integration of a new interface into the existing system may have a potential impact, requiring careful evaluation to ensure compatibility and to mitigate any risks to system performance or stability.
Maintenance of the LOC-OB is easier.	Standardised interfaces are required on the system boundaries of the constituents. Overall maintenance is worse when two constituents are defined since also the cross relation between constituents needs to be considered.

Table 2: Pros & Cons of Architecture based on D4.1 [6]

4.2.2 Option 2 – Eurobalise reader part of LOC-OB

The Figure 4Figure 4 illustrates the architecture with the Eurobalise reader and antenna as part of LOC-OB.

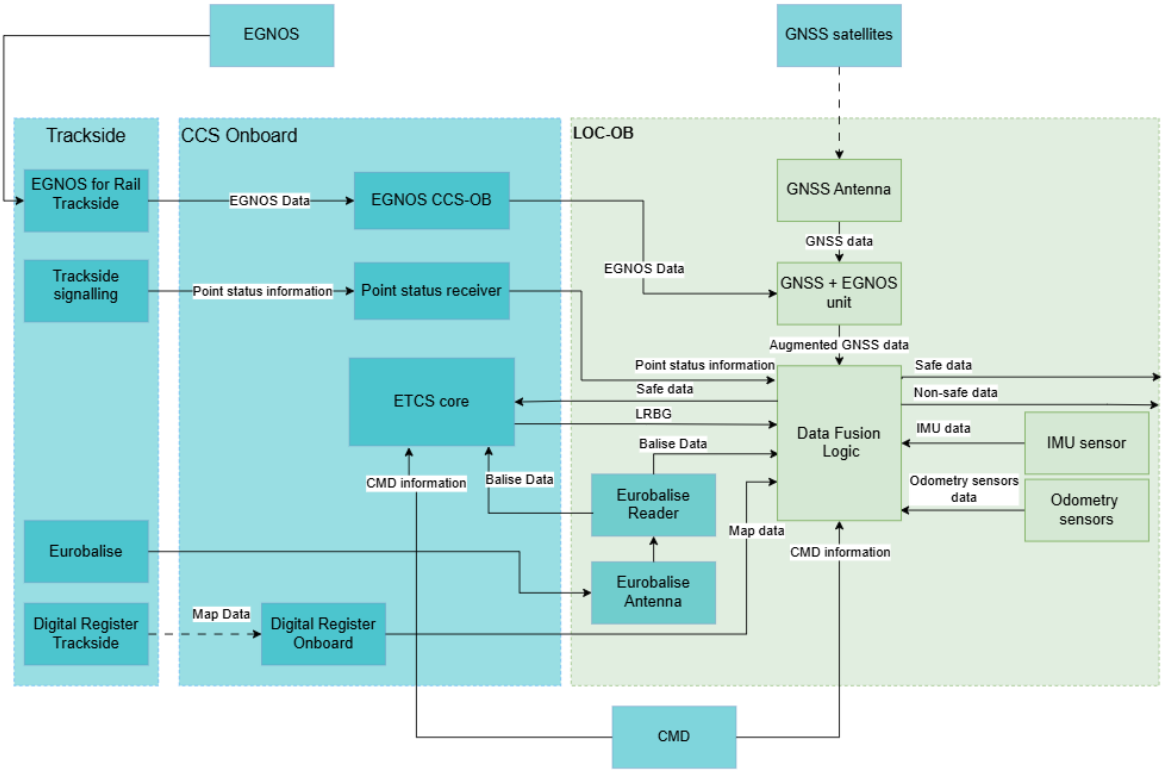

Figure 4: Eurobalise reader part of LOC-OB

Pros	Cons
LOC-OB can get benefit of the multiple Euroantenna available on the train.	Including the Eurobalise reader to the LOC-OB means a significant change of the existing ETCS onboard.
No need to define a detailed protocol between LOC-OB and the Balise Transmission Module (BTM) or the ETCS to acquire the balise telegram and especially the identification of the Euroantenna that detects the balise.	ETCS onboard still needs the balise information to determine the LRBG and provide it to LOC-OB. A more complex interface needs to be established and standardised.
	LOC-OB will be more complex and ETCS specific. Today, the Balise Transmission Module (BTM) is developed by ETCS suppliers, including it to the LOC-OB can create barriers for newcomers, as they must also adopt and implement it to compete effectively. This requirement can hinder their entry into the market, as it increases the complexity and costs associated with development, potentially limiting innovation.

Table 3: Pros & Cons of Eurobalise reader part of LOC-OB

4.2.3 Option 3 – EGNOS data provided via trackside and signal in space

The Figure 5 illustrates an architecture based on Option 1, extended to enable the reception of EGNOS data via trackside and additionally through Signal in Space (SiS).

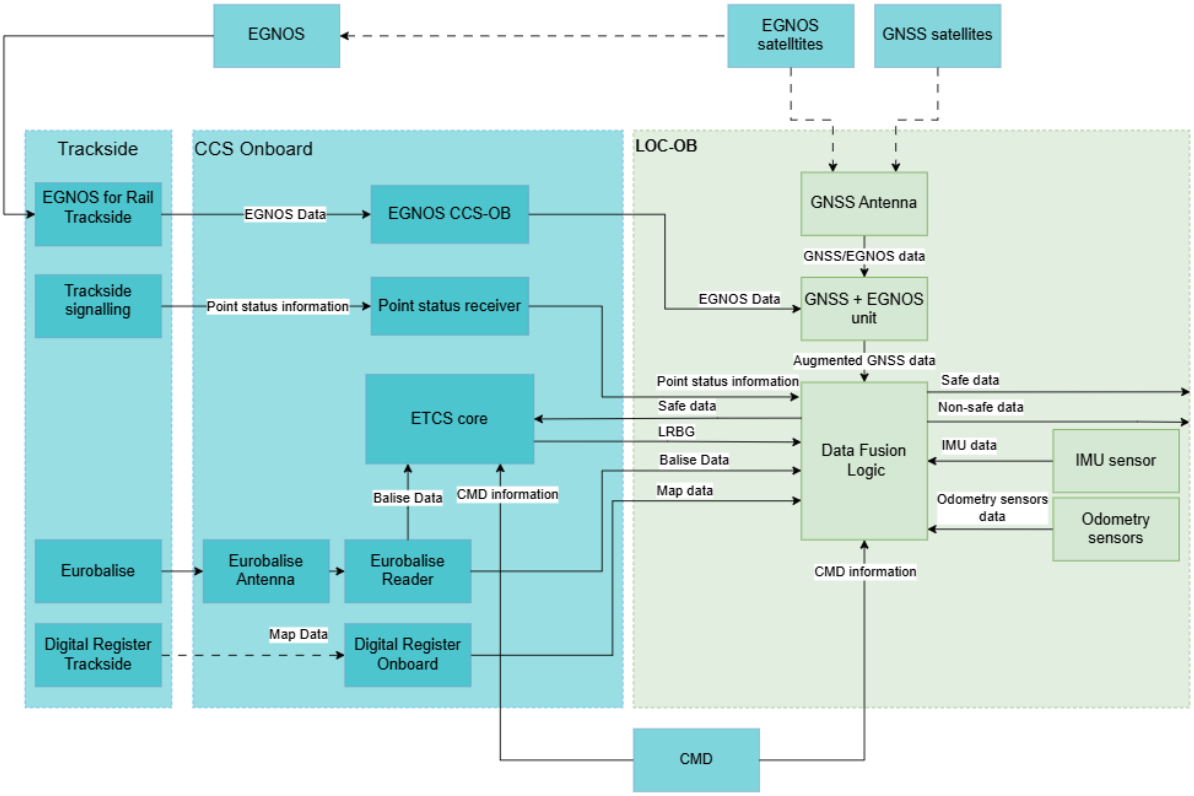

Figure 5: EGNOS data provided via trackside and signal in space

Pros	Cons
D4.1 [6] §2.1.4, complementing the EGNOS dissemination via trackside with the EGNOS SiS directly via the LOC-OB GNSS antenna offer stronger redundancy to terrestrial Euradio network. Which could offer the usage of EGNOS data in remote areas, regional lines where ground dissemination may not be complete. This combination also offers an obvious double independent links to ensure the required railway safety integrity level of EGNOS data dissemination from the EGNOS data stream up to the LOC-OB end users within a low latency for regional Time to Alert purpose.	Having both variants of receiving the EGNOS data increases the complexity of the system. Only one context can be used at a time, a switching needs to be performed.
Larger number of users could be supported without the need for high availability deployed RBCs.	

Table 4: Pros & Cons of EGNOS data provided via trackside and signal in space

5 Trade Factors & Implementation Requirements (constraints)

This chapter is about identifying appropriate trade factors and measures to differentiate the different architecture options and rank them.

The greatest impact of architectural variance based on a given functional architecture is on the functional interfaces becoming external or internal system interfaces. For those, becoming external interfaces, a FFFIS standardisation would be required.

With this interface context, some attributes are identifiable and can be used as trade factors to differentiate the architecture proposals.

5.1 Potential trade factors, identified from Pros & Cons of architecture proposals

From the pros and cons arguments in chapter 4 some common attributes with different estimations and ratings between the architecture proposals can be identified as potential trade factors for the trade-off analysis:

- Development and Deployment effort
- System Scalability
- End-to-end testing effort
- Maintenance
- Availability of the entire system/ failure modes
- Exchangeability/ Interchangeability
- Interface standardisation effort
- Market acceptance
- Modularity
- Certification effort
- Hardware effort

This list is the first source of input to the final selection of trade factors and arguments in chapter 5.4, based on the expected impact to the analysis.

5.2 Qualitative analysis of functional interfaces

The second source of potential trade factors and arguments is the qualitative analysis of the functional interfaces as in the Table 5 below. This kind of analysis is usually aimed to assess functional interfaces in a functional context to identify best fit system boundaries with regards to resulting types of interfaces. This is to take decisions on function allocation to sub systems by considering system requirements in terms of external interface standardisation and modularisation. Also, implementation requirements (constraints) can be derived. In the scope of CLUG 2.0 this analysis is used to identify ranking arguments for given interface definitions by the architecture options of chapter 4. It could be used to identify best interface definition in the scope of best system architecture to given system requirements, but this is not foreseen in the context of CLUG 2.0.

The existing exchange items as shown in the architecture diagrams in chapter 4 are of interest because they determine the type of interfaces dependent on the building block allocation of the involved interface partners. It decides if the interface becomes an internal or an external one.

Columns 1 – 3 are to be read as `interface partner 1` is connected by the `exchange item` with `interface partner 2`. Columns 4 – 6 are showing three different options of interface locations and which type of interface results by reading the different system architecture options.

The three types of interfaces are:

- **CCS-OB – LOC-OB:** The interface between the interface partners is an external interface, because one partner is allocated to CCS-OB, and the other partner is allocated to LOC-OB.
- **CCS-OB intern:** The interface between the interface partners is an CCS-OB internal interface, because both interface partners are allocated to CCS-OB.
- **LOC-OB intern:** The interface between the interface partners is an LOC-OB internal interface, because both interface partners are allocated to LOC-OB.

Arguments for interface options which are reflected in the architecture options are written in black.

All theoretical interface options which are not reflected in the architecture options are greyed out. The reason for also mentioning the theoretical interface options is to have some arguments in place to put the architecture trade-off results in a wider system context and conclude on limitations in the CLUG 2.0 context as well as give some recommendations for future initiatives if open the system boundary constraints.

Interface Allocation - Qualitative Analysis

No	Interfaces			Possible Interface location (allocation)		
	Interface Partner 1	**Exchange Item**	**Interface Partner 2**	**CCS-OB – LOC-OB (external interface)**	**CCS-OB intern (internal interface)**	**LOC-OB intern (internal interface)**
1	EGNOS CCS-OB	EGNOS DATA	GNSS+EGNOS Unit	• EGNOS CCS-OB is in the same functional context then RBC communication module – makes sense.	• GNSS+EGNOS unit would need to move to CCS. • new external interface between GNSS+EGNOS unit and Data fusion logic would be created • GNSS/ EGNOS data will be processed in CCS which is out of intention of CLUG2.0	• EGNOS CCS-OB can be removed. • receive EGNOS Trackside data directly by GNSS+EGNOS Unit • would require RBC communication module at LOC-OB • safes one interface
2	EGNOS satellites	SiS EGNOS Data	GNSS Antenna	N/A	N/A	• additional source of EGNOS data • increases availability and integrity
3	GNSS Antenna	GNSS Data	GNSS/EGNOS Unit	• creates additional external interface • potentially existing GNSS antenna in CCS-OB could be used	• safes one external interface to EGNOS CCS-OB, creates a new one to data fusion logic • GNSS antenna, GNSS/EGNOS unit and trackside EGNOS CCS-OB are in the same boundary, which offers some synergies	• Same boundary as Data fusion logic • Makes sense from the functional perspective
4	GNSS/EGNOS Unit	Augmented GNSS Data	Data Fusion Logic	• creates two additional external interfaces • GNSS antenna should be moved to CCS as well	N/A	• Same boundary as Data fusion logic • Makes sense from the functional perspective

Interface Allocation - Qualitative Analysis

No	Interfaces			Possible Interface location (allocation)		
5	ETCS core	LRBG information (to) & Position, Speed (from)	Data Fusion Logic	• ETCS core and Eurobalise reader is in the same boundary, makes sense from functional perspective • Key marker for independent constituent	• less interfaces • bad for modularisation and standardisation	• ETCS core would be part of LOC-OB • bad for modularisation and standardisation • change of ETCS architecture required, cost and homologation effort
6	Eurobalise Reader	Balise data	ETCS core	• ECTS core and Eurobalise reader in different modules – does not make sense from functional perspective	• ETCS core and Eurobalise reader are in the same boundary, makes sense from functional perspective • ETCS core is main consumer of balise data	• would require ETCS core as part of LOC-OB
7	Eurobalise Reader	Balise data	Data Fusion Logic	• ETCS core and Eurobalise reader are in the same boundary, makes sense from functional perspective	N/A	• Data fusion logic and Eurobalise reader are in the same boundary, makes sense from functional perspective • Need trade between both options
8	Digital Register onboard	Map data	Data Fusion Logic	• seems to be the best option in terms data provision and maintainability. • also rely on RBC data transfer	N/A	• DR-OB would be part of LOC-OB • Would require RBC receiver
9	IMU Sensor	IMU data	Data Fusion Logic	• external interface to fusion logic	N/A	• direct input to fusion logic
10	Odometry Sensors	Odometry sensors data	Data Fusion Logic	• external interface to fusion logic	N/A	• direct input to fusion logic
11	Point Status Receiver	Point Status information	Data Fusion Logic	• seems to be the best option in terms of data	N/A	• point status would be part of LOC-OB • Would require RBC receiver

Interface Allocation - Qualitative Analysis						
No	Interfaces			Possible Interface location (allocation)		
				provision and maintainability. • rely on RBC data transfer		

Table 5: Qualitative Analysis of functional interfaces

5.3 Modularity aspects

The CLUG 2.0 system architecture is assumed to be modular as per task description. Therefore, only modular system architectures will be evaluated in the trade-off analysis. But some general modularity aspects have to be pointed out which are valid for all traded modular system architecture options.

- Modular system architectures could offer certain benefits if it is accepted that the level of modularisation also sets the level of standardisation. It must be clear that any independent constituent requires standardised, open external interfaces to ensure seamless integration with other supplier independent system constituents.
- This also requires a supplier independent system integrator role taking responsibility for functional and safety integrity based on standardised test and safety cases.
- Any supplier must comply to the standardised interface specifications.
- To realise these pre-conditions, investment is required and need to be quantified.
- Those costs need to be traded against the benefits of modularity like improvements of:
  - Upgradeability
  - Interchangeability
  - Exchangeability
  - Lifecycle Cost
  - Migration effort
  - Other considerations

Such a study is not in scope of this document. The potential results are applicable to all modular architecture options analysed in this document and do not provide any measurable difference for the Pugh matrix. Therefore, the decision was made to exclude trade factors, specifically addressing modularity aspects. The rating for the trade factors in the next sections considers implicit modularisation arguments for the assumed system context as well, but not specific.

5.4 Selection of trade factors and measures for architecture trade-off analysis

Based on the qualitative analysis of the proposed architectures and the corresponding interfaces as well as the identified arguments in chapter 5.1, trade factors can be identified and substantiated. The table below shows the selection of trade factors for the architecture trade-off analysis with associated criteria, measures and rationales for the usage in Table 10 and in the Pugh matrix in chapter 6. Any factor will be rated for each system architecture option to be applied in the Pugh matrix.

In Table 6: , each row is to be read as:

IF (criteria) is assessed for the specific architecture option as (row: High, Medium or Low) then the rating for the Pugh matrix (head of column: HIGH (5), MEDIUM (3), LOW (1)) applies accordingly.

Factor	Criterias	Rating (Pugh Matrix)			Rationales
		HIGH (5)	MEDIUM (3)	LOW (1)	
	IF…	IS ASSESSED AS…			
Effort to exchange and upgrade single functional groups	Effort to specific functional system upgrades	Low	Medium	High	Open interfaces between modules increases flexibility for technology changes and upgrades.
Standardisation effort	Effort to change or introduce new TSI, STIP, Standards	Low	Medium	High	Number of external interfaces to be standardized, TSI Impact
Developement effort	Complexity, development time, number of involved suppliers	Low	Medium	High	The amount of external data interfaces to fusion logic is a measure of complexity. More partners mean more complex development processes.
End-to-End testing effort	Grade of modularity, number of involved suppliers	Low	Medium	High	More suppliers and modules cause more effort for testing and integration.
Certification	Effort to certify new technology	Low	Medium	High	Reuse of already certified components
Deployment effort	Complexity, deployment time, number of involved suppliers	Low	Medium	High	The amount of external data interfaces to fusion logic is a measure of complexity. More partners mean more complex deployment processes.
Availability of the entire system, failure modes effects	Impact of single point of failures to system effects, MTBF, system availability	Low	Medium	High	Failure effects and propagation on common platforms, multiple system faults due to single point of failure conditions.
Supplier acceptance	willingness of industry to support certain architectures based on business cases	High	Medium	Low	Low expected unit volume compared to high development costs due to high diversity of system requirements of variants can affect the business cases.

Table 6: Selection of trade factors and ratings for the architecture trade-off analysis

6 Architecture Trade-Off Analysis

6.1 Weighting

6.1.1 Weighting factors

Weighting factors are used to give the trade factors a certain priority to influence the final trade factor rating by multiplying weighting and trade factors to the final countable rating per trade factor.

The following weighting factors are identified and will be used in the Pugh matrix.

Weighting	1.00	low
	3.00	medium
	5.00	high

Table 7: Weighting factors for trade factors

6.1.2 Trade factors weighting

Trade Factors	Weighting	Rational
Exchange Effort	3.00	Good exchangeability can significantly reduce future development and deployment costs by enabling easier integration and replacement of system components. However, the impact on total costs may be relatively modest.
Standardisation Effort	5.00	High impact on cost and effort to involve all partners to standardise their products.
Development Effort	3.00	Development costs may not much differ for different architectures based on same functional blocks.
Testing	1.00	Test effort is almost the same for given functionality and implementation context.
Certification	3.00	Certification effort may not much differ for different architectures based on same functional blocks.
Deployment Effort	5.00	High deployment effort has high impact on cost and resource requirements, as it involves extensive integration, testing, and validation.
Availability	5.00	High system availability is a key performance requirement.
Supplier Acceptance	5.00	High market (supplier) acceptance is a precondition for supplier engagement and engineering investment.

Table 8: Trade factors weighting - Rationales

6.2 Rating

6.2.1 Rating factors

The trade factors will be rated in accordance with Table 6: . The rating reflects the ability of the architecture option proposal to address or perform the meaning of a certain trade factor.

The following rating factors are identified and will be used in the Pugh matrix.

Rating	1.00	low
	3.00	medium
	5.00	high

Table 9: Rating factors for trade factors

6.2.2 Trade factors rating

Trade Factors		Option 1		Option 2		Option 3	
		Based on D4.1		Eurobalise reader part of LOC-OB		EGNOS data provided via trackside and SiS	
		Rating	Rational	Rating	Rational	Rating	Rational
Exchange Effort		5	Good exchangebility, CCS-OB with ETCS and LOC-OB are independent modules	3	Worse exchangebilty, balise reader is part of LOC-OB, effort is higher	5	Equal to option 1
Standardisation Effort		1	Initial effort is high but then expected to be lower	1	Initial effort is high but then expected to be lower	1	Initial effort is high but then expected to be lower
Development Effort		3	Standard development effort, ETCS functionality remains at CCS-OB	1	Higher development effort due to balise reader is part of LOC-OB	3	Equal to option 1
Testing		3	Identical for all options	3	Identical for all options	3	Identical for all options
Certification		3	Standard certification effort	3	Equal to option 1	1	two ways of EGNOS data transmission to be certified
Deployment Effort		3	Identical for all options	3	Identical for all options	3	Identical for all options
Availability		3	Identical for all options	3	Identical for all options	3	Identical for all options
Market Acceptance		3	Market acceptance higher due to known architecture of CCS	1	Market acceptance is lower due to balise reader in LOC-OB	3	Market acceptance higher due to known architecture of CCS

Table 10: Trade factors rating - Rationales

6.3 Pugh matrix

A Pugh matrix is intended to consolidate all the results of the previous chapters in a competitive context to figure out the architecture option addressing underlying system requirements at the best. This method assesses several solution options based on defined and weighted criteria to identify the best fit option.

Trade factors are determined and qualified in Table 6: under consideration of the results of the pros and cons analysis in chapter 0 and the interface analysis in chapter 5.2.

Qualified argumentations to the different architecture options to compare and rate the trade factors for those is also given by the pros and cons analysis in chapter 0 and the interfaces analysis in chapter 5.2.

The determination and allocation of the weighting and rating factors to the trade factors is the result of an integrated effort of partners and specialists from the industry and several railway undertakings which have contributed to the entire document.

		Option 1		Option 2		Option 3	
		based on D4.1		Eurobalise reader part of LOC-OB		EGNOS data provided via trackside and SiS	
trade factors	**weighting**	**rating**	**rating x weighting**	**rating**	**rating x weighting**	**rating**	**rating x weighting**
exchange effort	3.00	5.00	15.00	3.00	9.00	5.00	15.00
standardisation effort	5.00	1.00	5.00	1.00	5.00	1.00	5.00
development effort	3.00	3.00	9.00	1.00	3.00	3.00	9.00
testing	1.00	3.00	3.00	3.00	3.00	3.00	3.00
certification	3.00	3.00	9.00	3.00	9.00	1.00	3.00
deployment effort	5.00	3.00	15.00	3.00	15.00	3.00	3.00
availability	5.00	3.00	15.00	3.00	15.00	3.00	15.00
market acceptance	5.00	3.00	15.00	1.00	5.00	3.00	15.00
Summary/ Ranking			**86.00**		**64.00**		**80.00**

Table 11: Pugh matrix for architecture trade-off analysis

CLUG 2.0 has received funding from the European Union's Horizon research and innovation programme under grant agreement **No 101082624**

7 Final Architecture Ranking

The following ranking results from the Pugh matrix in chapter 6.3:

1. **Option 1 – architecture, based on D 4.1**[6]
2. **Option 3 – EGNOS data provided via trackside and signal in space**
3. **Option 2 – Eurobalise reader part of LOC-OB**

Option 1 has turned out as the most satisfying architecture solution on the selected trade factors.

This option is based on the functional architecture, presented in D4.1 [6] and is built up by independent constituents as LOC-OB and CCS-OB. All legacy odometry functionality as well as new functionalities like IMU sensor and GNSS receiver are allocated to LOC-OB. ETCS core, Eurobalise reader, trackside information like point status, DR and EGNOS data receiver from trackside are allocated to CCS-OB. The CMD sensor is an external component and provides data input to the ETCS core and the data fusion logic via external interfaces. By this function allocation, external functional interfaces between CCS-OB and LOC-OB are created as shown in Table 12 below is:

CCS-OB	Interface direction	LOC-OB
EGNOS CCS-OB	→	GNSS + EGNOS unit
Point status receiver	→	Data fusion logic
ETCS core	←→	Data fusion logic
Eurobalise reader	→	Data fusion logic
Digital Register onboard	→	Data fusion logic

Table 12: Option 1 - external interfaces

Also, external interfaces are created from CCS-OB and LOC-OB to the CMD as well as GNSS satellites to LOC-OB.

Option 3 has also achieved a good ranking, like option 1, but with higher certification effort which leads to a lower scoring compared to option 1.

Option 3 has the same interface architecture as option 1, extended by an additional external interface between EGNOS satellites and LOC-OB to receive EGNOS data also from space (SiS).

Option 2 has achieved the worst scoring which is mainly caused by the penalty on the ETCS functionalities which are moved to LOC-OB.

This option is based on the functional architecture as option 1 where the Eurobalise reader with antenna is transferred to LOC-OB. This leads to the external functional interface configuration as in Table 13 below:

CCS-OB	Interface direction	LOC-OB
EGNOS CCS-OB	→	GNSS + EGNOS unit
Point status receiver	→	Data fusion logic
ETCS core	←→	Data fusion logic
ETCS core	←	Eurobalise reader
Digital Register onboard	→	Data fusion logic

Table 13: Option 2 - external interfaces

The penalties for this option are caused by the development effort to be applied to transfer the Eurobalise reader with antenna to LOC-OB. Also, the low market acceptance, exchangeability and upgradeability of this option drops down the scoring.

7.1 Observations

CLUG 2.0 has a very limited view to interface variations and possible system boundary options with regards to modularisation. The architecture trade off result is a very constraint result, limited by the architecture options.

For future initiatives it would be recommended to do an analysis on ALL functional interfaces which are relevant for the entire CCS context and perform an architecture trade off on system boundaries and function allocation to identify potential modules based on that. The result may differ from the CLUG 2.0 result.

The arguments in Table 5 show that the architecture options in chapter 0 reflect the most beneficial interface configurations very well.

But it can also be seen that some limitations are there with regards to trackside – onboard communication via the RBC. The RBC communication module allocation is constrained in this context to CCS-OB. If this constraint can be removed and an independent RBC communication module would be considered some interesting other interface options for related functions like EGNOS CCS-OB, point status receiver and DR onboard would be offered, e.g. being allocated to LOC-OB as well. This would create one external interface between RBC and LOC-OB and would save three external interfaces between CCS-OB and LOC-OB. The EGNOS CCS-OB, allocated to LOC-OB, would be put into the same boundary as GNSS+EGNOS unit and GNSS antenna, which would make sense from the functional perspective.

ETCS core and Eurobalise reader with antenna should always be allocated to the boundary of the same functional context as reflected in the winning architecture option 1.

All sensors should always be allocated in the boundary of the same functional context as the data fusion logic which is reflected in the LOC-OB boundary in architecture option 1 as well.

8 Conclusion

Typically, an architecture trade-off analysis is a systematic approach conducted to compare multiple architectures in depth, especially in the early stages of the system design. However, the system design process within CLUG 2.0 did not develop an alternative system architecture necessary for conducting a system architecture trade-off study. Instead, the focus was placed on exploring several functional architectures for the data fusion logic which were considered in the creation of the system architecture presented in the document. Consequently, no multiple architecture variants with the required level of technical maturity were available to perform an architecture trade-off analysis as described above.

This made it necessary to choose a qualitative approach for comparing multiple architecture alternatives.

The identified architecture variants largely originated from other initiatives, projects, and the general state of railway technology development. These were subsequently reviewed and aligned with the involved partners to ensure compatibility with the CLUG 2.0 objectives.

An initial comparison of pros and cons of each architecture revealed shared attributes across the identified architectures. These attributes served as indicators for potential trade factors like System Scalability, Development and deployment effort, Standardization, Certification effort. These factors helped to establish a structured framework for evaluating the strengths and limitations of each option.

The next step involved a qualitative analysis of the various interface configurations based on the identified architectures. This analysis provided robust arguments, supporting an informed decision-making process for the final ranking of the architecture options.

In the final step the identified architectures were systematically ranked in a matrix by evaluating them against the identified key trade factors. This evaluation was further supported with a qualitative insight derived from the interface analysis, providing solid basis for selecting the optimal architecture option.

This method highlighted that where the LOC-OB is considered as a separate constituent had scored higher for exchangeability, due to its modular, independent design, the system can be replaced or upgraded with minimal disruption to other components. The third option received the lowest score, primarily due to the relocation of an ETCS specific component, the Eurobalise reader from the CCS-OB to the LOC-OB. Including it to the LOC-OB can create barriers for newcomers, as it increases complexity and costs with development, potentially limiting innovation. The fourth where the EGNOS data reception is from the trackside and from geostationary satellites additionally, was ranked slightly lower than the second option, because it is affected by additional standardization and certification effort.

In conclusion, although not a traditional trade-off method was followed in this document, the approach taken and described in this document provided valuable insights and enabled us to identify the most preferred architecture. It is important to note that the final decision and consolidation of any architecture ultimately depend on the definition of the CCS-OB, which currently lies beyond the scope of CLUG 2.0. Consequently, several assumptions were made regarding the overall system throughout this analysis. Nevertheless, the findings obtained in this document can be instrumental for further initiatives and serve as input for the System Pillar of the EU-Rail Joint Undertaking, guiding future developments and decisions in this domain.

9 References

REF	Document/Source	Title/WEBSITE	Version	Date
[1]	CLUG 2.0 D2.1	Operational Needs and System Capabilities of the LOC-OB System	1.0	30/11/2023
[2]	CLUG 2.0 D2.2	Start of Mission and Track Selectivity	1.0	30/11/2023
[3]	CLUG 2.0 D2.3	LOC-OB System Definition and Operational Context	1.0	30/11/2023
[4]	CLUG 2.0 D2.4	LOC-OB System Requirements	1.0	30/11/2023
[5]	CLUG 2.0 D3.5	LOC-OB System functional Safety analysis	1.0	04/07/2024
[6]	CLUG 2.0 D4.1	LOC-OB Functional Architecture	0.4	30/09/2024
[7]	CLUG 2.0 D4.2	GNSS Receiver Interface Control Document	1.1	07/11/2023
[8]	CLUG 2.0 D6.6	Proposed Localisation On-Board System Requirements and Gap Analysis	1.0	24/02/2025
[9]	CLUG (1) D2.5	Preliminary Architecture Definition (CO)	3.8	12/04/2021
[10]	OCORA-TWS01-030	System Architecture	3.0	08/12/2022
[11]	OCORA-TWS01-101	Localisation-On-Board-(LOC-OB) - High-level Requirements	3.0	08/12/2022

CLUG 2.0 has received funding from the European Union’s Horizon research and innovation programme under grant agreement **No 101082634**