RCA

Reference CCS Architecture

An initiative of the ERTMS users group and the EULYNX consortium

Digital Map – Quality Framework

Preliminary issue

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1 Introduction

1.1 Release information

Basic document information:

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Support and Feedback: For feedback, or if you have trouble accessing the material, please contact rca@eulynx.eu.

1.3 Disclaimer

- The (Digital) MAP as a cross-cutting topic requires coordination with RCA/Trackside CCS Domain and OCORA/On-Board CCS Domain and Cross-Cutting Domain.
- The MAP process is divided into phases *Prepare Map Data*, *Publish Map Data to Trackside*, and *Publish Map Data to On-Board*.

1.4 Scope of this document

The sufficient quality of Map Data, which represents the infrastructure and enables functions of the RCA/OCORA subsystems, is crucial to achieving highly reliable trackside or on-board systems. While this is already true for today’s systems such as ETCS, it even becomes more critical in the context of new architectures such as RCA/OCORA since the number of subsystems and functions that rely on Map Data (e.g. localisation, perception, …) increases.

The intention of the workstream started with this document is to give answers to the following questions:

- What are the aspects of Map Quality? What does *Reliable Map Data* (or *Reliable Infrastructure Data*) mean?
- What are the impacts on Map Quality over the life cycle of Map Data?
- What is the sufficient quality level of Map Data, and what is a good balance between technical-driven Map Data consumer requirements and economical-driven Map Data preparation processes?
- How to ensure Map Quality during operation?
- What are the recommended process and the architectural needs to provide sufficient quality of Map Data?

So while this analysis does not deliver the Map Data requirements of subsystems, it provides the base to evaluate potential system requirements against the efforts and feasibility of the generation and validation of Map Data.

1.5 Related documents

The following documents provide related information:

[1] RCA System Architecture [RCA.Doc.35]
[2] RCA Digital Map – MAP Object Catalogue [RCA.Doc.49]
[3] RCA Digital Map System Definition [RCA.Doc.59]

[4] RCA Terms and Abstract Concepts [RCA.Doc.14]
[5] RCA Solution Concept MAP [RCA.Doc.54]
[6] RAILway Ground truth and digital mAP – RAILGAP project, deliverables under https://railgap.eu/
[7] SBB smartrail 4.0 Topo4 Functional Concept (published filename: ES TOPO4 45-Published Functional Concept.pdf), https://www.voev.ch/de/Service/content_?download=18086, 29.06.2022
[8] DB Netz, SafeRailMap project, see Annexe C – Summary SafeRailMap Project, DB Netz AG of this document
[9] DB Ril 883 ("Gleis- und Bauvermessung"), DB Netz AG, 2021
[10] AB EBV (Ausführungsbestimmungen zur Eisenbahnverordnung), Bundesamt für Verkehr, Switzerland, 01.11.2020
[11] CLUG Project Publication D5.4 Maps for localization, version 1.3, http://clugproject.eu/sites/default/files/2022-07/d5.4_maps_for_localisation_final_v1.3_pu_final.pdf
[12] SBB Study "Digital Map Concept - Track Geometry for ETCS Onboard Map", Andreas Wenz, 17.11.2021, https://www.voev.ch/de/Technik/Umsetzung-ERTMS/Fachpublikationen#Lokalisierung%20/%20Odometrie

1.6 Target audience

The target group consists of members of the RCA/OCORA.

1.7 Terms and Abbreviations

In general, the document is based on the terminology introduced in RCA Solution Concept MAP [5] and partially already generalised in RCA terminology [3]

- Engineering Data
- Engineering Input Data (IM Data)
- Map Data (in other publications, also referred to as *Infrastructure Data*)
- Reliable (Map) Data

New terms introduced in this document are:

- Map (Data) Quality: Map Data Quality results from the degree of fulfilment of the Reliable Map Data criteria (chapter 2).
- Contribution / Contributor: positive or negative impact on Map Data quality aspect.

2 Aspects of Map Quality

In previously published documents of the RCA Digital Map cluster, the term *Reliable Map Data* (synonym to *Reliable Infrastructure Data*) has been introduced, which implies a certain quality level of Map Data:

> *"Reliable (Map) Data refers to a typical characteristic of data that satisfies the qualities of being trustworthy/lower probability of incorrect information/lower fault rate of the information, current (not obsolete), complete, and accurate.*
>
> *Reliable data is not only about safety-related Map Data, but also non-safety-related Map Data that still needs to fulfil certain criteria for a specific function of consumer/system."* [RCA.doc.14]

The attribute "reliable" is not limited or coupled exclusively to safety-related functions since a sufficient level of quality is also required to guarantee a good performance, high availability, and reliability of non-safe functions such as realised by ATO or TMS. Hence, the data quality attribute *Reliable* means safety-related or non-safety-related data that satisfies the consumer's data quality requirements.

To make it more concrete, the attribute *reliable* comprises the following most important aspects, as it is similarly defined in the smartrail 4.0 project Topo4 [7] or the SafeRailMap project of DB Netze [8]:

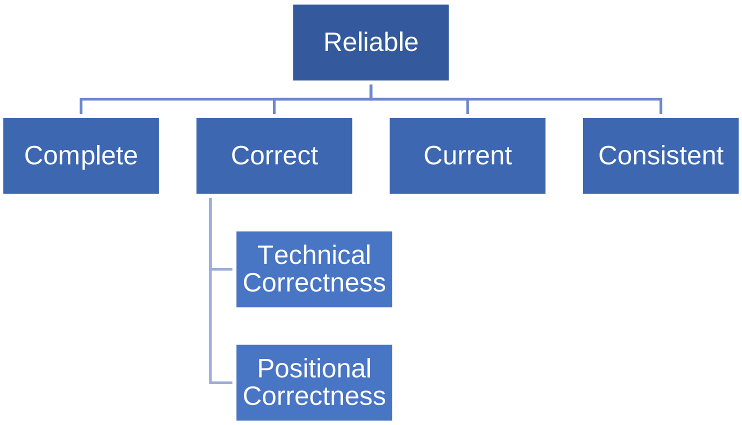


Figure 1 Aspects of Reliable Map Data

- *Complete*: All Map Data (i.e., tracks and elements/objects) within the scope of the application are present, and all attributes are populated
- *Correct*[1]*:* All Map data is correct regarding the following sub-attributes:
  - *Technical correctness:* the Map Data is valid in the sense that they conform to the rules (e.g., right element type, the minimum distance between balise groups)
  - *Positional*[2] *correctness*: the Map Data is correct in the sense that they conform to the real existing infrastructure (positional error ≤ accepted positional error)
- *Current*: The Map Data represents the valid information for the right time
- *Consistent*: No ambiguities or contradictions between different topical aspects, versions, or adjacent regions of Map Data

Regarding the problem of reliable Map Data, two clusters can be differentiated:

- Map Data parts with relation to infrastructure (geo-reference, topological) → positional correctness very relevant
- Map Data parts without regard to infrastructure → technical correctness relevant

While the following quality model will emphasise the infrastructure-related Map Data, another chapter will focus on ensuring overall quality through appropriate processes.

[1] The term "correct" is used instead of the formerly used term "accuracy" to avoid collisions with other meanings within this context

[2] In later iterations of this document this could be extended to „spatial" or „geometrical" correctness, if the dimensions of the positioned elements get relevant as well (i.e., for IPM, Perception systems)

2.1 Infrastructure-related aspects of Map Quality

Especially the aspects of *positional correctness*, *completeness,* and *currentness* are directedly connected to the sufficient representation of the existing infrastructure in the Map Data. While the Map Data also contains configuration parameters such as IDs or permanent topological/usage restrictions, it is undoubtedly dominated by infrastructure-related content. The infrastructure-related aspects are primarily influenced by the quality of Engineering Input Data (IM Data), random impacts, and processual measures during a realisation project and might be even subject to change during the operation of the systems (e.g. maintenance works). Consequently, these aspects related to reliable infrastructure representation are focused on by this Map Data Quality analysis in chapter 3.

This also includes the definition of positional correctness that makes sense not only from a technical but also from an economic point of view (i.e., potential re-use of existing inventory data, available range of sufficient and efficient data acquisition methods). Considering the financial perspective, the estimated costs to change existing processes or apply mitigation measures are also part of the evaluation – at least qualitatively.

In the end, the best balance between cost and sufficient positional correctness should be found. The *completeness* and *currentness* of Map Data must be fulfilled since incomplete or outdated Map Data are considered non-tolerated systematic errors, i.e., for safety-related applications such as localisation or supervision of train movements.

Finally, this document shall not only offer a static view but an adaptable model (see Annexe A – MAP Quality Model (MS Excel)) that can be calibrated regarding the system requirements (i.e., positional correctness) and IM-specific conditions (i.e., quality of IM Data, the performance of acquisition methods, specific quality contributions).

2.2 Overall Map Quality assurance

An appropriate tool-supported process that ensures a defined level of Map Data quality is required to effectively address the more generic and systematic aspects of consistency and technical correctness. The process should cover Map Data's generation, validation, and distribution to the consuming systems based on a single source of truth. Chapter 4 of this document sketches the essential phases of an at least partially standardised tool-based process. The actual contribution to the MAP Quality aspects and the most relevant requirements are highlighted for each stage. This includes not only the aspects of overall consistency and technical correctness but also the aspects mentioned above related to the representation of the infrastructure.

Finally, the *process must be acceptable* in the sense that it avoids systematic errors within the Map Data by appropriate measures.

3 Infrastructure Map Quality Analysis

Map Quality is influenced by various factors that occur during the life cycle of the map (including generation, validation, update,..). In each step of map creation, there are choices to be made that might enhance or degrade the Map Quality. In this analysis, we want to identify these different contributors to Map Quality, focusing on the sufficient representation of the infrastructure. The approach is as follows:

- Identify and quantify relevant Map Data Quality contributions to represent infrastructure in Map Data.
- Initialise the Map Data Quality model by the first set of requirements (regarding all aspects of reliable Map Data as introduced in the previous chapter)
- Perform a quantitative (positional correctness) and qualitative Map Quality analysis for infrastructure data: define scenarios and evaluate scenarios regarding resulting Map Quality.
- Select the most favourable scenario/mitigations to fulfil the requirements in the most efficient way

3.1 Map Life Cycle from a Quality Point of View

At the point in time when a consuming function uses Map Data during railway operation, the data's quality attributes are determined by several impacts and influences that emerge during the life cycle of the Map Data before its consumption and which might enhance or degrade the Map Quality.

Since Map Data is a cross-cutting topic, it can be subject to many influences from several railway domains. The main effects are assumed to be the engineering (including construction and commissioning) activities within a given engineering project and the maintenance activities during railway *operation*. Figure 2 presents the relevant contributors to the Map Quality attributes from these two life cycle phases. The identified contributors are picked up in the subsequent chapters to estimate their impacts on the overall quality of the Map Data assets.

As indicated in Figure 2, the feedback of data from infrastructure acquisition activities to other activities could be applied to adapt the Engineering Data (or the infrastructure). Please note that the figure does not represent the actual process but rather a potential sequence of the main contributions. The possible process chains are developed by the scenarios in secion 3.4 below to calculate the achievable data quality considering the applicable contributions or mitigations.

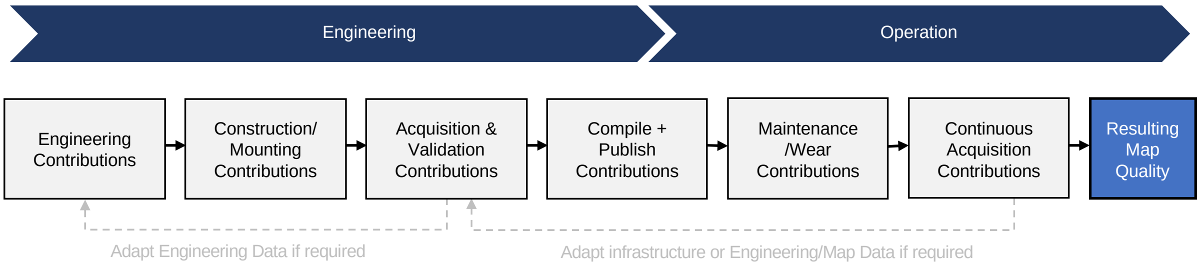


Figure 2 Map Life Cycle from a Quality Point of View

The contributors are described in the subsequent section 3.2.

3.2 Map Quality Contributions in Detail

This section describes the contributors, introduced in section 3.1 above, in detail. We define several implementation variants for each contributor and analyse the Map Quality contribution for those variants. Since the Map Quality contribution depends strongly on the underlying assumptions, we clearly state which assumptions apply to which variant. The result is a set of Map Quality contributors with different implementation variants. For some implementation variants mitigating action exist that might improve the Map Quality. In the subsequent section 3.4.2, we then construct map implementation scenarios based on a generic process introduced in section 3.1, which combines the different implementation variants and sums up the Map Quality contributions over the implementation scenario, see Figure 3.

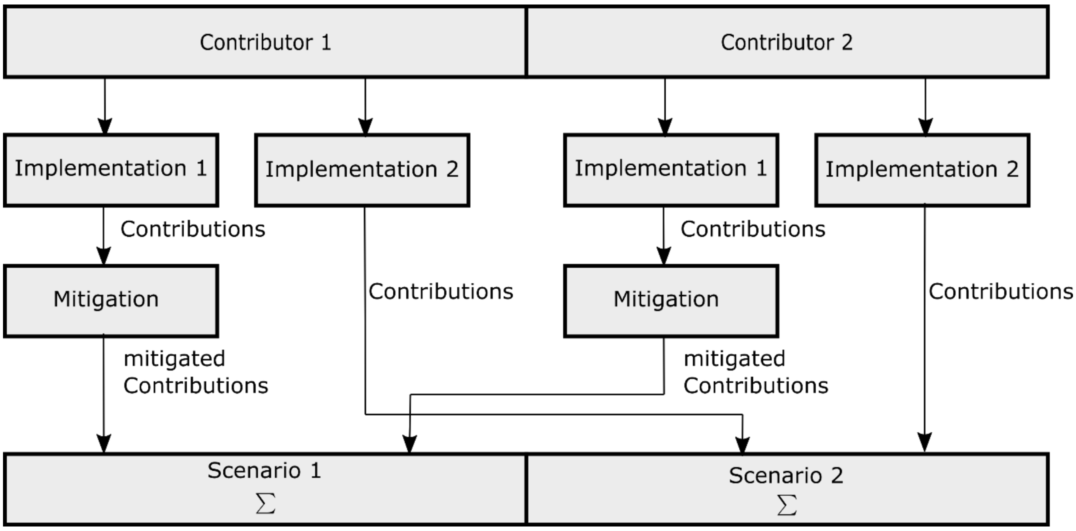


Figure 3: Methodology Map Quality Contributions

The considered analysis dimensions are based on the definition of reliable data introduced in chapter 2 with the following modifications: As argued in chapter 2, technical correctness and consistency are excluded from this infrastructure-related analysis but are covered in chapter 4. Furthermore, to support a trade-off analysis between Map Quality and economic aspects, the analysis *aspects* are supplemented by one-time investment costs (e.g., process change) and ongoing costs (e.g., additional project or maintenance efforts). The collected *analysis aspects* are:

- positional correctness (quantitatively: positional error)
- completeness (added probability of incompleteness, e.g. 50% means every second project faces the problem of incomplete infrastructure data)
- currentness (added possibility for outdated data, e.g. 50% means every second project faces the problem of outdated infrastructure data)
- additional continuous costs (estimated cost increase, calculated in the percentage of overall project costs)
- to be invested one-time costs (qualitatively: no, low, medium, high, very high)

Where applicable, it is distinguished between track geometry (track axis) and element position.

The positional correctness is Boolean and states if the Map Data satisfies the Map Data consumer's accepted positional error requirement. The positional error for the contributions is examined to quantify the positional correctness. Subsequently, it will be compared against acceptable tolerances (see section 3.4.2 below). Systematic errors that impact all projects or independent measurements are excluded from the analysis because they are covered by structured development processes (incl. required testing, certification, calibration of measurement equipment,...) for the tools/systems supporting the overall management of Map Data (see also conditions/requirements of chapter 4)[3]. Hence, this analysis focuses on the *random error* aspect of the positional error and leaves out systematic errors. The positional error comprises, in the context of this analysis, the following dimensions of spatial position and altitude:

- Spatial positions as illustrated in Figure **4**:
  - Associated positional error represented as a vector with the x-y position in the north-east plane and height z perpendicular to the north-east plane: $p = \vec{p} = (x, y, z)$

[3] As required by the EN5012x standards, appropriate methods shall be applied to exclude systematic errors, especially in the safety-related context.

- Positional error represented as vector $\Delta p = \Delta\vec{p} = (\Delta p^{\parallel N-E}, \Delta p^{\perp N-E}, \Delta p^{\perp z})$ ($\Delta p^{\parallel N-E}$: longitudinal to track in north-east plane, $\Delta p^{\perp N-E}$: transversal to track in the north-east plane, $\Delta p^{\perp z}$: height/perpendicular to the north-east plane)

* Altitude:
  - Gradient: pitch angle
  - Cant: roll angle
  - Heading: yaw angle
  - Note: The heading is (very likely) part of Map Data but is not considered in this document because the heading information is already implicitly included in the track axis.

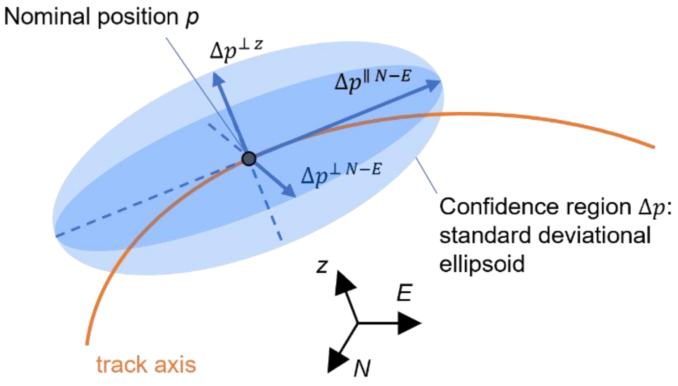


Figure 4: Confidence region positional error

For the positional error contributions for which statistical data is available, the positional error is stated as a 1σ confidence interval (e.g., measurement accuracy for dynamic acquisition). Where no statistical data is available, estimated error limits are given (e.g., mounting error) and are to be understood as 1σ confidence intervals as well[4].

3.2.1 Ground truth

In this document, the *ground truth* corresponds to the final planned and approved track axis, as it will be or was restored after maintenance work (such as tamping). This applies analogously to the element positions, which are also planned, built, and checked for compliance with the planning (in case of deviations planning or position of the element must be corrected). The *ground truth* is the reference for all process steps and their contributions, which might influence the deviation from the *ground truth.*

Note: The required accuracy for element and track data and the availability of digital planning data, which can be used as reference/ground truth, is specific for each Infrastructure Manager. In case of missing information, acquiring track geometry and/or element data is the only option to fill the gap. Due to this reason, the acquisition of infrastructure data is incorporated into the process (section 3.1 above).

3.2.2 Contributions from Engineering

3.2.2.1 Engineering of track axes and trackside infrastructure (inventory or new design)

If the Map Data is based on Engineering Data, positional errors or other contributions introduced by the engineering activities are propagated to the Map Data (if not mitigated).

For the usual case in CCS projects where no track axis construction takes place (e.g., only trackside assets are engineered and mounted), a discrepancy between an engineered track axis and a real track axis in the field can occur, based on the quality of the used Engineering Input Data (IM Data) or

[4] 1 sigma was chosen for consistency in the document/model. The resulting values can be converted to higher confidence levels if required

Acquisition Data. Table 1 gives an overview of the contributions with rough estimates of the quantitative impact for several implementation variants. The column headers follow the aspects introduced in section 3.2 above including the defined confidence.

Contributor/ implementation	Assumption	Longitudinal N-E [m]	Transversal N-E [m]	Height [m]	Gradient [1/1000]	Cant [deg]	Outdated or Incomplete	Cost Increase/ invest	Consider
Import existing IM Data (inventory data) as base for engineering (“brownfield”)	QFW_ A001	2	2	1	0.1	1	50%	50% /no	yes
Digitalization of Inventory Data from paper plans as engineering basis	QFW_ A002	5	5	5	1	5	50%	50% /no	no
Engineering of new-build line (“greenfield”) or upgrade projects (“brownfield”)	QFW_ A003	0	0	0	0	0	0%	0% / high	yes
Transformation of geo-reference systems during import of Inventory Data (e.g., WGS84 to ETRS89)	QFW_ A004	0.01	0.01	0.01	0	0	0%	0%	no

Table 1: Contributions to the engineering of track axes and trackside infrastructure

Assumptions:

QFW_A001 The actual error contribution largely depends on the IM-specific situation regarding the quality of existing IM data (Engineering Input Data), grade of digitisation, and so on. The estimated contributions should represent the current situation of partly unknown or not comprehensively guaranteed data quality.

QFW_A002 The actual error contribution of digitising paper plans essentially depends on the quality of the drawings and the proper use of tooling, so the estimated contributions can be even worse (e.g., some railways estimate a max. contribution of 5m). Also, existing paper plans are usually inconsistent, incomplete, or outdated.
Due to the mentioned contributions, the possibility of digitising paper plans shall be excluded. Therefore, it is not considered for further analysis.

QFW_A003 Concerning the engineering itself, no additional errors are expected. To achieve this, a minimum quality of digitalised engineering processes and tools is required (data-driven instead of plan-centred processes, georeferenced instead of km-referenced planning, digital instead of manual data transfers, the feedback loop from engineering to central databases to maintain data quality beyond project duration, see also principles and requirements from chapter 4.1).
Note: Of course, discrepancies between the engineered data and the constructed track axis or newly installed elements can still arise from other contributions (e.g., track construction or element mounting, see section 3.2.2.2).

QFW_A004 *Export requirement to chapter 4: A sufficient CRS (Coordinate Reference System) must be used without contributing to positional incorrectness due to transformation or temporal effects.*
Therefore, this contribution is not considered for further analysis.

3.2.2.2 Track Construction and Element Mounting

Additional discrepancies between the engineered track axis and the constructed track arise from the positional errors introduced during construction: Even though the commissioning process requires the constructed track axis to match the engineered track axis closely, specific tolerances are accepted, which contribute to the positional error of the Engineering Data. The same applies to mounting trackside CCS elements like balises, usually with higher tolerances than track construction.

Even if no construction of tracks or assembly of new elements takes place in the project, the error contribution remains a deviation between data and reality unless later measures mitigate it.

The contributions are estimated as follows:

Contributor/ implementation	Assumption	Longitudinal N-E [m]	Transversal N-E [m]	Height [m]	Gradient [1/1000]	Cant [deg]	Outdated or Incomplete	Cost Increase/ invest	Consider
Track construction error (tolerance)	QFW_A005	0.015	0.015	0.025	?	0.6	10%	0% /no	yes
Element mounting error	QFW_A006	0.6	0.1	0.1	-	-	10%	0% /no	yes
Mitigation: Improved element mounting	QFW_A007	0,025	0,025	0,030	0	0	0%	10% /med.	yes

Table 2: Contributions Track Construction and Element Mounting

Assumptions:

QFW_A005 The possible error contribution is strongly limited by the low tolerances in track construction, e.g., DB Ril 883.3500 ("Geodätische Fahrbahnvermessung; Geodätische Abnahmetoleranz") [9] with absolute 2D tolerance ≤ 15mm (or 25mm after tamping) and ≤ 25mm (height) in DB_REF2016[5] or swiss railway regulation/Eisenbahnverordnung AB-EBV [10] with +-25mm transversal and +-30mm height tolerance for standard gauge (The AB-EBV tolerances also include operational effects in addition to the construction. Therefore the construction tolerance values from DB Ril 883 are applied here)
Due to insufficient feedback loops, the engineering process might be unaware of potential ad-hoc changes in the field, leading to outdated/incomplete data (even if the safety is ensured by alternative solutions, i.e. additional paper documentation).

QFW_A006 The possible error contribution is limited to the maximum installation tolerance during assembly, here estimated with +/- 1 sleeper distance (60cm) as a typical value for balises. Other element types, such as axle counters, could have higher (eg. Axle counters) or lower tolerances (e.g. ATO precision stopping balises with 10cm accuracy). In any case, it is a very relevant contribution to the overall positional error, especially if other deviations caused by human errors are

[5] DB_REF2016 is uniform and exclusively the geodetic reference and mapping system for all spatial applications of Deutsche Bahn AG. It can be derived from the ETRS89 (see DB Ril 883.9010 [9]).

	considered as well (assumption here: human errors are to be detected and eliminated by procedural measures). Due to insufficient feedback loops, the engineering process might be unaware of potential ad-hoc changes in the field, leading to outdated/incomplete data (even if the safety is ensured by alternative solutions, i.e. additional paper documentation).
QFW_A007	Element Mounting tolerance reduced and controlled by sufficient measures, i.e. geo-referenced engineering process, synchronised with Digital Twin, already considers actual mounting possibilities for balises, delivers exact mounting position incl. plan coordinate AND the engineering process is aware of all remaining ad-hoc changes during mounting by the fully digital process. The extra costs for engineering projects are fully compensated by reduced project risks and faster reaction to practical changes during mounting. The condition for improved mounting is an improved engineering process described by QFW_A003.

The presented contributions can be partially mitigated by a subsequent infrastructure acquisition step, see section 3.2.2.3.

3.2.2.3 Validation by Acquisition

The previous sections listed some possible negative contributions to Map Quality along the engineering process. Acquisition of the existing infrastructure can be performed to confirm or improve the quality of infrastructure-related Engineering Data. Hence, the acquisition can sufficiently address the quality aspects of positional correctness, completeness, and currentness.

While the infrastructure acquisition as a control measure can mitigate the contributions of the previous engineering activities, it also adds its error contributions. For an estimation of the introduced positional errors, see section 3.2.4 below.

Moreover, the integration of acquisition into the project also comes with additional efforts and costs:

- Directly by the efforts/costs of measurement, post-processing, analysis (extract features such as tracks and elements), and comparison/merging with the Engineering Data.
- Indirectly, the efforts/costs of the potential adaption process of Engineering Data still ensure compliance with all engineering rules and reveals potential conflicts with the update of Engineering Data.

The overall process of acquisition and validation is covered in more detail in chapter 4. The additional costs/efforts are roughly considered in this quality analysis by the contributor *extra costs* (see section 3.2.3 below).

3.2.2.4 Compile (& Publish)

The compile step creates Map Data in the respective consumer's needs regarding data structure and contents based on the available Engineering Data. When Map Data is compiled, the following contributions to the Map Data's positional error can occur:

Contributor/ implementation	Assumption	Longitudinal N-E [m]	Transversal N-E [m]	Height [m]	Gradient [1/1000]	Cant [deg]	Outdated or Incomplete	Cost Increase/ invest	Consider
Data Model: Point-based representation of track axes	QFW_A 008	0.1	0.1	0.1	0	0	0 %	0% /low	No (variable density only)
Data Model: Point based representation of track axes w/ variable point density	QFW_A 009	0.01	0.01	0.01	0	0	0 %	0% / low	as additional contrib.
Data Model: Vector based representation of track axes (according to RCA data model)	QFW_A 010	0	0	0	0	0	0 %	0% / low	Yes
Consumer specific Map Data: Gradient profile modelling (averaging of track sections)	QFW_A 011	-	-	-	2	-	0 %	0% / low	no
Transformation of geo-reference systems (e.g., WGS 84 to ETRS 89)	QFW_A 012	0	0	0	-	-	0 %	0% / low	No

Table 3: Contributions Compile (incl. modelling)

Assumptions:

QFW_A008 The contribution is conservatively estimated for a fixed 0.1 m distance between the track points that describe the track axis discretely (see also approach description and error budget evaluation in CLUG [11] section 2.4.2.2 or the SBB study [12]. Since the other point-based approach with variable density offers much lower contributions to the positional error, the fixed point-based approach is not considered in further analysis.

QFW_A009 The contribution is reduced compared to fixed-point distance (see QFW_A008) since the point density can be decreased in sections with small radii so that the interpolation error can be limited sufficiently.

QFW_A010 The vector-based representation of track-axes avoids any interpolation impacts and adds no further contribution (see also SBB study [12]).

QFW_A011 The contribution of gradient modelling, e.g., for the ETCS application, is a typical value based on engineering rules in actual projects. This contributor is not considered yet in this version due to some missing gradient values from other contributors.

QFW_A012 There is no relevant positional error regarding the transformation from WGS84 to ETRS89 (if necessary). Moreover, the positional error of transformation into legacy or local coordinate reference systems can be omitted and is not considered a contribution.

Export requirement to chapter 4: A sufficient CRS (Coordinate Reference System) must be used without contributing to positional incorrectness due to transformation or temporal effects.

After the compilation, the Map Data is published to all the consuming systems that need the data. Since the Map Data remains unchanged, the publishing process adds no further contributions to the quality of Infrastructure Data.

3.2.3 Contributions from Operation

The following effects on the quality of the Map Data during the operation were identified.

Note: The effects are time-dependent and may accumulate over time. They are estimated here as error limits with fixed values for simplicity.

3.2.3.1 Track Maintenance/Wear

During operation, a track axis can change over time due to wear and maintenance activities like tamping. The change leads to a discrepancy between the Map Data and the actual track axis. During the regularly applied tamping, the track axis is corrected to match the Engineering Data, but a residual error remains due to tolerances.

Contributor/ implementation	Assumption	Longitudinal N-E [m]	Transversal N-E [m]	Height [m]	Gradient [1/1000]	Cant [deg]	Outdated or Incomplete	Cost Increase/ invest	Consider
Standard Track Maintenance: Track wear and tamping	QFW_ A013	0.025	0.025	0.030	?	0.6	10%	0% /no	yes
Improved Track Maintenance: e.g. Track Tamping interval reduced by 50%	QFW_ A014	0.013	0.013	0.015	?	0.3	-	100% /high	yes

Table 4: Contributions Track Maintenance/Wear

Assumptions:

QFW_A013 This contribution depends on impacts like track tamping interval, season, and track usage/axle load. However, the contributor is limited by the track tolerances of the infrastructure managers/national regulations, e.g. as defined by AB-EBV [10] as overall track tolerance covering the construction and operation phase (values see section 3.2.2.2 above). Based on expert discussions, the contribution during operation between two maintenance intervals is conservatively assumed to not exceed values as defined above.
Sufficient monitoring of relevant events that should trigger additional tamping/track works is recommended.
The maintenance interval of standard processes today should already ensure 100% coverage, so no impact on completeness or currentness is expected (within the accepted tolerances).

QFW_A014 The contribution accumulating over time can be reduced if the preventive maintenance of tracks (tamping) is done with higher frequency (e.g. doubled), which comes with substantial additional costs (incl. impact on regulations,..). Also, the initial investment is considered high due to additional tamping/maintenance machines.

3.2.3.2 Element Maintenance/Wear

During operation, the position of trackside elements can change over time due to track or element maintenance activities, which can include remounting of elements. The change leads to a discrepancy between the Map Data and the actual position of the elements.

Temporal effects with impact on the positional error of Map Data concerning trackside elements:

Contributor/ implementation	Assumption	Longitudinal N-E [m]	Transversal N-E [m]	Height [m]	Gradient	Cant [deg]	Outdated or Incomplete	Cost Increase/ invest	Consider
Standard Element Maintenance: (e.g., remount balise at different sleeper)	QFW_ A015	0.60	0.60	0.03	-	-	10%	0% /no	yes
Improved Element Maintenance: e.g. limitation of element maintenance tolerance	QFW_ A016	0.013	0.013	0.015	-	-	0%	20% /med.	yes

Table 5: Contributions Element Maintenance/Wear

Assumptions:

QFW_A015 The error contribution usually depends on the national guidelines and processes of element maintenance. The actual tolerance today is assumed to be element type-specific. To simplify this analysis, a general tolerance of 60cm is considered a restrictive estimation, e.g. a balise is mounted one sleeper away from its original position due to mounting issues (e.g. not possible to mount at original position due to damage). *Note: Regarding new elements such as ATO precision stop balises new accuracy restrictions in the range of 10cm are expected.*

Regarding the height contribution, the value has been re-used from track maintenance to estimate the wear effects.

Due to missing digital feedback loops, the potentially relevant results of maintenance works could be processed not or too late in the Map Data.

QFW_A016 The error contribution of element maintenance shall be limited by more restrictive element tolerances for maintenance works, which must be confirmed by appropriate methods (4 eyes principle, measurement...). If the deviation exceeds this lower limit, a correction of the element position or an update of Map Data with the newly determined element position (e.g. acquisition) must be performed.

In addition, the maintenance work should be digitally connected to the Map Data toolchain so that the Engineering Process is aware of relevant events during maintenance (investment).

3.2.3.3 Further temporal effects

Over time, continental drift can induce positional discrepancies between Map Data and reality, depending on the chosen geo-reference system:

Contributor/ implementation	Assumption	Longitudinal N-E [m]	Transversal N-E [m]	Height [m]	Gradient [1/1000]	Cant [deg]	Outdated or Incomplete	Cost Increase	Consider
Continental drift over time (change per year)	QFW_ A017	0.018	0.018	-	-	-	-	-	No
Temperature/weather related influences	QFW_ A018	0.005	0.005	0.005	?	?	-	-	No

Table 6: Contributions Further temporal effects

Assumptions:

QFW_A017 This contributes to uncompensated drift (about 2cm per year). Since the effect act globally (from the perspective of an infrastructure manager) on all tracks and objects, only absolute positions change, but relative positions and distances are conserved.
The contribution is not considered due to the following requirement:
Export requirement to chapter 4: A sufficient CRS specific to the continent must be used so that the continental drift effect is mitigated (e.g. ETRS89 for European Countries)

QFW_A018 Seasonal effects such temperature/weather can be relevant depending on the required accuracy of Map Data. The contribution is roughly estimated based on discussion within the author team and must be verified in later iterations. It must be noted that the effects can be significantly higher locally (e.g. bridges, not considered here yet).
In the first initialisation of the quality analysis, the influences are not included under the condition that they can be neglected for the required accuracy level (>=0.1m).

3.2.3.4 Continuous Acquisition

The previous sections listed some possible negative contributions to Map Quality during operation, mainly caused by maintenance errors. Similar to the engineering phase, the error contribution might be limited by the acquisition of infrastructure, which is applied continuously during operation. In this approach, e.g. operational trains are equipped with extended recording systems that (permanently) collect data during operation.

However, continuous data collection is only suitable to a very limited extent for the reliable and timely detection of potential maintenance faults. Hence, the acquisition should also be locally triggered in case of defined events (e.g. finished maintenance works, environmental impacts,…).

Concerning the track axes position (geometry), the dynamic method would have to have a very high accuracy (<= cm range) to provide more up-to-date data than the original alignment (which comes with high costs and time expenditure!). According to the estimated contributions of acquisition (see section 3.2.4 below), this order of magnitude looks pretty challenging for dynamical measurement methods, as they are applied here to avoid impacts on the line capacity.

This method of continuous acquisition, on the other hand, is suitable for the gradual adjustment of element information in the map data, e.g. to compensate for the seasonal changes if relevant for landmarks of perception systems. Moreover, due to the high amount of remeasurement repetitions, a high level of trust can be built up in the infrastructure data (a counterargument is that the data already must comply with the required properties when the infrastructure is put into operation).

Moreover, the integration of acquisition into the operation also comes with additional efforts and costs:

- Directly by the efforts/costs of measurement, post-processing, analysis (extract features such as tracks and elements), and comparison/merging with the implemented Engineering Data or Map Data.
- Indirectly, the efforts/costs of the potential adaption process of Engineering Data / Map Data still ensure compliance with all engineering rules and reveals potential conflicts with the update of Engineering Data / Map Data.

Finally, the potential positive effects of infrastructure data collection and updating Map Data during operation must be balanced against the high running and investment costs. In addition to the vehicles to be equipped, the masses of acquired data must be evaluated within acceptable time period (i.e. to put all data into value), efficiently, and reliably.

The additional costs/efforts are roughly considered in this quality analysis by the quality parameters *cost increase* and *invest* in section 3.2.4 below.

3.2.4 Acquisition of Infrastructure Data

Besides creating an engineering base, acquiring Infrastructure Data can be utilised to confirm or update Engineering Data or Map Data. Therefore, it can be applied as a control measure to mitigate poor data quality (positional correctness, completeness, currentness of infrastructure-related Map Data). When used as a mitigation, the previous positional error would be replaced by the positional error of the acquisition. The following Table 7 estimates the positional error contribution, taking into account the extraction of features with specific errors for track geometry and elements:

Contributor/ implementation	Assumption	Longitudinal N-E [m]	Transversal N-E [m]	Height [m]	Gradient [1/1000]	Cant [deg]	Outdated or Incomplete	Cost Increase/ invest	Consider
Triggered acquisition and validation of infrastructure**:** e.g., by mobile mapping during engineering phase	QFW_ A019	0.03	0.03	0.035	0.5	0.004	0%	50% /med	Yes (engineering)
Continuous acquisition and validation: Repeated dynamic acquisition during operation	QFW_ A020	0.021	0.021	0.025	0.354	0.003	10%	80% /high	Yes (operation)
Extraction of track axes, e.g. from Point Cloud	QFW_ A021	0.000	0.030	0.030	?	?	-	-	Yes
Extraction of elements	QFW_ A022	0.025	0.025	0.025	-	-	-	-	Yes

Table 7: Contributions Dynamic Acquisition of Infrastructure Data

Assumptions:

QFW_A019 This contribution depends on the measurement accuracy/precision of the applied acquisition method. The assumed positional errors (1σ confidence interval) are defined for a state-of-the-art mobile mapping setup, utilising INS, and PPK/RTK augmented GNSS under open sky conditions. Furthermore, a positional error of ~

0.1 m is achievable by dynamic acquisition methods, as also discussed by RAILAGAP [6]. In case of bad GNSS conditions, sufficient measures like trajectory correction based on ground control points, additional sensors, or alternative acquisition methods must be selected. Of course, the acquisition method is not limited to train-borne mobile mapping but can be complemented by techniques like airborne or static measurements. The selection of methods should also consider that reduced line capacity by required track closures or slow measurements is not acceptable.

QFW_A020 For the continuous acquisition, it is assumed that each situation is measured at least twice during an interval. Hence, the contribution as estimated by QFW_A019 is reduced by an additional measurement run, which delivers a measurement result fulfilling the conditions to sufficiently confirm the previous result (or existing infrastructure data). Following the process, as defined in section 4.3 (Validation), the confirmation by the second measurement is estimated to improve the measurement precision by the factor $1/\sqrt{2} = 0{,}71$, which is applied to the contributions of QFW_A019.

QFW_A021 The contribution is estimated based on the uncertainty caused by rail detection algorithms, especially if the connection or siding tracks are extracted from mobile measurement data, which are not covered by trajectory information.
Additional contributions might occur if existing alignment data is not just confirmed, but instead, new track axes are derived as vectors or alignment elements (curve, straight, transition curve…) from the acquisition data.
Generally, the contribution correlates strongly with the resolution and quality/accuracy of the acquisition data (e.g., in the form of a point cloud), i.e. ground-based methods have an advantage here.

QFW_A022 The specific contribution of extracting element positions strongly correlates with the acquisition data's resolution and quality/accuracy (e.g., in the form of a point cloud). Other contributions (e.g. human error, not clearly defined reference points of elements...) must be excluded by sufficient analysis processes (see 4.2)

3.3 Required Map Quality

The above-introduced contributions and control measures offer many possible combinations resulting in a broad distribution of Map Quality attributes. The analysis here aims to outline the means to achieve a *sufficient Map Quality* with reasonable costs.

What *sufficient Map Quality* means, of course, strongly depends on the data consumer's needs. We make the assumption here:

QFW_A023 For applications like ATO, APS, TMS, vehicle localisation, perception, and incident & prevention management, a Map Data positional error of ~ 0.1 m (positional error in all three directions and 1σ confidence interval) is sufficient. For a first approach, this value is valid for track geometry and elements in the same way.
Rationale: 0,1m is considered as an order of magnitude that should allow efficient acquisition on the one side and improve the today's situation regarding engineering data quality of CCS subsystems on the other side. In addition, the CLUG project derived the same assumption based on the localisation algorithm (see chapter 2.4.2.2 in [11])

Based on this assumption, we start calibrating the Map Data quality model for the different phases of *engineering* and *operation*. It has been decided to separate both lifecycle phases and allocate a budget to each stage, which can be used independently. This separation also helps to reduce possible permutations of possible contribution combinations. As for simplification to the safe side, the budgets of engineering and operation are accumulated to an accepted overall budget.

The accepted deviations between Map Data and the actual situation can be defined as follows:

Table 8: Requirements [Source: MAP quality model]

Accepted Quality (Positional Correctness: 1 sigma)	2D Track position [m]	2D Element position[m]	Height Track Imprec. [m]	Height Elem Imprec. [m]	Probability Incomplete	Probability Outdated	Cost Increase Project/ Interval	Invest
Overall	0,14	0,14	0,1	0,1	0%	0%	40%	-
Budget "Engineering"	0,10	0,09	0,07	0,07	0%	0%	20%	-
Budget "Operation"	0,04	0,05	0,03	0,03	0%	0%	20%	-

- For the position, the total 2D positional error is calculated by applying the vector norm (the root of summed squares) based on the following components:
  - position error longitudinal N-E $\Delta p^{\parallel N-E}$ = 0,1m
  - position error transversal N-E $\Delta p^{\perp N-E}$ = 0,1m
- The tolerated height error is as high as the positional error
- There is no accepted probability of incomplete or outdated data.
- The maximum cost increase for both phases is 40% (20% per engineering project, 20% per maintenance interval)
- Gradient and Cant errors are not considered during this exemplary model initiation and are hidden, although these aspects are already calculated in the model.

3.4 Analysis

All contributions for the phases *engineering* and *operation* that are identified and considered according to the previous section are summarised and grouped as possible implementations (e.g. Mounting) or mitigations (e.g. Improved Mounting).

In the next step, the implementations are grouped into possible scenarios. While the first scenario represents a default case and does not include any mitigation, the following scenarios improve the situation by contributing mitigations.

After that, each scenario is evaluated to which degree the accepted quality levels are met. A scenario is categorised as *accepted* if at least the following critical criteria are fulfilled:

- Positional correctness
  - Correct 2D Track Pos (incl. position error longitudinal + transversal N-E)
  - Correct 2D Element Pos (incl. position error longitudinal + transversal N-E)
  - Correct Track Height
  - Correct Element Height
- Completeness
- Currentness

Cost-efficiency should be considered as an additional parameter, i.e. if several scenarios are possible based on the results regarding critical criteria.

Due to the independent error budgets for both phases (engineering and operation), the phases can be analysed individually, avoiding many possible scenarios.

3.4.1 Phase Engineering

3.4.1.1 Scenarios

The considered implementations and mitigations are used in the following engineering process scenarios, which lead to the summed-up contributions to the resulting quality of the scenario:

Table 9: Engineering Scenarios [Source: MAP quality model]

Implementation (Mitigation)	2D Pos Track Imprecision [m]	2D Pos Elem Imprec. [m]	Height Track Imprec. [m]	Height Elem. Imprec. [m]	Probability Incomplete	Probability Outdated	Cost Increase Project	Invest
Import	2,83	2,83	1,00	1,00	50%	50%	50%	no
Engineer.	0,00	0,00	0,00	0,00	0%	0%	0%	no
Mount.	0,00	0,61	0,00	0,10	10%	10%	0%	no
Impr.Mount	0,00	0,02	0,00	0,03	0%	0%	10%	low
Constr	0,02	0,00	0,03	0,00	0%	0%	0%	no
Acquisition	0,07	0,08	0,07	0,06	0%	0%	30%	medium
Comp/Pub	0,00	0,00	0,00	0,00	0%	0%	0%	low
Engineering Scenarios								
Accepted contribution	**0,10**	**0,09**	**0,07**	**0,07**	**0%**	**0%**	**20%**	**-**
ES0: Import+Engineer.+Mount.+Comp/Pub	2,83	3,44	1,00	1,10	60%	60%	50%	no
ES1: Import+Engineer.+Mount.+Acquisition+Comp/Pub	0,07	0,08	0,07	0,06	0%	0%	55%	medium
ES2: Acquisition+Engineer.+Impr.Mount+Comp/Pub	0,09	0,10	0,09	0,09	0%	0%	40%	high
ES3: Engineer.+Constr+Impr.Mount+Comp/Pub	0,02	0,02	0,03	0,03	0%	0%	10%	low

According to Table 9, the following scenarios are derived for further evaluation:

- ES0: Import IM Data + Engineering + Mounting + Compile/Publish
    - A typical upgrade project, based on available IM Data with partially bad or unknown quality (QFW_A001)
    - No changes regarding track geometry
    - Mounting of elements with tolerances of today's processes (QFW_A006)
    - No acquisition of new infrastructure data or other improvements by mitigations
    - Compile and Publish process with no generic error contributions (QFW_A010)
- ES1: Import IM Data + Engineering + Mounting + Acquisition + Compile/Publish
    - ES0 scenario is improved by the seamless integration of new data acquisition at the end of the project (after mounting elements) for validation purposes.
    - The quality of the resulting Map Data corresponds to the achievable measurement accuracy, which accordingly replaces error contributions from previous engineering activities (data generation, mounting...).
    - Condition: All validation findings by acquisition data are corrected in the Engineering/Map Data.
      Note: if a specific deviation between engineering and measurement is allowed, the precision decreases accordingly
    - The rest remains unchanged; see ES0.
- ES2: Acquisition + Engineering + Improved Mounting + Compile/Publish
    - The scenario ES1 is adapted by integrating the acquisition at the beginning of the project to update and control the quality of the IM Data.
    - In addition, the mounting of elements is optimised by much lower tolerances. Potential deviations are detected reliably and returned as feedback to the engineering process. Consequently, the overall contribution of element mounting is reduced to a minimum. (QFW_A007)
- ES3: Engineering new-build line + Construction + Improved Mounting + Compile/Publish
    - This scenario covers the achievable quality in projects with new build tracks (special case)

- Since the tracks are newly engineering and sufficient tool quality is assumed, there is no contribution of engineering estimated.
- Construction of new tracks with tolerances (QFW_A005)
- Elements are placed with limited tolerances of the improved mounting process
- Compile/Publish process with no generic error contributions (QFW_A010)

3.4.1.2 Evaluation

The evaluation of the engineering scenarios leads to the following grade of fulfilment for critical and non-critical criteria and the required acceptance levels:

Table 10 Evaluation Engineering Scenarios [Source: MAP quality model]

Evaluation Engineering Scenarios	Correct 2D Track Pos	Correct 2D Elem Pos	Correct Track Height	Correct Elem Height	Complete	Current	(Cost efficient)	Invest	Acceptable
Reference	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	-	-
ES0: Import+Engineer.+Mount.+Comp/Pub	4%	3%	7%	6%	40%	40%	70%	no	✘
ES1: Import+Engineer.+Mount.+Acquisition+Comp/Pub	130%	122%	108%	117%	100%	100%	65%	medium	✔
ES2: Acquisition+Engineer.+Impr.Mount+Comp/Pub	112%	96%	78%	82%	100%	100%	80%	high	✘
ES3: Engineer.+Constr+Impr.Mount+Comp/Pub	130%	130%	130%	130%	100%	100%	110%	low	✔

Based on Table 10 above and the chart in Figure 5 below, the following can be concluded:

Two different scenarios with the following mitigations can fulfil the criteria:

- ES1: Import IM Data + Engineering + Mounting + Acquisition + Compile/Publish
  - Applicable mainly for upgrade projects (“brownfield”); regarding new-build projects (“greenfield”) the ES3 scenario is recommended.
  - Further optimisation with improved element mounting is recommended to reduce correction efforts during final validation based on acquisition data.
- ES3: Engineering new-build line + Construction + Improved Mounting + Compile/Publish
  - Applicable for new-build lines only (“greenfield”)
  - Alternatively to the improved element mounting, the final validation by acquisition could be applied, which leads to the same quality achieved by ES1. However, it is much more recommended for efficiency reasons to directly address the mounting effects and save the efforts of additional acquisition runs, as this scenario aims.

As a result, a possible way to achieve the required data quality is shown for both upgrade projects and new construction projects.

Even the additional contribution from layer-specific compiling of the track-axis as track points with variable density QFW_A009 would not exceed the tolerated precision.

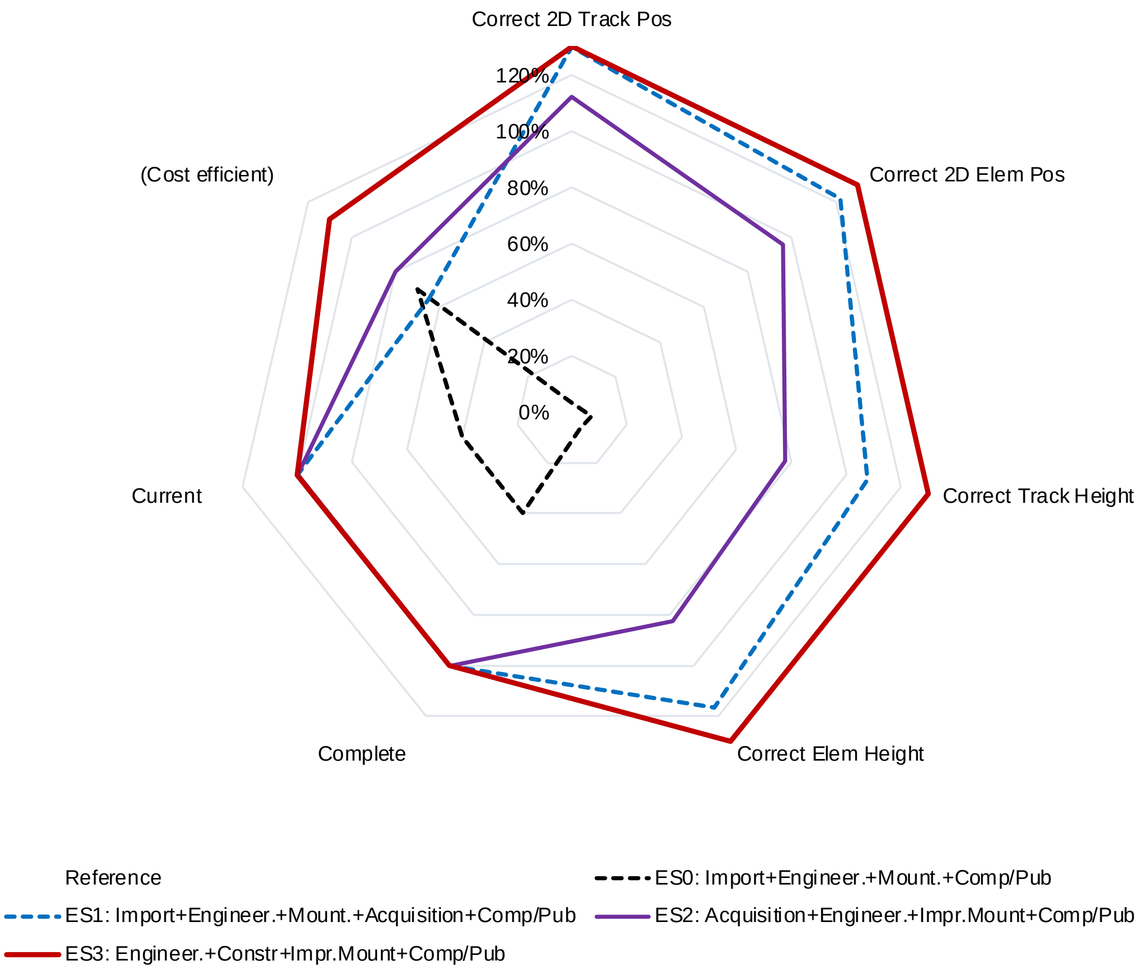


Figure 5: Chart Evaluation Engineering Scenarios [Source: MAP quality model]

3.4.2 Phase Operation

3.4.2.1 Scenarios

The considered implementations and mitigations are used in the following operation process scenarios, which lead to the summed-up contributions to the resulting quality of the scenario:

Table 11: Operation Scenarios [Source: MAP quality model]

Implementation (Mitigation)	2D Pos Track Imprec. [m]	2D Pos Elem Imprec. [m]	Height Track Imprec. [m]	Height Elem. Imprec. [m]	Probability Incomplete	Probability Outdated	Cost Increase Interval	Invest
Standard Maintenance	0,04	0,85	0,03	0,03	10%	10%	0%	no
Standard Track + Impr. Elem. Maint.	0,04	0,04	0,03	0,03	0%	0%	20%	medium
Improved Track + Impr. Elem Maint.	0,02	0,04	0,02	0,03	0%	0%	80%	very high
Continuous Acquisition	0,06	0,07	0,05	0,05	10%	10%	80%	high
Operation Scenarios								
Accepted contribution	**0,04**	**0,05**	**0,03**	**0,03**	**0%**	**0%**	**20%**	**-**
OS0: Standard Maintenance	0,04	0,85	0,03	0,03	10%	10%	0%	no
OS1: Standard Track + Impr. Elem. Maint.	0,04	0,04	0,03	0,03	0%	0%	20%	medium
OS1: Improved Track + Impr. Elem Maint.	0,02	0,04	0,02	0,03	0%	0%	80%	very high
OS3: Continuous Acquisition	0,06	0,07	0,05	0,05	10%	10%	80%	high

According to the table, the following scenarios are derived for further evaluation:

- OS0: Standard Maintenance
  - This scenario without any improvements shall describe a typical situation based on today’s processes. While the track axis can be assumed as sufficiently stable (assumption: maintenance measures like tamping within the required intervals), the grade of freedom regarding maintenance of elements can cause contributions that exceed the budget allocated to operation. (QFW_A013, QFW_A015)
- OS1: Standard Track Maintenance + Improved Element Maintenance
  - To limit the contributions, a scenario with improved element maintenance is introduced. By acceptable methods, the stability of infrastructure is approved. If the limited tolerance is exceeded during maintenance works, the necessity of a Map Data update must be considered (→ Phase Engineering). (QFW_A016)
- OS2: Improved Track Maintenance + Improved Element Maintenance
  - To further reduce the contributions of the operation phase, the track maintenance is also improved by increasing the frequency of maintenance works like tamping.
- OS3: Continuous Acquisition
  - Continuous acquisition of infrastructure data is considered an alternative (or addition) to the mitigations of previous scenarios. If these measurement units detect errors higher than tolerated, the need for a Map Update must be checked (→ Phase Engineering).

3.4.2.2 Evaluation

The evaluation of the operation scenarios leads to the following grade of fulfilment for critical and non-critical criteria and the required acceptance levels:

Table 12: Evaluation Operation Scenarios [Source: MAP quality model]

Evaluation Operation Scenarios	Correct 2D Track Pos	Correct 2D Elem Pos	Correct Track Height	Correct Elem Height	Complete	Current	(Cost efficient)	Invest	Acceptable
Reference	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	-	-
OS0: Standard Maintenance	120%	5%	100%	100%	90%	90%	120%	no	✗
OS1: Standard Track + Impr. Elem. Maint.	120%	130%	100%	100%	100%	100%	100%	medium	✓
OS1: Improved Track + Impr. Elem Maint.	130%	130%	130%	100%	100%	100%	40%	very high	✓
OS3: Continuous Acquisition	71%	71%	55%	60%	90%	90%	40%	high	✗

Due to the relatively small budget margin allocated to the operation, the maintenance process must maintain a very high level of Map Data quality. Table 12 above and the chart in Figure 6 below show that improving element maintenance with a very low tolerance for re-mounting assets can fulfil the requirements. The scenario OS2, which also enhances the track maintenance, is better evaluated regarding positional correctness. However, the costs of, e.g. lower tamping intervals are estimated to be very high (more tamping efforts including investment into machines) compared to the additional effect, so the scenario OS1 *Improved Element Maintenance* is the preferred one in this phase of operation.

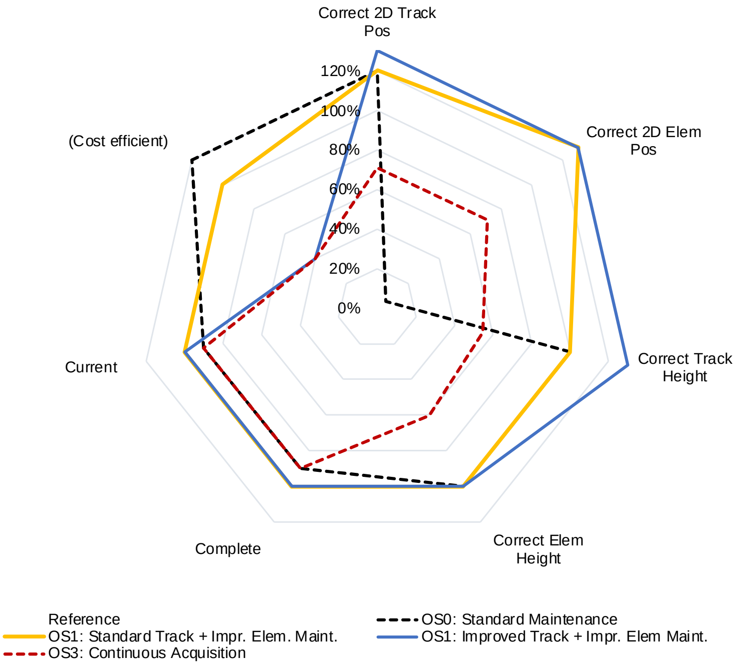


Figure 6: Chart Evaluation Operation Scenarios [Source: MAP quality model]

Due to the specifics of dynamic acquisition technologies, the continuous acquisition seems not to fulfil the required positional correctness. It could be argued that the continuous acquisition updates the Map Data and, therefore, can use the entire budget, including “engineering errors” of positional correctness. However, an update of Map Data also requires the check of potentially relevant engineering rules or other dependencies within the Map Data. Therefore, the critical core of Map Data (tracks, edges, nodes, balises,..) should be kept stable for as long as possible. In addition, continuous recording is generally not beneficial for the track axes, whose tolerance between maintenance intervals is significantly lower than the achievable measuring accuracy.

Conversely, the continuous acquisition can be used to update uncritical Map Data layers with fewer dependencies on other information (e.g. spatial object data for perception systems). Another use case of continuous acquisition is the detection of anomalies in the field, which could trigger a maintenance or even engineering process, if necessary. The engineering process needs to decide if Map Data must be updated, the infrastructure should be adapted or if the detected deviation is acceptable.

3.5 Results

A Map Data quality model (see Annexe A – MAP Quality Model (MS Excel)) has been introduced, which has been applied for the first time to model the contributions of engineering and operation activities. These activities follow a high-level generic process that has been introduced at the beginning.

While all values chosen in this document are justified by assumptions, they should be considered as initial calibration of the model. They can be adjusted according to developing system requirements or IM-specific estimations of contributions.

Based on the first set of requirements and the evaluation of scenarios that accumulate certain groups of contributions, it is concluded:

- The infrastructure data acquisition is an effective and efficient control measure for element position quality during the engineering phase, i.e. for typical upgrade projects ("brownfield"). This also holds for the track geometry during engineering unless the max. positional error is already below the possibilities of a dynamic acquisition due to the tolerance requirements for track construction and appropriate engineering methods (tools, database,..), as is the case for new-build lines.
- To avoid or reduce the need for data corrections by acquisitions in engineering projects, an *improved element mounting process* is highly recommended, ensuring accurate, reliable assembly.
- During the phase *operation,* the solution of standard track maintenance but *improved element maintenance* (with more restrictive element tolerances) seems to ensure the stability of Map Data in the best and most cost-efficient way.
- The positive effects of dynamic acquisition during operation are practically limited to updating layer-specific Map Data information (e.g. landmark specifics for perception system) land and detecting anomalies, which might trigger an engineering process to update the Map Data according to the new situation or correct the infrastructure consistent with the Map Data.
- In general, additional control measures (beyond the standard maintenance procedures) for track geometry during operation are not necessary for the required accuracy.
- A positional error for track geometry and element positioning of 0.1 m (positional error for each direction (longitudinal, transversal, perpendicular to the north-east plane) in 1σ confidence interval) or better can be achieved with the proposed mitigations.

This leads to the following set of contributions along with the recommended scenarios. The derived process for overall map quality assurance is more detailed in the next chapter.

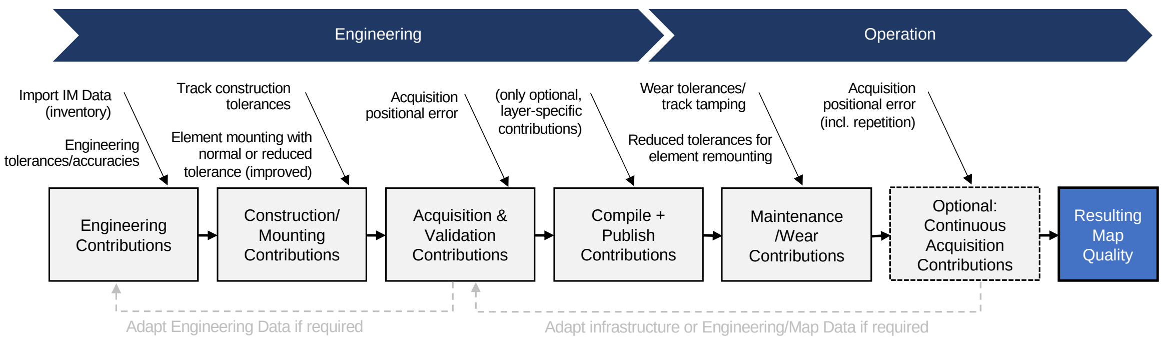


Figure 7: Contributions of recommended scenarios

4 Overall Map Quality Assurance

Reliable Map Data require acceptable processes to avoid systematic errors caused by insufficient Map Data quality. Due to the systematical error characteristic, a quantification of acceptable risks/hazards is not possible. Possible hazards may only arise through the use of map data in the functions of the systems, so the evaluation of the safety relevance must be carried out specifically for each system function. While this evaluation is the responsibility of the subsystem development process, this document focuses on process scenarios (previous chapter) and overall processual measures/conditions to achieve a certain level of Map Quality as specified (later) by the subsystems.

Possible causes of systematic errors in the map data must be adequately addressed in an acceptable process. In addition to the correct representation of the infrastructure, the overall Map Data quality also requires

- compliance to technical correctness conditions, which are usually defined by engineering rules, and
- overall consistency, i.e. without contradictions or conflicts between the different layers of Map Data.

A sufficient process must assure the overall quality of Map Data, supported by appropriate tools and systems to achieve a high level of trust and efficiency over the complete life cycle. This includes the following phases of Map Data, which also take into account the recommended measures of chapter 3.

The overall process and basic requirements for the preparation (incl. engineering) and publishing of Map Data are described in the basic solution concept document of Digital Map [5]. Since this document only covers the potential core of standardisation, we extend the scope here and collect additional requirements for overall Map Quality assurance, even though these aspects must be solved on the IM level.

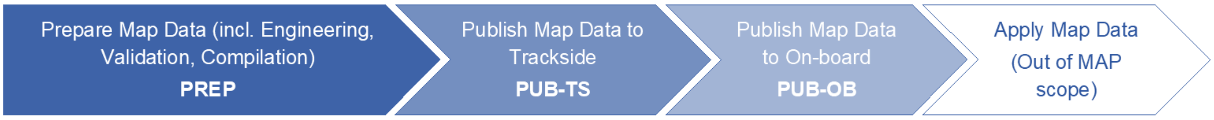


Figure 8: High-level phases and activities of Map Data process [RCA.doc.54]

The high-level process introduced in [5] follows the following phases:

- **Map Preparation process (PREP):** Engineering (incl. mounting), validation and compilation of Map Data according to the engineering rules and the actual infrastructure situation. This includes the potential synchronisation with acquisition data, which has been confirmed as an appropriate method for gaining sufficient Map Data quality (chapter 3).
  This process is triggered in the context of actual engineering projects (i.e. technology rollout, capacity improvements) or after relevant infrastructure changes detected by the appropriate methods during railway operation (i.e. improved maintenance, see chapter 3).
- **Map Publishing process (PUB)**: Distribution of the next Map Data version to the trackside (PUB-TS) and on-board (PUB-OB) consuming systems.
  - ➢ **Trackside Map Publishing process (PUB-TS)**: This trackside publishing process must deliver the Map Data to all trackside systems to activate it synchronously as soon as all subsystem-specific conditions for the Map Data update are fulfilled. This process is triggered in case of relevant Map Data updates created by the Map Preparation process.
  - ➢ **On-board Map Publishing process (PUB-OB)**: After that, the data is also published to the on-board subsystems (or other movable objects that require Map Data to work) according to the actual need along the journey of the vehicles.
    This process is triggered in case relevant Map Data is loaded and activated in the trackside systems (PUB-TS) but also works continuously during operation since the

Map Data is loaded and applied according to the need of the moving object like a train.

These phases are relevant for initial Map Data versions in the same way as for the later update of Map Data versions (including decommissioning old Map Data versions). Therefore, the basic principles to assure the required Map Quality over the whole life cycle of Map Data are described for each phase.

More details about the conceptual approach and architecture are given in the basic solution concept document of Digital Map [5], which describes the basic functions and requirements of the mentioned processes. This concept defines a standardisable, tool/system-supported core process that complies with broader national Infrastructure Manager approaches, such as the SafeRailMap project by DB Netze [8] or the projects EDP, Topo4, and DCM as part of the former SBB smartrail 4.0 program [7].

4.1 Map Data Preparation – Engineering

The Engineering phase, which typically consists of planning activities by the IM and further processing by the selected supplier, aims to collect all essential information and enrich additional data needed to configure the systems (e.g. interlocking, ETCS) for a specific application. The engineering process follows defined engineering rules, which are today very IM and supplier-specific.

However, a new architecture such as RCA offers new possibilities for standardisation also regarding the following engineering process aspects:

- Standardised Engineering Input Data format could be used to import Inventory Data from existing IM databases or new acquisitions.
- Standardised Engineering Rules come from the RCA system design, which offers more generalisation potential due to abstraction and less specific configuration (replaced by dynamical functions). By increasing the number of generic engineering rules as part of the RCA system design (important driver: APS), the economic grade of automatisation of engineering activities is increased accordingly.
- Generic functions automatically enrich the input data with engineering information as the consuming systems require.
- Generic functions to support the engineering workflow such as object- and release-level versioning, management of unique object IDs, management of construction phases,…
- Standardised Engineering Output Data format, which is used later on as a base to compile the Map Data for each RCA subsystem.

More details in [5], i.e. chapter 4. Besides the added value that could be expected from standardisation, a lot of IM-specific optimisations are required as well, such as:

- Build a digital toolchain that connects across the trades and synchronises the planning results efficiently
- Avoid manual data transfers and replace them with standardised data formats for each phase
- Introduce digital workflows also in communication and verification/validation activities (e.g. verification with digital signature)
- Automate repetitive tasks as much as economically and technically possible to minimise the potential of human error
- Ensure acceptance/approval/trust of tools incl. automation, so no project engineer needs to check the results of automated functions
- Implement data-centred instead of plan-centred workflows, so the digital database is the master instead of the drawings (the plan becomes just a view of the data)
- Allow georeferenced planning/engineering to simplify the processes of exact mounting and synchronisation with acquisition data.
- A sufficient CRS (Coordinate Reference System) must be used without contributing to positional incorrectness due to transformation or temporal effects.

- A sufficient CRS specific to the continent must be used so that the continental drift effect is mitigated (e.g. ETRS89 for European Countries)
- Connect the engineering process with a centralised master database that ensures the achieved data quality during and beyond the project
- Introduce appropriate engineering tools that follow the mentioned principles and support the engineer in the best way with a high grade of usability
- Ensure sufficient quality of engineering input data (IM Data) to avoid project risks, additional costs, and efforts spent for correction (for new acquisition, see section 4.2). Of course, this situation depends mainly on the specific situation at the IM, while all conditions can be met, such as:
    - ➢ Accurate, complete and current infrastructure data for tracks and elements are available, but it is capsuled in plans and non-machine-readable data formats, or it is not trusted as a reliable data source
    - ➢ Sufficient infrastructure data for the engineering of track geometry is available, but not for all types of elements (e.g. axle counters).
    - ➢ The available data is very accurate and current but not complete for the whole required network
    - ➢ The available information is complete and updated but not precise enough….

4.2 Map Data Preparation – Acquisition incl. Analysis

As shown in the previous chapter, acquiring existing infrastructure is a very efficient measure to avoid incomplete, outdated or inaccurate Engineering Data or Map Data. Thus, the acquisition should be integrated into the data preparation phase to provide good Engineering Input Data or validate Engineering Data against the existing infrastructure. The same methods could detect non-tolerated deviations during the operation phase. A vital pre-requisite and also one of the biggest challenges for the successful integration of infrastructure acquisition (also referred to as digitisation campaigns) is the rapid and reliable analysis of measurement data (point clouds, videos, trajectories,..) to the structured input data, that is required for data preparation or maintaining data quality (tracks, nodes/edges, elements like signals, balises,…). The key challenges to be solved are

- Apply measurement methods that fulfil the required accuracy level
    - ➢ The required accuracy must be within a range that is technical and economically feasible and optimised (e.g. consider acquisition efforts/times within projects (not possible in real-time), avoid too restrictive mm/cm accuracy, …)
    - ➢ The provided accuracy must be within the tolerated range (e.g. as defined in chapter 3.2.4)
    - ➢ The suitability of the measurement method must be confirmed within the framework of appropriate tests/certifications/approvals.
    - ➢ Control points could be used if necessary and reasonable from a technical/economic point of view to confirm the suitability of the measurement method during application.
      Note: additional maintenance efforts and increased trackside elements due to detectable control points must be avoided
    - ➢ Regular maintenance and calibration of the measuring system shall continuously ensure its suitability.
    - ➢ The recorded data (e.g. point cloud) must provide sufficient density to minimise the error of feature extraction (analysis)
- Apply acceptable analysis methods to extract the tracks and elements from the measurement data
    - ➢ The system/tool implementing the analysis functions (incl. extraction of tracks and track elements) shall be implemented safely and robustly (incl. error handling…).

One appropriate solution is the independent analysis by at least two channels, which are compared by a safe validation tool.

- ➢ a high degree of automation regarding post-processing and analysis is required to avoid process barriers and consider all acquisition data for better Engineering or Map Data quality
- ➢ the exact reference position that needs to be measured must be defined for each element type
- ➢ The extraction shall allow precise positioning of the tracks and elements within the permissible tolerances (e.g. as described in chapter 3.2.4)
- ➢ The correctness of other extractable information (such as element type) shall be guaranteed by reliable tools/processes.

- All tool support (i.e. automatisation) must be done in a reliable way to make the resulting data acceptable for SIL4 functions. (e.g. tool certification according to EN 50128/9)
- Efficient validation and merging of Engineering Data with acquisitioned infrastructure data (see chapter 4.3)

Since the need and the applied methods for the acquisition and analysis part is typically an IM-specific topic (e.g., the SafeRailMap initiative of DB Netze), it is not subject to standardisation. To tackle the issue of technical feasibility and get a common understanding of the acquisition, including the analysis process, the exchange of RCA Digital Map with the European initiative RAILGAP has been launched.

4.3 Map Data Preparation – Validation

During the validation, the next release of Engineering Data, which will later be the base to compile the Map Data, is proved to fulfil the different attributes of Reliable Map Data. Two main checks are divided here in the potentially standardised context:

- The automated comparison between Engineering Data and acquisitioned infrastructure data ensures a sufficient positional error, completeness and currentness compared to the existing infrastructure.
  Note: The automated comparison and synchronisation of Engineering Data (as Map Input Data) with actual infrastructure data will improve the integration of acquisition procedures into the data preparation a lot since today it is a considerable challenge to compare spatial infrastructure information with planning data, that is topological only for the most cases.
- The automated rule check ensures the technical correctness against engineering or generation rules and avoids human reviews' efforts and potential errors.

Both aspects (especially the rule check) are candidates for standardisation since it is a generic problem for all IMs, as pointed out and more detailed in [5], i.e. chapter 4. Also, the topic is covered by the SafeRailMap project of DB Netze [8].

Regarding the development of the mentioned functions, the following conditions must be fulfilled to support the improved Map Data quality:

- the system/tool implementing the validation functions is considered safe and robust (incl. error handling…)
- a high degree of automation is required to avoid process barriers and process all validation results
- The detected errors must be prepared as reports so that an efficient root cause analysis and elimination can occur (e.g. adaptation of the engineering data).

A safe compare functionality can be used to prove that the inputs of two independent data channels deliver results with deviations more minor than a given tolerance, e.g. to check

- Engineering Data vs acquisitioned infrastructure data during a project or operation, or
- Acquisitioned infrastructure data of measurement 1 vs independently acquisitioned infrastructure Data of measurement 2, or

- other pairs of independent infrastructure data input.

Consequently, the compare feature can be used to improve the reliability of Map Data by ensuring positional correctness, including a required positional error as defined for selected confidence.

The methodology, how the input data are compared and merged into a resulting data basis, should be based on the following principles:

- The process of *acquisition* and *validation* is triggered in case of any need to update Map Data, i.e. if modifications of the infrastructure during an engineering project or operation/maintenance are known or cannot be excluded
- The *validation* compares the new measurement/*acquisition* data with the Engineering Data.
- The latest acquisition data is merged with the existing IM data as follows
    - ➢ IF *the Engineering Data is not completely available*
      OR *the Engineering Data positional error is unknown*
      OR *the position deviation of Engineering Data vs acquisition is too high (means: position distance incl. estimated precisions do exceed defined tolerance/threshold)*
      THEN: Use position including the precision of new acquisition and update Engineering Data
    - ➢ ELSE:
        - ▪ IF *precision of IM data shall be increased AND new position confirms Engineering Data sufficiently*
          THEN: Calculate new position with the weighted mean value of Engineering Data and new acquisition and update Engineering Data → precision is improved
        - ▪ *ELSE (stability of Engineering is preferred over improved precision due to economic reasons):* Keep Engineering Data stable and existing position value unchanged → precision is estimated with ½ tolerance/threshold
- The whole process is repeated if the resulting precision of the Engineering Data still does not fulfil the required precision for certain confidence.

If the Engineering Data is updated, it must be rechecked if the changes are still compliant with the engineering rules, e.g. by the mentioned rule check functionality of the tool-supported validation process.

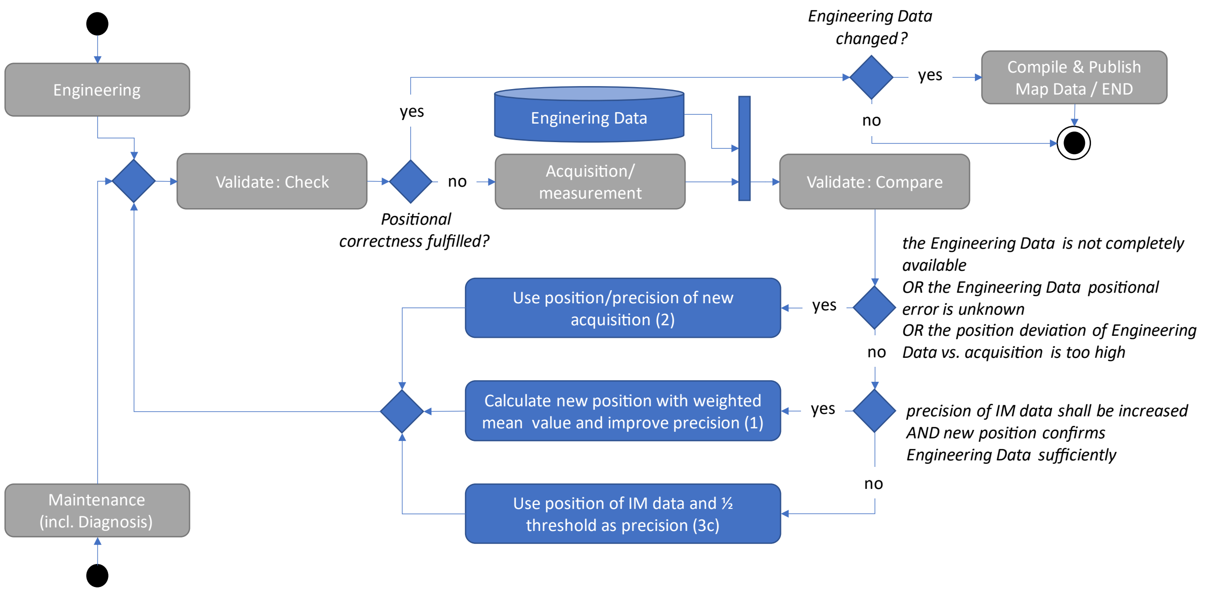


Figure 9: Validation process

4.4 Map Data Preparation – Compile

Suppose a sufficient quality level of Engineering Data has been proven by the validation process. In that case, the Engineering Data is automatically converted to the Map Data structure, including the layers required by the different trackside or on-board subsystems. This process is generic and should be completely standardised by the specification of required Engineering Data (e.g. according EULYNX PREP) input and output Map Data (according to RCA Object Catalogue [2]). The minimum scope of standardisation is the unified specification of the output Map Data. It is referred to [5] for more details, i.e. chapter 4.

Since all the layers containing the subsystem-specific representations of the same Engineering Data source are generated in a fully automated way, the error potential (and efforts) is vastly decreased. It avoids subsystem-specific data preparation (e.g. ETCS, interlocking, TMS, ATO) with potential inconsistencies.

Regarding the development of the mentioned functions, the following conditions must be fulfilled to support the improved Map Data quality:

- the system/tool implementing the compile function is considered safe and robust (incl. error handling…), so consistency over all layers of information is assured.
- the relationship between Engineering Data and resulting Map Data is defined unambiguously and completely (MAP Object Catalogue [2])
- the data model shall avoid positional error contributions due to interpolation, so at least on the primary layer, a lossless vector-representation of Map Data (or dynamical point density with sufficiently small point distances) shall be offered (see also section 3.2.2.4)
- additional positional error contributions by system-specific information (e.g. gradient profile model of ETCS) must be aligned with the consuming systems.
- A sufficient CRS specific to the continent must be used so that the continental drift effect is mitigated (e.g. ETRS89 for European Countries)

4.5 Map Data Publishing to Trackside

4.5.1 Description

Publishing Map Data to the trackside systems should follow a uniform process using standardised interfaces to distribute Map Data updates. The approaches are described in [RCA.doc.54], i.e. chapter 5.

A standardised process to deliver Map Data updates to all trackside systems should essentially decrease the efforts and duration of the data distribution and activation process. Therefore, the frequency of Map Data updates can be increased to maintain a high level of Map Data quality during operation (e.g. along with the actual construction phases) and reduce the need for operational restrictions.

In addition, the Map Data consistency for all systems is ensured by a synchronised activation approach.

Regarding the development of the mentioned functions, the following conditions must be fulfilled to support the improved Map Data quality:

- the systems implementing the publishing function are considered safe and robust (incl. error handling…)
- Each system ensures a safe Map version transition considering the map version update conditions.

4.6 Map Data Publishing to On-board

The digital chain for distribution of Map Data is extended to the onboard systems during the operation and according to the actual needs of a specific vehicle along its journey. This process is more detailed in several documents referenced in [RCA.doc.54] chapter 5.

By coupling the moving objects like vehicles to the map distribution process, it is ensured that the updated Map Data is always applied during the operation and quick updates can be published. This supports the currentness of Map Data.

In addition, the connection to the vehicles can be used to get information regarding potential inconsistencies between the Map Data and information provided by other sensors. This data can be used to focus on the need for Map Data updates, e.g. by performing additional local infrastructure acquisitions.

Regarding the development of the mentioned functions, the following conditions must be fulfilled to support the improved Map Data quality:

- the systems implementing the publishing function are considered safe and robust (incl. error handling…)
- potential sensor inconsistencies to Map Data are provided from on-board to trackside

4.7 Assure Map Data quality during Operation

Besides publishing Map Data to on-board systems and the feedback from on-board to trackside regarding potential sensor inconsistencies as diagnostic function, there is no standardised process to assure Map Quality during operation. It follows the logic that each infrastructure change is organised within a planned engineering project or maintenance effort. Therefore, the engineering and maintenance processes should be optimised, as discussed in chapter 3.

Environmental impacts, which could influence infrastructure and Map Data quality, should be detected by external systems (i.e. IPM). In case of events, an appropriate reaction should be carried out (e.g. usage restriction and adapt engineering or adapt infrastructure).

Additional, specifically equipped trains to capture the existing infrastructure during operation could also be used to detect temporal changes and trigger updates of certain Map Data parts accordingly (e.g. dimension of landmarks for perception system). More details about the limitations and potential role of continuous acquisition are given in section 3.4.2.2 above.

5 Conclusion

The result of this document is a generic model for Map Data quality that sums up all the contributors according to the scenarios that have been recommended after discussion (chapter 3, Annexe A – MAP Quality Model (MS Excel)). Based on this recommendation and already existing efforts on a national and international level, a high-level process with basic requirements to achieve and maintain a sufficient Map Data quality level has been sketched (chapter 4).

The model itself can be adjusted to different IM-specific situations regarding estimated contributions. Also, the required Map Quality parameters, as the Map Data consuming systems demand them, can be changed according to the current stage of development and knowledge.

RCA Cluster Digital Map - MAP QUALITY MODEL

REQUIREMENTS

Accepted Quality (Positional Correctness: 1 sigma)	2D Track position [m]	2D Element position[m]	Height Track Imprec. [m]	Height Elem Imprec. [m]	Probability Incomplete	Probability Outdated	Cost Increase Project/ Interval	Invest
Overall	0,14	0,14	0,1	0,1	0%	0%	40%	-
Budget "Engineering"	0,10	0,09	0,07	0,07	0%	0%	20%	-
Budget "Operation"	0,04	0,05	0,03	0,03	0%	0%	20%	-

SCENARIOS

Phase "Engineering"

Implementation (Mitigation)	2D Pos Track Imprecision [m]	2D Pos Elem Imprec. [m]	Height Track Imprec. [m]	Height Elem. Imprec. [m]	Probability Incomplete	Probability Outdated	Cost Increase Project	Invest
Import	2,83	2,83	1,00	1,00	50%	50%	50%	no
Engineer.	0,00	0,00	0,00	0,00	0%	0%	0%	no
Mount.	0,00	0,61	0,00	0,10	10%	10%	0%	no
Impr.Mount	0,00	0,02	0,00	0,03	0%	0%	10%	low
Constr	0,02	0,00	0,03	0,00	0%	0%	0%	no
Acquisition	0,07	0,08	0,07	0,06	0%	0%	30%	medium
Comp/Pub	0,00	0,00	0,00	0,00	0%	0%	0%	low

Engineering Scenarios								
Accepted contribution	**0,10**	**0,09**	**0,07**	**0,07**	**0%**	**0%**	**20%**	**-**
ES0: Import+Engineer.+Mount.+Comp/Pub	2,83	3,44	1,00	1,10	60%	60%	50%	no
ES1: Import+Engineer.+Mount.+Acquisition+Comp/Pub	0,07	0,08	0,07	0,06	0%	0%	55%	medium
ES2: Acquisition+Engineer.+Impr.Mount+Comp/Pub	0,09	0,10	0,09	0,09	0%	0%	40%	high
ES3: Engineer.+Constr+Impr.Mount+Comp/Pub	0,02	0,02	0,03	0,03	0%	0%	10%	low

Phase "Operation"

Implementation (Mitigation)	2D Pos Track Imprec. [m]	2D Pos Elem Imprec. [m]	Height Track Imprec. [m]	Height Elem. Imprec. [m]	Probability Incomplete	Probability Outdated	Cost Increase Interval	Invest
Standard Maintenance	0,04	0,85	0,03	0,03	10%	10%	0%	no
Standard Track + Impr. Elem. Maint.	0,04	0,04	0,03	0,03	0%	0%	20%	medium
Improved Track + Impr. Elem Maint.	0,02	0,04	0,02	0,03	0%	0%	80%	very high
Continuous Acquisition	0,06	0,07	0,05	0,05	10%	10%	80%	high

Operation Scenarios								
Accepted contribution	**0,04**	**0,05**	**0,03**	**0,03**	**0%**	**0%**	**20%**	**-**
OS0: Standard Maintenance	0,04	0,85	0,03	0,03	10%	10%	0%	no
OS1: Standard Track + Impr. Elem. Maint.	0,04	0,04	0,03	0,03	0%	0%	20%	medium
OS1: Improved Track + Impr. Elem Maint.	0,02	0,04	0,02	0,03	0%	0%	80%	very high
OS3: Continuous Acquisition	0,06	0,07	0,05	0,05	10%	10%	80%	high

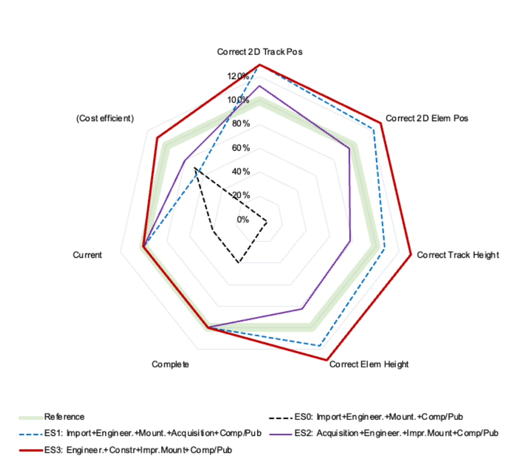
EVALUATION OF SCENARIOS

Phase "Engineering"

Evaluation Engineering Scenarios	Correct 2D Track Pos	Correct 2D Elem Pos	Correct Track Height	Correct Elem Height	Complete	Current	(Cost efficient)	Invest	Acceptable
Reference	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	-	-
ES0: Import+Engineer.+Mount.+Comp/Pub	4%	3%	7%	6%	40%	40%	70%	no	✗
ES1: Import+Engineer.+Mount.+Acquisition+Comp/Pub	130%	122%	108%	117%	100%	100%	65%	medium	✓
ES2: Acquisition+Engineer.+Impr.Mount+Comp/Pub	112%	96%	78%	82%	100%	100%	80%	high	✗
ES3: Engineer.+Constr+Impr.Mount+Comp/Pub	130%	130%	130%	130%	100%	100%	110%	low	✓

EVALUATION DIAGRAMS

Engineering scenarios: fulfilment of Map Data quality critieria



Operation scenarios: fulfilment of Map Data quality critieria

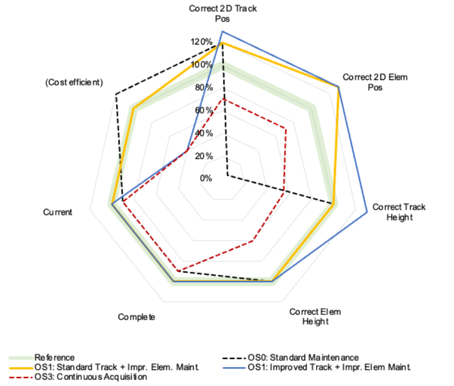


Figure 10: Map Quality Model [Annexe A – MAP Quality Model (MS Excel)]

Besides its flexibility, the here presented Map Data quality model offers a high grade of transparency and an integrated view over different disciplines or railway domains:

- Track axes alignment and construction process
- CCS element engineering and mounting

- Geographical coordinate systems, measurement tools and processes incl. post-processing and feature extraction
- Data structuring and its impact on data quality
- Maintenance processes for tracks and elements
- Tools and databases for infrastructure data management, engineering, validation, compiling and publishing
- Interface to monitoring systems during operation

As a basis for the model, the term *Map Data Quality (*synonym to *Infrastructure Data Quality)* was defined using the aspects of *Reliable Map Data (*synonym to *Reliable Infrastructure Data)*:

- Complete
- Correct (incl. positional and technical correctness)
- Current
- Consistent

For each of these aspects, a target value is to be defined according to the requirements of the consuming systems (e.g. 10cm for positional correctness and 0% probability for incompleteness). In the end, the model tests each constructed scenario for compliance with all aspects of data quality according to the defined requirements.

While the model is a first approach and subject to further development, it already offers the possibility to discuss technically and economically feasible Map Data requirements. Based on the initial calibration of the model by this document, one possible path for the balance of technically and economically feasible Map Data requirements is presented. Of course, the actual implementation of the mitigation measures must be discussed in each IM-specific context.

Hence, the model is not a fixed recommendation but a platform for structured discussion considering all the contributions and aspects of Map Quality (incl. costs).

5.1 Outlook

The following next steps could be relevant for further progress of the MAP Quality Framework/Model:

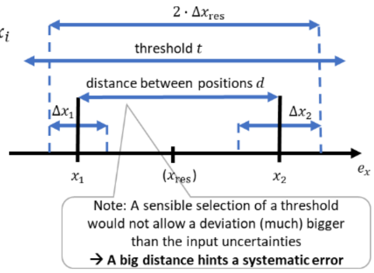
- Extend the quality model regarding gradient, CANT, radius other infrastructure-related information
- Validate the contributions by application for other infrastructure managers
- Develop a bottom-up view of system requirements regarding Map Quality together with RCA subsystems/clusters
- Mirror the Map Quality requirements of the consuming subsystems against the technically and economically achievable Map Quality according to this parameterised model
- Develop the tool/process requirements to provide sufficient Map Data quality

6 Annexe A – MAP Quality Model (MS Excel)

Filename: DigitalMap Quality Framework RCA.Doc.77 Annexe A Quality Model.xlsx

Link:
https://nextrail.sharepoint.com/:x:/r/teams/RCADigitalMapCluster/Freigegebene%20Dokumente/General/50%20Requirements/Evaluation%20Map%20Quality%20Model/MAP%20Quality%20Impact%20Analysis.xlsx?d=w9aefb5945d4f4ff7a46833cb0327ca9b&csf=1&web=1&e=pMzg9E

7 Annexe B – Excursion: Combine multiple infrastructure data sets



Goal: Confirm data from independent measurements with uncertainties for same object $x_i \pm \Delta x_i$ (e.g., confirm engineering data by acquisition); Try and combine data.

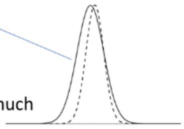
Ansatz: Regard objects within threshold as confirmed, see geometric consideration. Validation condition: $t \geq \Delta x_1 + \Delta x_2 + d$

Resulting position and uncertainty <u>if threshold condition is fulfilled</u>:

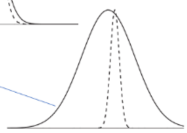
Best Case

- Option (1) If individual errors of same magnitude ($\Delta x_1 \sim \Delta x_2$) and objects not separated too much ($d \leq \Delta x_1, \Delta x_2$): Calculate new position & uncertainty with weighted mean

$$\bar{x} = \frac{\sum_i^n \frac{x_i}{\Delta x_i^2}}{\sum_i^n \frac{1}{\Delta x_i^2}} \ , \quad \Delta\bar{x} = \sqrt{\frac{1}{\sum_i^n \frac{1}{\Delta x_i^2}}}$$



- Option (2) If very different uncertainties ($\Delta x_1 \ll \Delta x_2$) and objects not separated too much ($d \leq \Delta x_1, \Delta x_2$): Use more accurate measurement ($x = x_1 \pm \Delta x_1$).

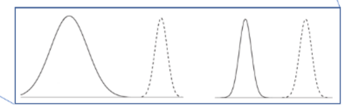


- Option (3) If objects are strongly separated ($d > \Delta x_1, \Delta x_2$):
  - (3a) Use position & uncertainty from single/more accurate measurement.
  - (3b) Calculate mean & estimate uncertainty based on geometric consideration:

$$\Delta x_{\mathrm{est}} = \frac{\Delta x_1 + \Delta x_2 + d}{2} \leq \frac{t}{2}$$

  - (3c) Use position from one measurement (e.g., data to be confirmed), recalculate uncertainty on geometric consideration.

Worst Case



8 Annexe C – Summary SafeRailMap Project, DB Netz AG

Henning Nitzschke, DB Netz AG

Introduction SafeRailMap

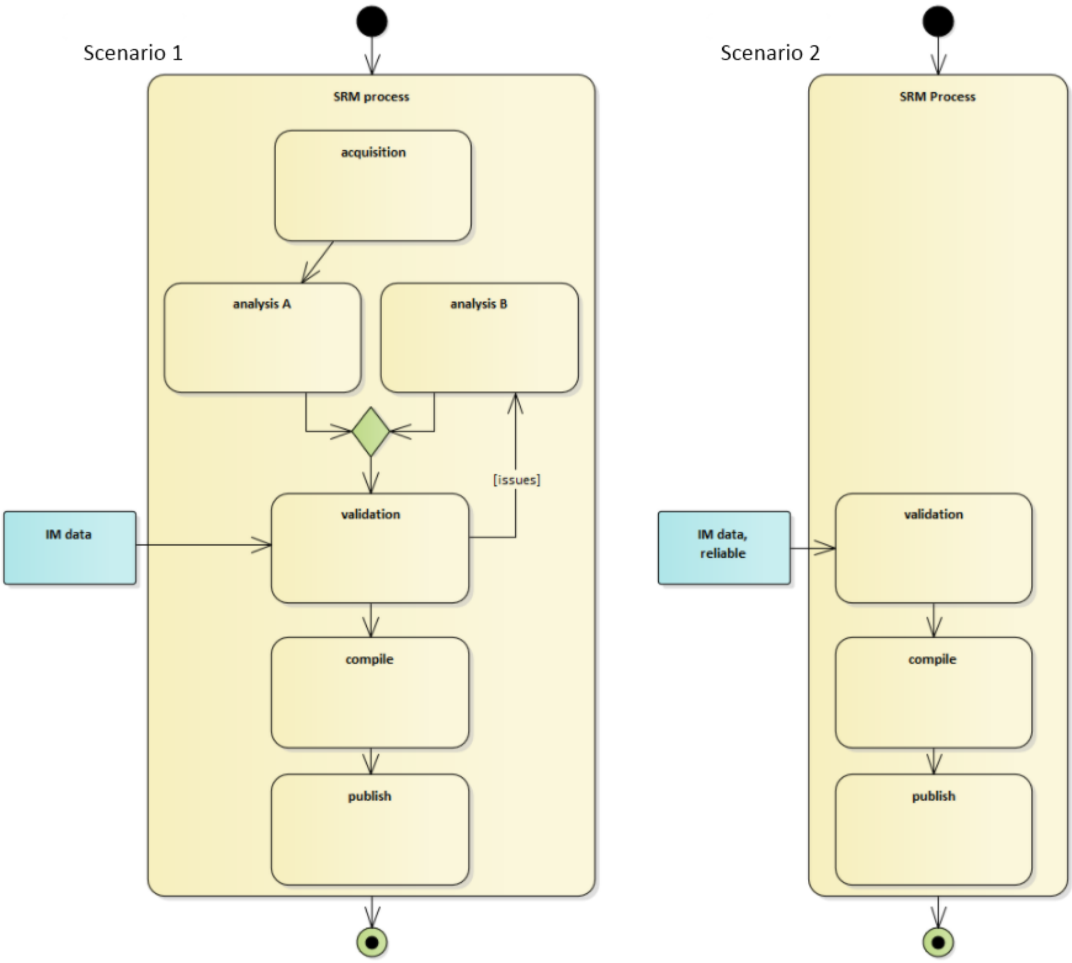
To support the localisation in safety-relevant applications (SIL (Safety Integrity Level) 1-4, according to CENELEC), it is necessary to have reliable map data. Reliable map data shall fulfil the following aspects:

- Complete: All map data (i.e., tracks and elements/objects) within the scope of the application are present, and all attributes are populated
- Accurate:
  - Technical accuracy: the map data is correct in the sense that they conform to the rules and reality (e.g., right element type)
  - Measurement accuracy: the location data (e.g., absolute position, relative position on track section) has a defined degree of precision (significance) within a specified tolerance
- Current: the map data accurately represents the current situation
- Consistent: no ambiguities or contradictions between different topical aspects, versions, or adjacent regions of map data

For reliable map data within safety-relevant applications, a dedicated map-generating process is needed to ensure the aspects mentioned above. The SafeRailMap process shall cover this. For the SafeRailMap process, two scenarios are possible. On the one hand, existing infrastructure management systems (IM data) do not provide reliable map data; on the other hand, infrastructure management systems provide reliable map data. The following picture shows the workflow of both scenarios, and in addition, a Management Process (see section Management Process) exists to control and monitor the complete SafeRailMap process.

Acquisition

The acquisition sub-process shall combine several independent acquisition methods (e.g., static acquisition, rail-bound acquisition, satellite acquisition etc.). The recorded raw geo-referenced acquisition data from previous acquisition campaigns shall also be considered. With these steps and a verifying step, the acquisition sub-process shall ensure the integrity of all data artefacts throughout the entire process by appropriate measures (e.g. hash/signature creation and check during all write or read operations, respectively). A pre-condition for current (sub-attribute of reliable) data is the acquisition carried out at the right time, i.e., not before the construction efforts are completed, with which the SafeRailMap process is associated. Therefore, the SafeRailMap process must be integrated into the existing engineering and commissioning process (see Management Process).



Analysis and Validation

In the most common case (especially for the onboard localisation use case) of scenario 1, the validation sub-process creates reliable map data by comparing the data from two diverse, independent input data channels to each other. The two validation input channels are populated with analysed acquisition data and with (not reliable) externally supplied data from the infrastructure manager system. Suppose it turns out during import or validation that the external IM data is not complete or of insufficient quality or that there are unresolvable discrepancies in the comparison. In that case, data from additional analysis channels is added until voting (e.g., 2 out of 3) results in an unambiguous and current representation of the real world in the map data. The additional analyses required to solve the deviations must differ from the initial analysis. The case when no external data is available is also covered: two independent, diverse analysis iterations, based on a common acquisition data set, are carried out and compared by the validation sub-process.

Regardless of the data's origins (analysed acquisition data or IM data), all channels are regarded as equal in the validation sub-process unless the externally supplied data is already classified as reliable. The latter case is addressed by validation scenario two and applies when an external authority has already approved the imported IM data (e.g., DB Netze engineering and commissioning processes). In this case, the validation sub-process only manages the external IM data, checks its quality attributes, and forwards it to the subsequent sub-processes. In addition to the presented validation sub-process, the process can follow feedback loops in case of data or process issues (e.g., repeat analysis after unsuccessful validation, request external clarifications). The management process handles both validation configurations and feedback loops, which are presented in detail in the next section.

Compile and Publish

The compile sub-process and the publish sub-process maintain the data quality by integrated verification steps and safe development according to CENELEC and derived appropriate measures (e.g., diverse implementation). Data that can be derived or transformed automatically unambiguously is calculated after validation by a safe function (inside the compile sub-process). A pre-condition for current (sub-attribute of reliable) data is that publishing new map data to production is carried out at the right time, i.e., no activation before the engineering and commissioning efforts with which the SafeRailMap is associated are completed. Therefore, the SafeRailMap process must be integrated into the existing engineering and commissioning process (see Management Process).

Management Process

The SafeRailMap process is always applied in the context of a specific project. An external engineering activity creates a project on request (e.g., to keep the map data updated after planned modifications to tracks and trackside infrastructure). Hence, SafeRailMap process activities are permanently embedded into an external engineering and commissioning process. The management process accompanies the core sub-processes and handles the respective project's execution. The management process has workflow management responsibilities: it initiates, controls, and tracks all associated tasks and handles interaction with external stakeholders (e.g., engineering project, infrastructure manager). It is assumed that there will be both manual and automated tasks to be managed. The project scope is created during the initial creation of a project based on the requirements of the requesting engineering project.

Furthermore, the project scope contains the validation scenarios (if an external infrastructure manager system is used/required and if an acquisition is necessary, see section Validation and Analysis). E.g., if an acquisition is needed, the acquisition scope is created based on the project scope. The acquisition is not triggered before the associated engineering project signals *ready for acquisition*. If external infrastructure manager system data is required, the management process requests it from the respective external stakeholder(s) (e.g., geodatabase, engineering) and receives the returned data.

All core sub-processes create reports containing work results and status information (e.g., successful, finished with issues, errors during execution); the respective management process' steps evaluate the returned reports and derive flow decisions, if applicable. If an unexpected issue/error or a runtime excess of a core sub-process occurs, the associated evaluate report step switches to troubleshooting mode.

When all tasks were completed successfully (the completely validated and the compiled map was successfully published) or a decision to abort the project was made, the close project combines the reports of all core sub-process into a consolidated project report and closes the project.