Conférence Européenne des Directeurs des Routes

Conference of European Directors of Roads

AMSFree

CEDR TRANSNATIONAL ROAD RESEARCH PROGRAMME

Exchange and exploitation of data from Asset Management Systems using vendor free format

Deliverable 4.1

Definition of an Asset Management reference process

February 2021

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1 Introduction

1.1 Work package 4: Data fusion and semantic transformations

Current asset management systems consist in many cases of several systems which are poorly connected. In addition, there are other data sources that are not owned by NRA's, but relevant to asset management. These data need to be used, processed and displayed together. Unfortunately, the semantics of this data is not consistent, and transformation may be needed. In a research project (Bernard, Marschal, & Hajdin, 2015) the inconsistency was tackled by establishing a reference database that imports the unchanged source data and then transforms them to be used in an asset management system.

In Work package 4, the IAMS processes of the NRAs are analysed and explained so that an overarching generic process can be defined. To merge the data, three steps were identified both for pavement and bridges, which lead to the storage and updating of the data. These steps, and how to elaborate them, are described in chapter 2.2.

To enable the semantic transformation, exemplary data requirements are created and explained in chapter 2.3. With these requirements, a data model for the creation of the prototype is developed in D 4.2 combined with the planned D 4.3 and its structure is explained.

2 Task 4.1 Definition of an AM reference process model

2.1 General approach

Based on the results of work packages 2 and 3, a reference process model for the national road authorities (NRA) is developed. The current procedures and maturity levels of asset management can be derived from work package 2. There was some delay in receiving information from NRA's so that this document was developed in several steps. Ultimately, all relevant system information from the NRA is included, so that a uniform understanding of the overall asset management process was derived. The following basic assumptions were made:

EN ISO 55000, whose elements represent the basic requirements and the framework for the process model, were followed. EN ISO 55000 describes three levels, a strategic, a tactical, and an operational level. Their tasks must be clearly defined, as it has been documented in previous reports. Nevertheless, there is a country-specific understanding of each level, which has been funnelled into a general model in the present context. However, a system definition must be made as to which tasks are performed in asset management and where is the boundary to traffic planning considerations.

- The general process model describes an AMS, and its sub-processes relevant in the context of this research project are identified. At the same time, this means that the developed data model should be able to accommodate data exchange between sub processes of the AMS. Depending on the tasks within each sub process, data requirements have to be defined as well as the level of detail and data content. A bottom-up approach is adopted, in that the requirements are defined at the object level. The network level is then described by aggregating the data available at the object level.

The approach used in the current project was based on Figure 1. A distinction is made between the definition of strategic asset management plan and operational asset management plan. The operational asset management plan is subdivided into the inspection, maintenance planning and the implementation of the maintenance measures. The tasks in the present context are thus clearly outlined; the focus of the processing therefore refers to the operational asset management as described there. In an overarching consideration, relevant information from Belgium, Austria, Sweden, Finland, the Netherlands and Germany could be evaluated. These results were used to confirm the previous results from WP 2. In detail, the AMS approaches and process models from the three selected countries, namely Denmark, Germany and the Netherlands were analysed in detail and from these results, the general process model was derived. Subsequently, the basic structure of the data flow was presented, whereby different data requirements are presented depending on the national data processing models. In some topics, there is a high degree of conformity, but in other tasks, different technical approaches were used, which makes it difficult to define a common and unique data model. However, this is not considered necessary from a technical point of view. For instance, the integration of bearing capacity measurements, which are an integral part of pavement evaluation in Denmark but are not used in Germany. In such cases, it is not necessary to show data models that are only used nationally, in the context of the project. This is taken into account below by showing common areas of application, also by at least showing examples for nationally required extensions.

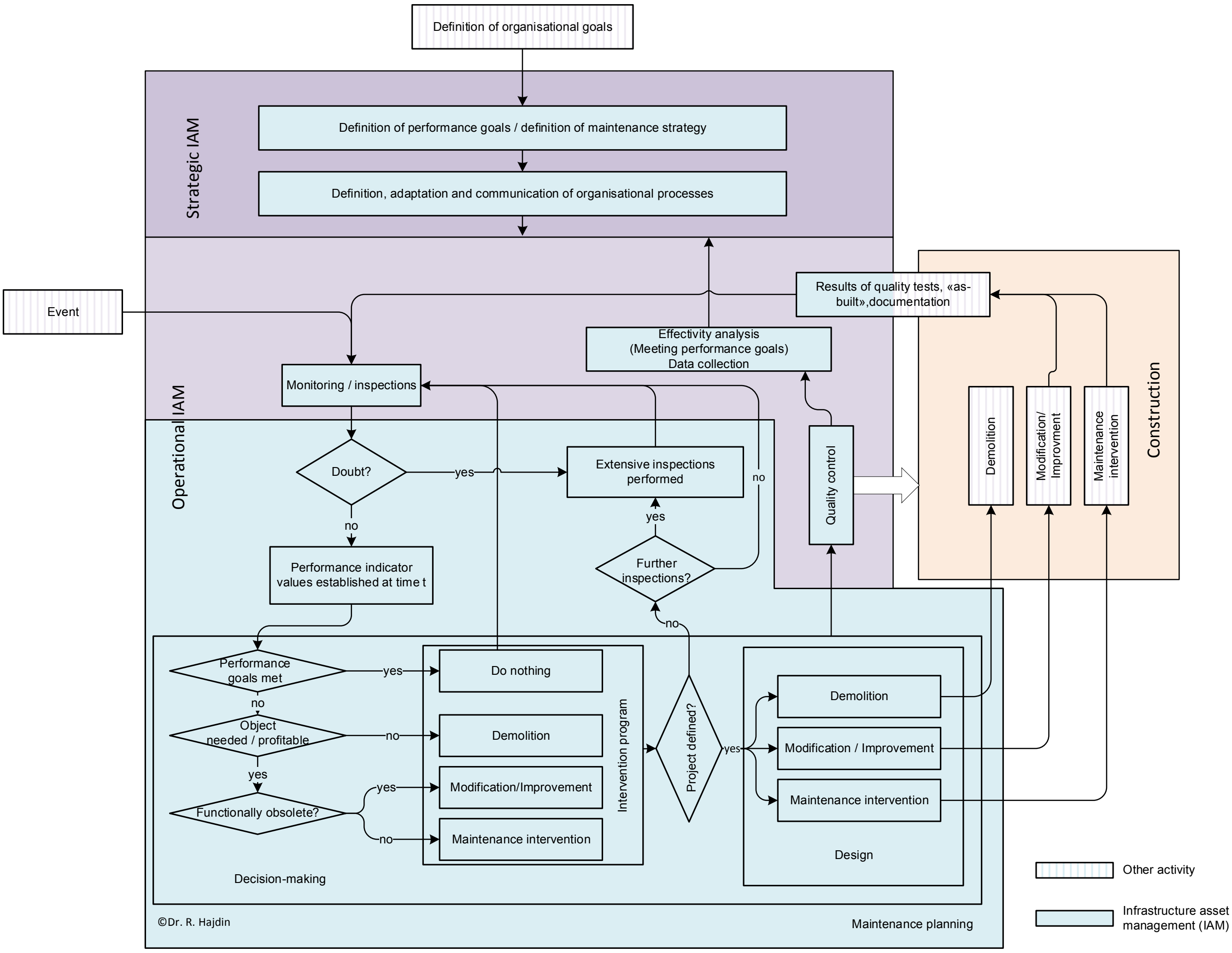

Figure 1: Generic AMS process [Diagramm: Prof. Hajdin]

What is described in the projects above for national cases or single assets like pavements, becomes much more difficult in an integral asset management since different assets types have to be brought together in one model. Based on this consideration, the processes of an asset management system must be described adequately regarding the workflow between different stakeholders. Therefore, a process model from the results of the previous work packages 2 and 3 is derived. The aim is to ensure that this process model can be applied as far as possible to the different NRAs and should be able to be adapted according to different use cases.

The main challenges of asset management systems are the handover and transformation of data that are incompatible with the system's demands. Therefore, to illustrate the suitability of the proposed AM process, three instances of data updates/feeds in the data base have been identified, as shown later. The first update/feed emerges from the inspections and monitoring of structures and condition survey and assessment (S&A) for pavements. The localization data from the database will be used to locate the assets and perform the S&A for pavements or inspection for structures. The results of the S&A are transferred to the database and enhance the asset information. For the second update/feed, the maintenance planning and as result the maintenance program is implemented. The S&A or inspection results were processed to determine the need for operational and maintenance measures. After financial optimization, the priorities among assets and corresponding measures are set. With that, the maintenance program based on different optimisation and prioritisation procedures can be created. With the data on the maintenance program, the database gets the second update/feed. The information delivered at this stage are; location, type of measure to be performed, cost of these measures and planned year for execution. This maintenance programme (aka work programme) is a basis for tendering of design and construction works related to planned maintenance measures. To this end the data are transferred to designer and contractors, who use them in design and construction process. In general, the designers and contractors use their own software tools, which may include databases and collaboration applications. Once the construction phase is finished contractors are bound to deliver the final "as-built data" to the owner or operator. This "as built data" are ideally integrated in the AM System after the acceptance of the construction work and lead to the third data update/feed to AM database.

2.2 Process model

2.2.1 Process model Denmark

At the Danish Road Directorate, the aim of the Asset Management is to create safe roads, preserve investments and to maintain the function of the road over time in the short-term as well as in the long-term. Both maintenance and operation follow the strategy on ensuring safety and function. In maintenance, also the economic efficiency is part of the strategy. The operation additionally follows the strategy to provide a politically desired level of service. (Vejdirektoratet, 2020)

Briefly, the aim is to provide an overview of all assets, including their condition and their need for operation or maintenance measures and thus be able to make a prediction of what it costs to undertake upgrades to the condition of the main roads. However, the AMS should be able to show in a valid, transparent and reliable way the consequences, if budgets are not sufficient (Vejdirektoratet, 2020)

i.e., the maintenance measures cannot be performed in a timely manner.

The process of the DRD for Asset Management (Figure 2) is built up in several parts, based on (Vejdirektoratet, 2020):

(I) The registration of assets with information as to location, type, year of construction and more. The data will originate from the BIM of new roads. The level of detail of the data in the registration of an asset varies depending on management needs.

(II) In the process of condition assessment, a range of different sensor data are used. GPS-based data is captured with different tools of measurement, e.g. data from cars on road condition, data from construction machinery, sensors on assets, drone mapping, and laser scanning. The assessment of the condition is systematically performed and documented. It provides information for each asset and therefore the entire portfolio of assets.

(III) The performance of simple life cycle models, degradation models, or replacement policies, which can be used to predict the condition at a given point in time. Based on the criteria for safety, function and financial optimum, the need for maintenance and operational measures is determined. Depending on the asset type, different models are used to determine the financially optimal point in time and to define operation and maintenance measures. In addition, scenarios can be created for individual assets to determine the economic impact if measures cannot be executed at their optimum point in time.

(IV) Optimisation of intervention times and type of operation and/or maintenance measure will be determined. This is done for individual asset types in terms of safety criteria, functional criteria and financial optimality. Processed asset information is used for this purpose.

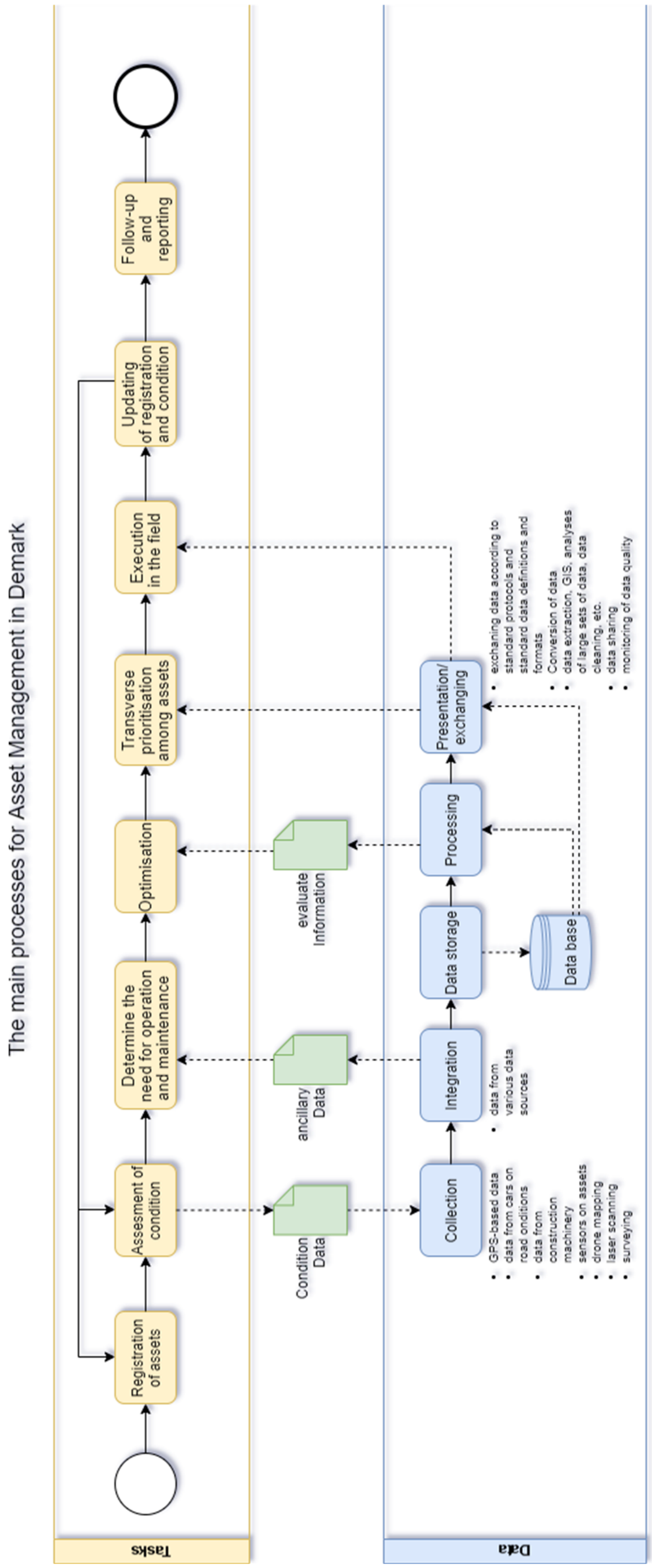

Figure 2: Main process for asset management in Denmark based on (Vejdirektoratet, 2020):

(V) Cross prioritization takes place between the assets. This is done based on the results of IV, the individual demand reports of the assets and the profitability considerations. The goal of cross prioritisation is to make the best possible use of the available financial resources throughout the network. For this purpose, the results of the previous steps must be used to create scenarios based on various financial prerequisites such as budgets and expected additional costs if the measures are postponed.

(VI) Execution in the Field: Following the tender process, contract and project management will be performed by an external provider. This includes the comprehensive preparation of tender documents, the evaluation of tenders and commissioning of contractors, suppliers and consultants to prepare and execute the operation and maintenance measures. Service level requirements initiate execution during ongoing operation. The Items (II) through (VI) are dependent on what is required to maintain the service level.

(VII) Updating of registration and condition, including coupling to BIM.

(VIII) Follow-up and reporting, annual reports, analyses, etc.

2.2.2 Process model Germany

One of the fundamental tasks of the German IAMS is to forecast maintenance needs, which are used for the strategic allocation of the available budget on the network level. From these steps on, maintenance programs can be derived in further processing steps. The different tasks for calculating the maintenance requirements for assets can be roughly divided into the following points: Geo-located inventory, periodic asset survey and assessment resp. inspections, Data preparation as input for an IAMS, and data analysis based on PMS calculation and prioritisation procedure for structures. These results are used for the Federal Transport Infrastructure Plan as well as yearly budgeting and area-specific maintenance programmes, as further detailed in the AMSFree report of WP2.

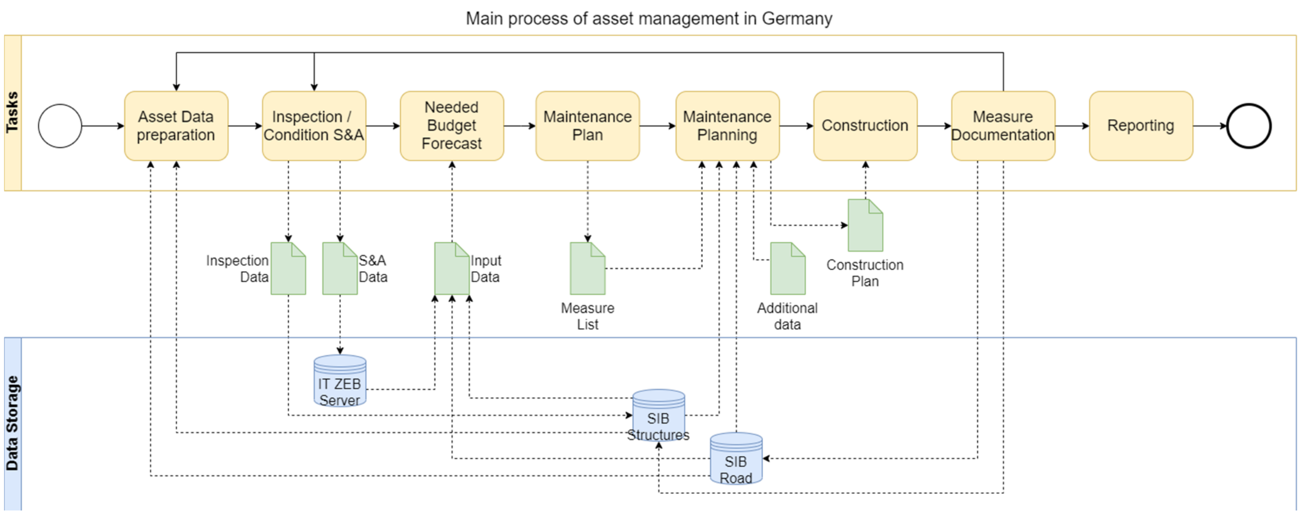

Figure 3: Main process for asset management in Germany

The process of asset management in Germany, from data preparation to documentation and reporting of measurements and is structured in several tasks as in Figure 3 and can described as follows:

(I) Asset Data preparation

Existing data is compiled from structural and road databases. The administrative data, such as localization data, material data or stakeholder information, is prepared for further use in the subsequent process of condition recording.

(II) Condition S&A / Inspections

During the survey and assessment of the pavement condition, data such as longitudinal evenness, transverse evenness, roughness, surface properties, bearing capacity and texture are recorded using various measurement methods and sensors. GPS-based measurement results are used to calculate indicators that describe the condition of the road and are stored on the IT-ZEB server as well as measurement data and documentation.

The inspection results comprise the evaluation of individual damage, which are then aggregated to ratings of groups of structural elements and whole structures.

(III) Budget Forecast

Using asset condition data, as well as inventory data and structural data, financial forecasts are developed that assess the residual value of the asset and determine the projected cost to operate and maintain the asset. This is based on the politically targeted level of service. For this purpose, the asset condition forecast is estimated using predictive models. This is necessary to determine at what point of time maintenance measures are to be executed.

(IV) Maintenance program

The maintenance program describes the network-based approach to asset maintenance. To create this plan, the required measures on assets and between assets are compared with each other, and an economically optimised plan for maintenance is determined. For this purpose, additional information on the existing budget, condition forecasts, and costs of measured are included. The calculated optimal maintenance planning is reviewed by experts and adapted to further needs.

With a confirmed maintenance program, the design process for object related measures can begin until contracts can be awarded and placed. For this purpose, construction plans for individual measures are developed from the maintenance program.

(V) Construction

The maintenance measures are carried out by contractors after the project planning process. These prepare an offer, complete construction drawings, and carry out the measure. In the process, information is collected on materials used, asset structure and geometry.

(VI) Documentation on performed measures

The collected data of the construction project will be checked by the contractor and, if complete, transferred to the road database and the structure database. The aim is to be able to present a digital image of the current situation and to store an as-built model into the databases.

(VII) Reporting

The process ends with reporting, which includes a financial statement.

2.2.3 Process model Netherlands

The process of asset management of the Netherlands could only be presented in general terms, as no detailed information on the process was available. Therefore, there is no information presented about the usage of a data base. The information is extracted from the functional description of the asset management and publicly accessible sources of Rijkswaterstaat (RWS). Nevertheless, the AM of the Netherlands ensures that the maintenance of the condition of the assets is within the financial optimum and at the same time, the politically required level of service is achieved.

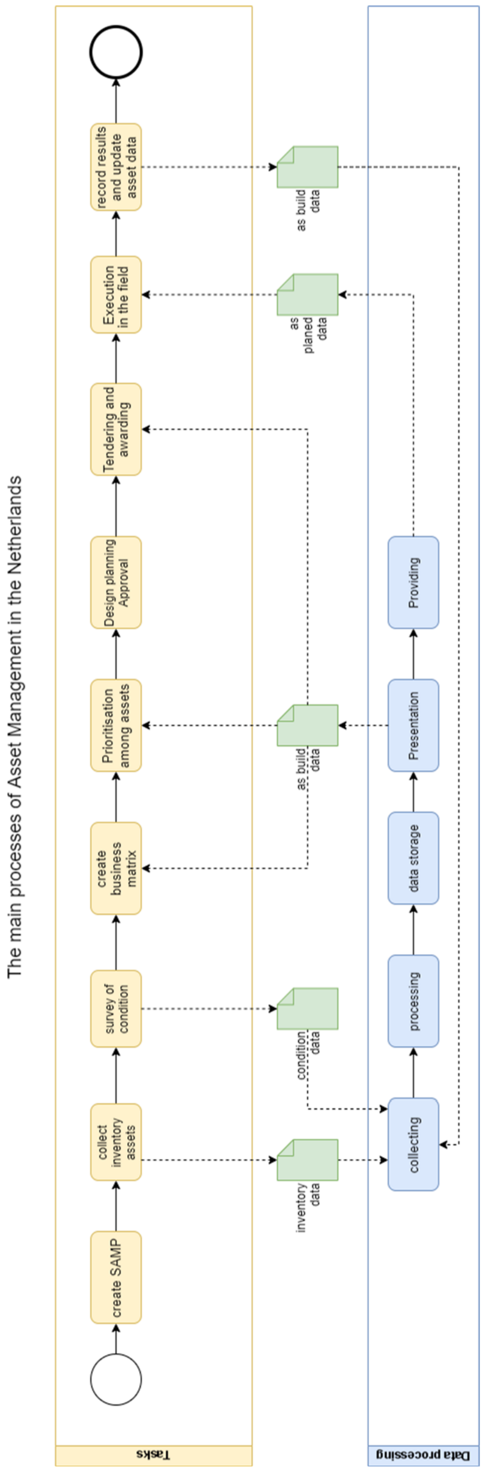

Figure 4: Main process for asset management in the Netherlands

(I) Create Strategic-Asset-Management-Plan

In order to outline the strategic approaches and processes, a Strategic Asset Management Plan (SAMP) as prescribed in ISO 55'000 was created. This includes, among other things, a stakeholder analysis, a discussion regarding opportunities and risks, the interpretation of opportunities and risks, and the achieved agreements within the organization. In summary, the SAMP specifies how the organizational objectives can be converted into asset management as well as the AM strategy of the organization.

(II) Collect inventory assets

To implement the asset management process, road data is compiled from existing databases. These enable the planning of the inspection and surveying campaigns.

(III) Survey of condition

Based on the visual inspection and sensor data, the road condition is assessed. The captured data is georeferenced using GPS and can thus be assigned to the roads in the database. The condition data is used to evaluate the need for maintenance measures of each asset.

(IV) Create a business matrix

The objective of the business matrix is to provide a final assessment of opportunities and risks in terms of defining and planning network-wide activities and measures. It is composed of the following components of the AMS: Development Agenda, Improvement Plan, Result of Internal and External Stakeholder Analysis, Assessment of Assets against Key Performance Indicators (KPIs). The Enterprise Value Matrix include the provincial government's requirements and is therefore the criterion for AM decisions.

(V) Prioritization among assets

The opportunities and risks shown by the business matrix are applied with regard to the budget to prioritise the measures. Thus, it is calculated which measures have to be implemented preferentially for the optimal maintenance of the road network.

(VI) Project planning approval

Construction plans are drawn up based on the planned measures, which are approved by the road authority.

(VII) Tendering and awarding

The measures are put out to tender and awarded to external companies.

(VIII) Execution in the field

The maintenance measures are carried out by contractors. Information about construction work is collected.

(IX) Record results and update asset data

The collected data of the implemented measures, are recorded, checked and if complete, written to the road database. Thus, an up-to-date as-built model is stored.

2.2.4 AMSFree generic process model

The basic generic model assumed for the project is the model of an AMS according to EN 55'000, as shown in Figure 1. The model presented there intentionally does not contain an assignment to an object-related or a network-related view. For this purpose and the common understanding, it is not necessary and can now be carried out in accordance with the specifications of EN ISO 55'000 and the national approaches as described above. In the next step, all required tasks within an AMS for the road infrastructure over its life time were clarified. This result goes beyond the aim of the present research project but is considered necessary for the understanding of the overall context of AMS. The tasks of the project were therefore identified, and an overall general process model for the tactical part of a road infrastructure AMS was derived. This general process model is structured in relevant sub-processes, as far as this is necessary for the modelling of the data flow. Therefore, it should already be pointed out that all process descriptions do not describe further subtasks within the processes. On the one hand, the focus is on the clear representation of the data transfer interfaces in the later IFC/BIM context. On the other hand, country-specific regulations exist for the processing of individual subtasks, which cannot be comprehensively represented in the present project. First, the necessary tasks for an overall AMS were identified and structured (Figure 5). There, the essential areas of asset management of the road infrastructure are presented and shown for the asset elements as Pavement Management System as well as structures as Structure Management.

This overall AMS model shows the framework of a strategic AM Plan focused on a road administration, consisting of legal and technical requirements, determination of the desired level of service as well as of the general objectives and targets. Further elements are the tactical and operational AM, described for Pavement Management, Bridge Management and Operation. These steps are divided into inspection respectively survey and assessment, maintenance planning, implementation of measures and performance review. This overview delivers a basic structure for the further development of the generic process model and subsequently the data flow model, whereby only the sub-processes needed within the project context are considered in the following steps. This overall description in Figure 5 delivers the basic understanding of AMS as well as the definition of the further described processes.

For the present project, the sub-steps in which relevant data transfer for AMS is required are of particular interest. These sub-steps are an inventory model, the data from the condition assessment and evaluation, the data of the maintenance planning as well as the data of the as-built model from the implementation of the measures. Based on these assumptions, the process model for the transportation infrastructure lifetime was developed. The basic structure is shown in Figure 6. The process description is focused on the important data update/feeds the process is based on an existing inventory or as-built model, which adequately represents the infrastructure inventory for a lifecycle assessment. In the overall process, three important updates of the database are identified, referred to below as Update I, II and III. These are firstly an update of the results from the inspection or condition survey and assessment, secondly the update of the prioritized maintenance measures and thirdly the update of the "as-built" model after construction work that has been carried out. The decision for these three updates ensures, that the final work results for every sub-process should be saved, as far as they deliver the needed information for the following step in the life cycle. It is not important to define data updates/feeds results within these sub-processes, which shows only importance within the respective sub-process, but not for the life cycle itself. Tasks within a sub process are usually handled with authoring software. For example, it is assumed that during the sub process for planning measures, the update of the planning up to execution in accordance with the LOD concept is not saved back into the IFC/BIM database, but the "as-built" model should be saved.

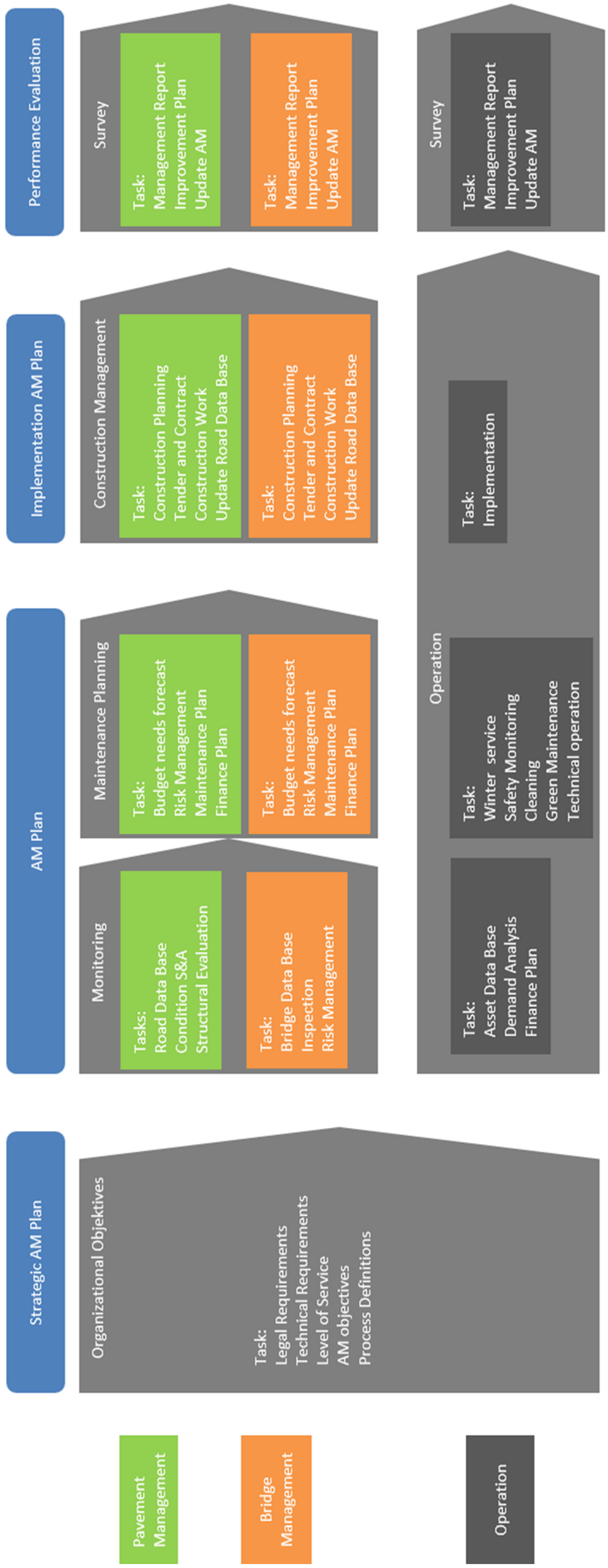

Figure 5: Main AMS tasks

As shown in Figure 6, a rough distinction can be made between the four sub-processes. These are the condition survey and assessment for pavements and the inspection of structures, summarised as inspection and survey. The next sub-process comprises all evaluations that can be assigned to the field of maintenance planning. This is the determination of the maintenance requirements, a financial needs forecast, the prioritisation of the maintenance measures, and the scheduling of maintenance programs, which delivers the list of future maintenance measures as a result. The object-related planning process, design and implementation of the maintenance measures follow this. The planning process depends on the complexity and scope of the measure, as well as the preparation of the tender documents and the procurement of the contract. Usually, separate BIM processes are implemented and applied for this process part. The final sub-process is the implementation of the measures in the construction site. The idea behind this process is that the data is stored and maintained in a uniform database, and only the data transfer points relevant for AMS to be identified. In actual data systems, there are separate databases for structures and pavements. However, this does not need to be discussed at this point, since the three mentioned updates are defined at important points in the main process, namely at the end of the first sub-process, condition assessment and evaluation, at the end of the second sub-process, maintenance planning, and at the end of the fourth sub-process, construction.

Therefore, the main sub-processes are

(1) the inspection/condition survey and assessment sub-process,

(2) the maintenance planning sub-process consisting of the financial requirements forecast and the establishment of the maintenance program,

(3) the execution planning and procurement sub-process, and

(4) the construction execution sub-process.

The asset management process must be based on an inventory model, i.e., an as-built model from the previous construction/maintenance measures. This results in the essential sub-processes that are to be considered further in the present project and the data to be transferred is to be defined as far as possible in a generally valid manner. It has already been noted that country-specific characteristics do not permit a comprehensive generally valid definition, but that this is only possible in partial areas.

Given the bottom-up approach adopted means modelling the processes and the associated data at an object level. This level has the highest data requirements regarding the level of detail. According to the previous logic, processes (1), (2) and (4) should be considered, since these are relevant for data exchange. In the next step, all relevant sub-processes are briefly outlined in order to completely map the data flow presented in the superordinate process model. According to these results, it will be possible to identify all required data types and properties, which will be needed for working in the following sub-processes. So, the AMS processes can be seen in detail, as well as an AMS reference database, where possible in the project. Nevertheless, the AM processes are described in detail with the following steps, as well as first AM reference databases requirements.

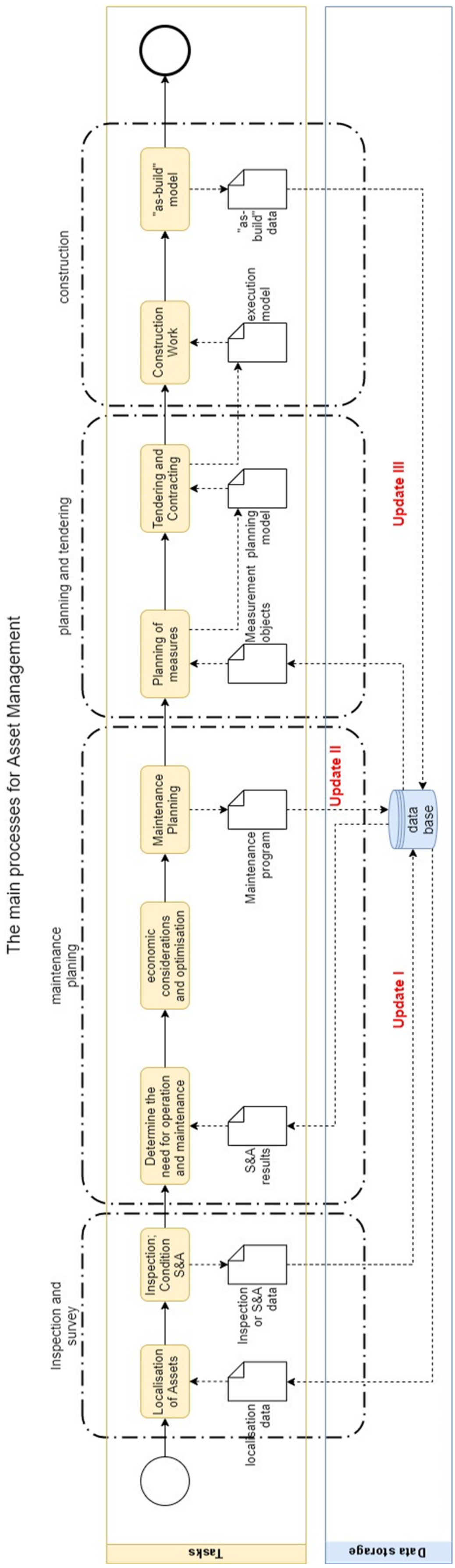

Figure 6: Main process for asset management

As an example, the data sets required for the inventory model is shown for a pavement section in Figure 7. A data set is a collection of related sets of information belonging to on topic and part of asset. Figure 1 the layers including material properties and data about traffic volume (planning data). The condition data can be assumed in very good condition, as it should be for a new road.

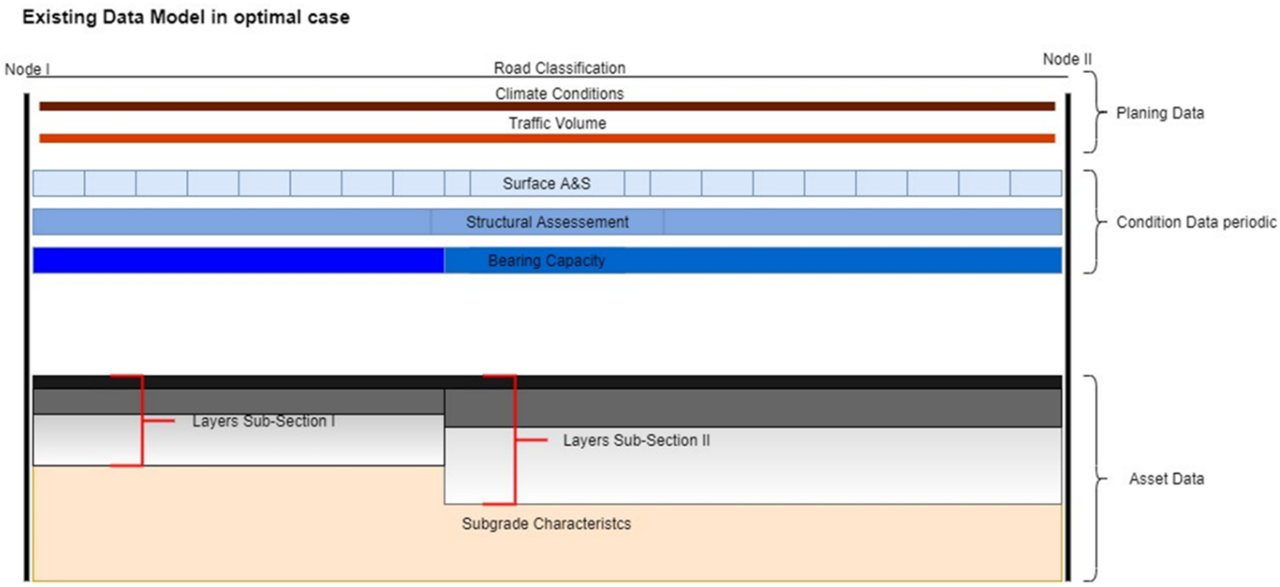

Figure 7: Data sets for the inventory model, new constructed pavement section

2.2.4.1 Sub process “Inspection and Survey”

The sub-process "Inspection and Survey" (S&A) is formulated regardless of whether structures or pavements are considered. In order to complete the task of inspecting structures or performing S&A of pavements, there is a lane for a contractor, as some national authorities will place an order to external service providers will do this. The road administration itself acts as the tendering body but enforces out extensive quality control within the process. In principle, quality control plays a decisive role in the accuracy and reliability of the condition data and thus the condition assessment. The sub-process is shown in Figure 8.

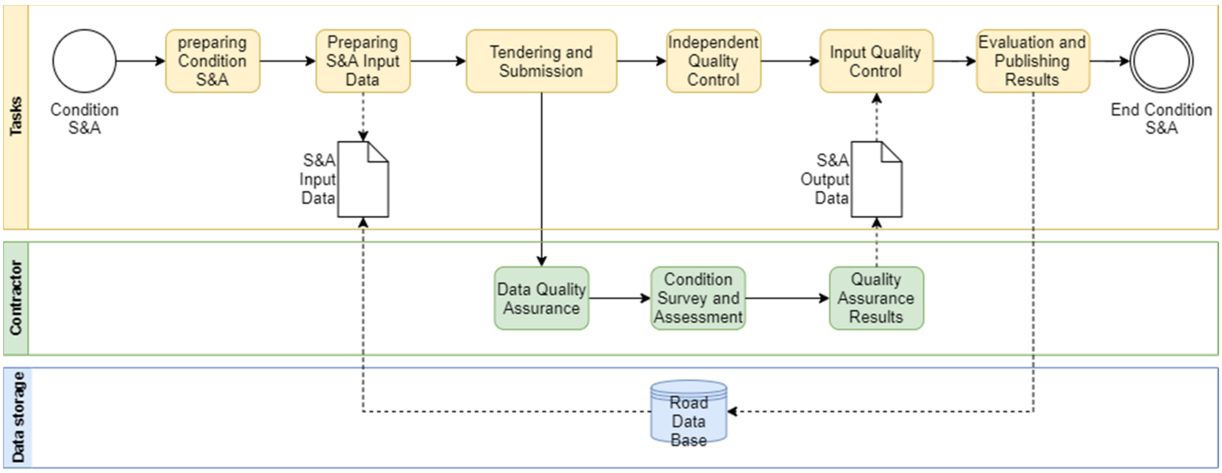

Figure 8: Sub-Process “Inspection and Survey”

In the preparation of the inspection or S&A, data for the localisation of the asset, the geometry and inventory are needed. Therefore, only a partial data set from the as-built model, which is necessary to perform the inspection task, is required. The data set will be extracted from the database, checked by the road administration and transferred to the S&A team. The localisation data thus defines the respective work order. The data processing within the S&A (pavement only) will be an internal task; the process ends with the transfer of the so-called raw data and the result files, if applicable. This step is currently not common for structures as inspection results can be directly used in maintenance planning. However, with increased instrumentation of structures this situation could change in the future. The results of S&A or inspection will be transferred back into the database, which leads to "Update I" by showing the current asset condition data.

With regard to the transfer of raw data, a distinction must be made between the case of inspection of bridges and the condition survey and assessment of road surfaces and structural properties. Raw data represents the physical measurement data, as well as image data gives detailed information on the asset condition. An example of image data is shown in Figure 9. It shows a so-called high-resolution orthophoto from an asphalt road surface. The orthophoto of a pavement must then be evaluated and then the identified damage type coded according to a defined scheme. The further evaluations are then based on the coded data and not on the photo itself. Such photos play a more important role for the evaluation of structures.

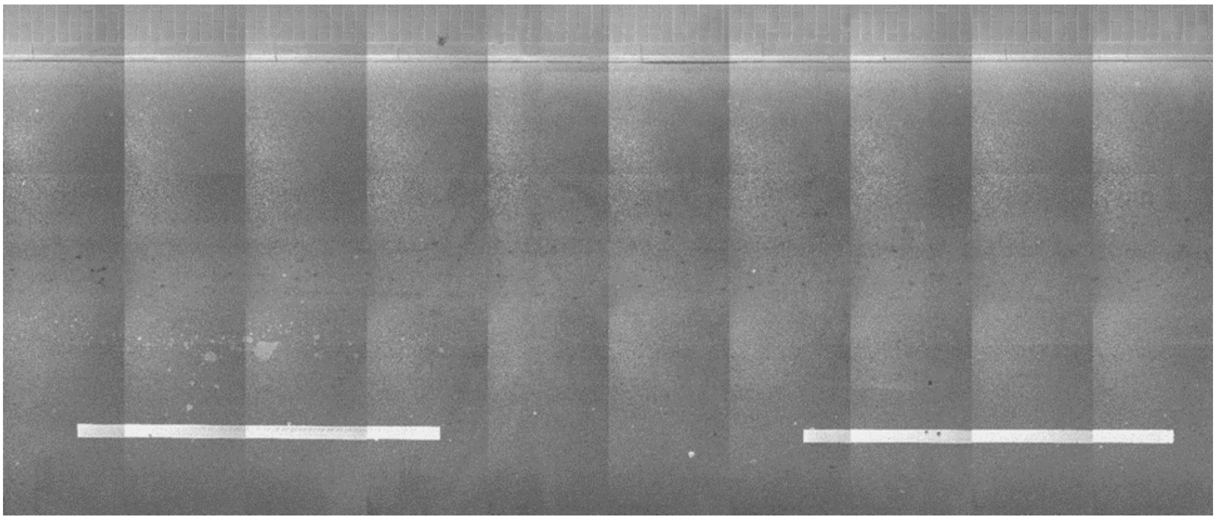

Figure 9: Example Orthophoto Asphalt Pavement

The data sets for the update I are shown as an example for a pavement section in Figure 10. They can be differentiated in the group of periodic survey and assessment data, namely surface properties, which are quite common for all regarded countries and structural and/or bearing capacity data, which will be used different in the countries. The second group comprise additional needed condition data such as non-destructive GPR measurements or destructive material samples for example cores. These are needed in case to supplement incomplete data sets. So, update I is related to the condition data set.

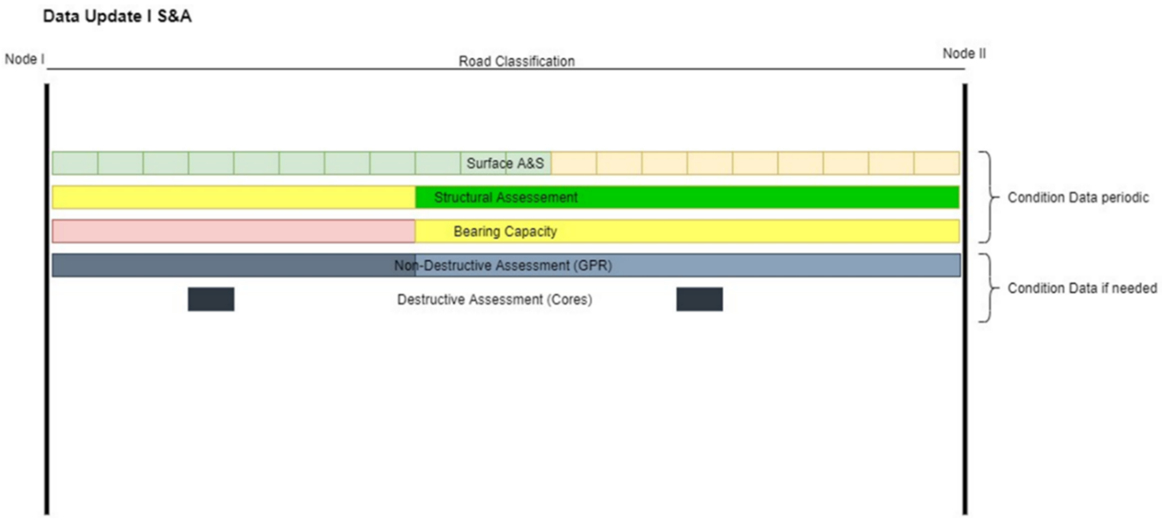

Figure 10: Data sets for update I, example for a pavement section

The question of raw data storage is not shown in Figure 8, but it is an important question. This approach has the disadvantage that later needed changed evaluations with a different evaluation background are only possible to a limited extent with the information available in the database. The advantage of this approach is that the data is already available ready for use and therefore comparatively large data volumes do not have to be stored, as it would be the case with the raw data. Raw data can be regarded as facts; evaluated data can be regarded as engineering interpretation.

EU countries differ in terms of data storage. In Germany, the raw data for pavements will be stored on the so-called IT-ZEB server, making it possible to have access to the raw data, various processing steps and all image files at any time. Therefore, a new assessment can be performed very easily, and the assessment results can be transferred to the database, which means a new update of the assessed condition data. In Denmark, the IT-system Danbro+ is used to manage structures, road data is registered in “vejman.dk” and exported into “Belægningsoptimering”, in NL only the result files are transferred to the road construction administration. Nevertheless, there are significant differences in the data content among the countries under consideration, which will be discussed below.

2.2.4.2 Sub process “Maintenance planning”

From all three sub-processes, the maintenance planning sub-process has the highest requirements in terms of data demand. This is mainly because the maintenance planning is an algorithm-based calculation process, i.e. deterioration models for condition forecast or the decision-making process for estimation of financial needs or for maintenance programs. For example, depending on the model used, the deterioration models require detailed information, especially on the material properties of the various asset elements. Basically, all information, which has an influence on the technical lifetime prognosis of the regarded asset elements will be needed.

The information needed can divided roughly into three parts, shown for an example pavement section in Figure 11. The first group “Asset data” contains information on materials and material properties, which are needed to apply the deterioration models. This information will be delivered from the as-built model and mainly from the later regarded sub-process 3 “Construction”. The second group delivers information about the asset condition and is mandatory for the maintenance planning process. These data results from the update I as described below. The third group, described as planning data contains information about external factors, which also has an influence on the lifetime behaviour. This group includes information on factors such as the actual traffic load or climatic influences. In this context, this sub-process is decisive for the formulation of the data models in the present project.

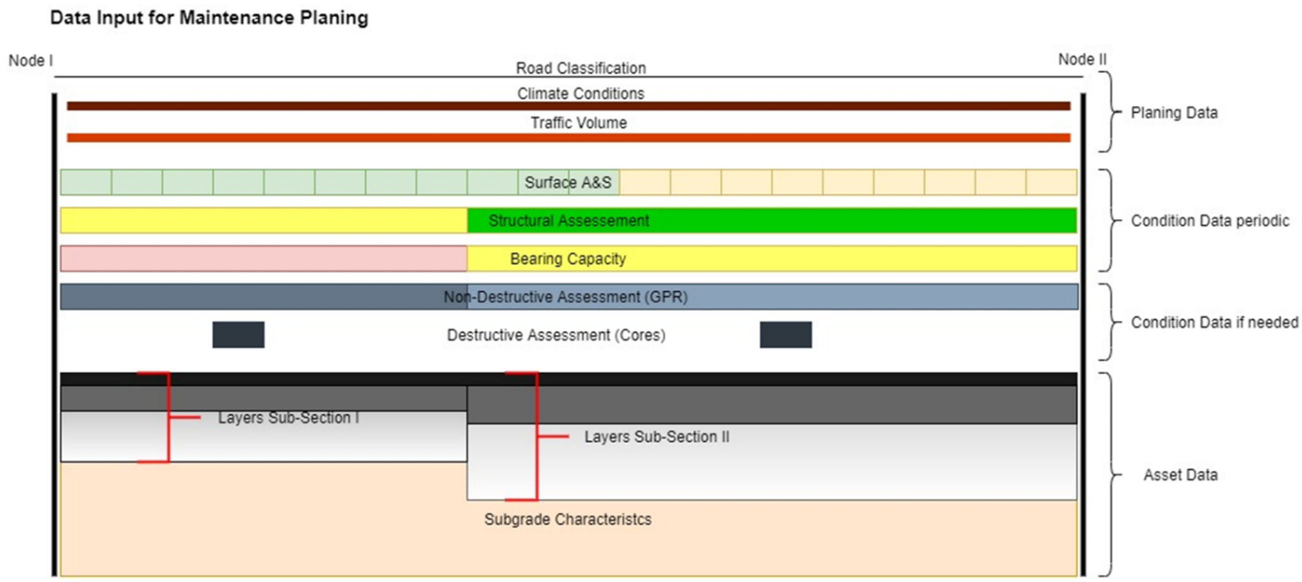

Figure 11: Data sets as input in pavement maintenance planning process

With respect to bridges, the input data for maintenance planning is obtained in a similar manner, as shown in Figure 12. Whereas inventory data on asset is stored in BIM, the structure's condition is usually periodically assessed by the means of visual inspection. An in-depth investigation is performed only if triggered by the visual inspection. The result of the inspection is an inspection finding, which is a broad term, defining any irregularity relevant for reporting. An example of inspection finding is damage. The inspection finding is quantified by assigning the condition rating. This can be done either on element level (e.g. Dutch and Danish NRA do it this way), or by rating each damage directly (e.g. German NRA uses this approach). Condition rating is then used for updating BIM (Update I).

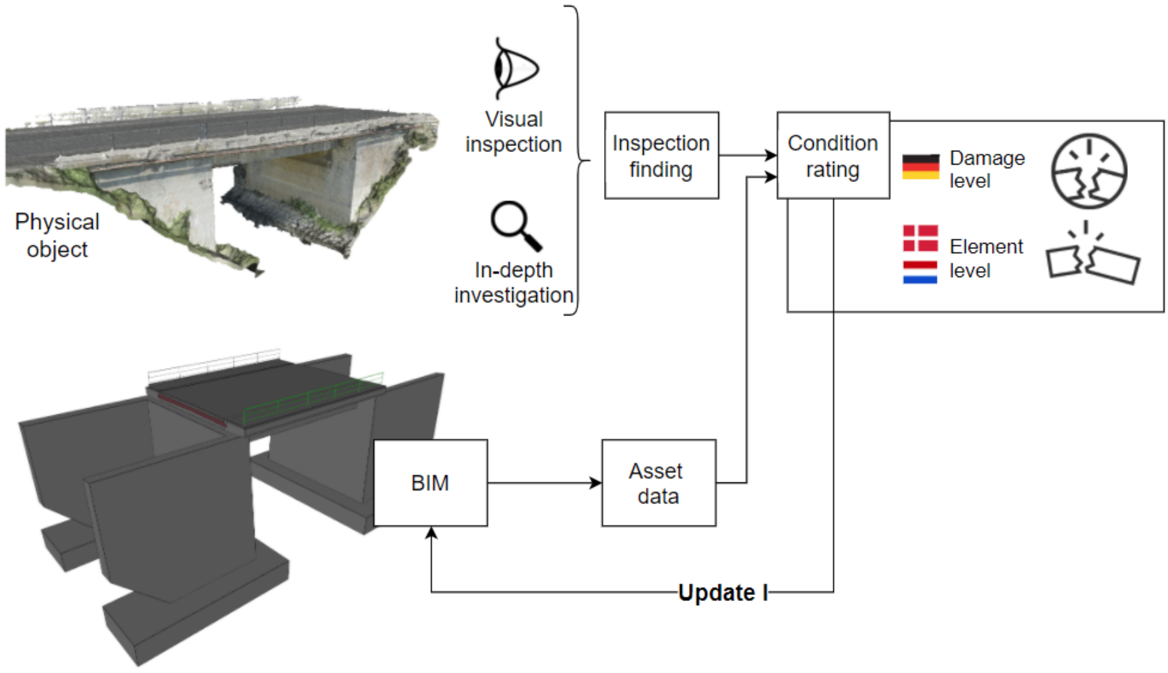

Figure 12. Data groups as input in structure maintenance planning process.

The requirements formulated here also provide the specification of what must be transferred with the as-built model out of the third sub-process construction (Figure 13).

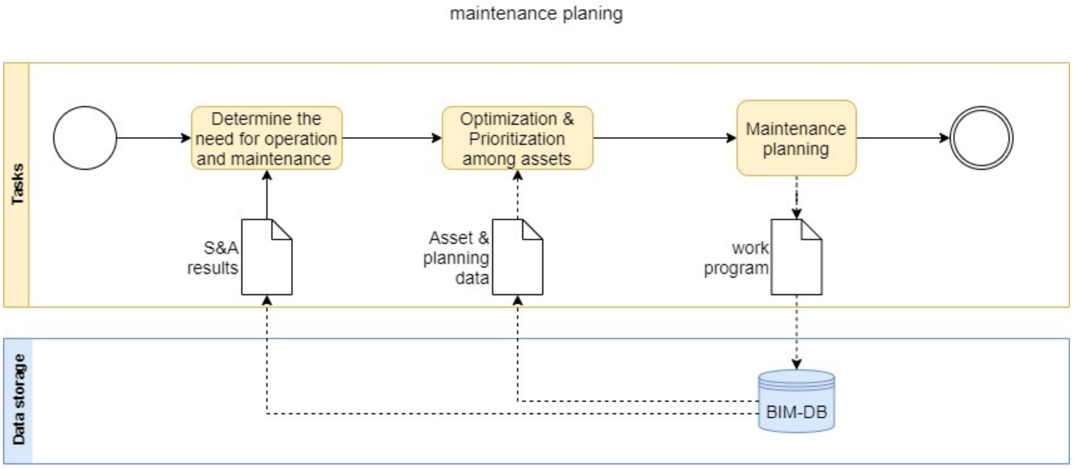

Figure 13: Sub-Process “Maintenance Planning”

Generally, as the first part of maintenance planning, a financial need forecast over several years to maintain or improve the asset condition will be estimated, from which the annual budgets are determined and given back to the strategic decisions. This step will not be discussed here, as there are some significant country-specific differences. Nevertheless, it must be ensured that all relevant data is available for this step, as mentioned before. This will be discussed later and considered as far as possible in the data definitions. The following definition of the maintenance planning starts with the definition of the maintenance sections, their prioritisation and the allocation and cost estimation of measures. Different approaches are used for this task among the countries involved, but the result in each case is a prioritisation of maintenance measures linked with a cost estimation. Based on the available information on the assets, it may be necessary to carry out additional tests or surveys. This data needs to be stored in the database as well and can lead to a partial update of information of the database for defined objects. For example, if single cores will be extracted, this information should be saved in the database. However, this could also mean non-destructive tests like GPR data or even destructive material testing. The type and scope of such tests are regulated on a country-specific basis and not discussed in this context. Nevertheless, it should be regarded to keep every model scalable for this purpose, as shown later. This is because such knowledge may be of importance for prioritisation and fixing the measure type in detail, but the network-wide recording of such parameters in advance is mostly too time-consuming or even too cost-intensive. It should also be regarded, that the pavement evaluation differs from the evaluation of structures, where any further required investigations are usually carried out directly after inspections if the latter are not conclusive. The decisive factor, however, is that both, the results of the extended additional evaluations/investigations and the results of the prioritised maintenance program, will be transferred in the as-built model. This will be led then to update II in the main process. This update II is very simple and should only deliver information about assets, which are listed in the maintenance program (Figure 14). This is the needed project information, which is needed to start the planning, tendering and construction process. It should contain the geometrical part of the asset, type, year and estimated cost of the measure.

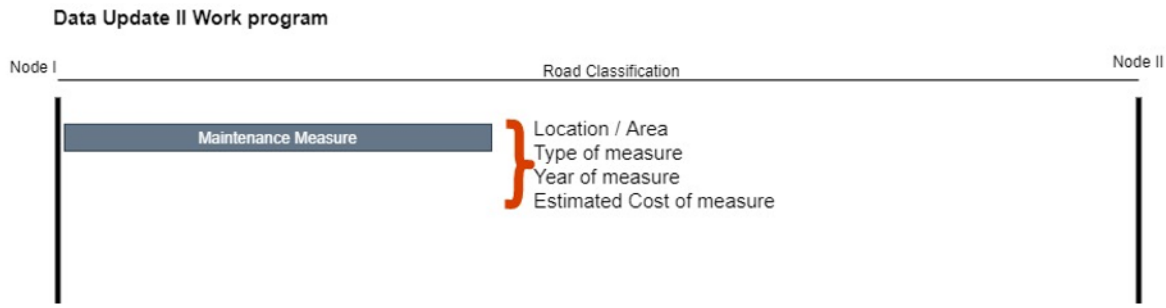

Figure 14: Maintenance object information in update II; example for a pavement section

The Update II for structures differs from the one for roads. Contrary to addressing the maintenance information to specific road sections, in the management of structures, this information refers to the entire asset. This is shown in Figure 15

Figure 15. Maintenance information for bridges.

2.2.4.3 Sub process construction work

While the processes 1 and 2 show a more network-oriented view, even though some considerations are object-based, the process 3 “Constructions” is purely object-related and addresses a single maintenance object in each case. A defined maintenance measure is now selected for construction from the list of the maintenance program in Update II and taken into account in the subsequent planning process. The description of the planning process up to the start of construction is omitted because this part of the process has no impact on asset management. It is a project-related part in which the as-built model is taken from the database as a planning model, and then will be developed into an execution model in various planning stages. For this task, the LOD concept described in Deliverable 2.1 can be used. For the aim of asset management, the as-built model implemented by the construction measure is decisive, which is derived from the LOD 500 model.

In Figure 16, the sub-process construction work is described. This process ends with the handover of the as-built model after finishing construction work. A takeover of different intermediate steps from the different planning stages of the asset management database is not necessary, as used project-related in the author software or in the coordination software. The level of detail in the planning process also occurs in the conventional planning process, in which a first draft will be scaled up to the execution planning with increasing level of detail in each step. The data to be saved into the as-built model results from the requirements of the technical regulations as well as the requirements for data types and contents for the different applications within the asset management in the life cycle. Therefore, this is a very decisive part of the AMS.

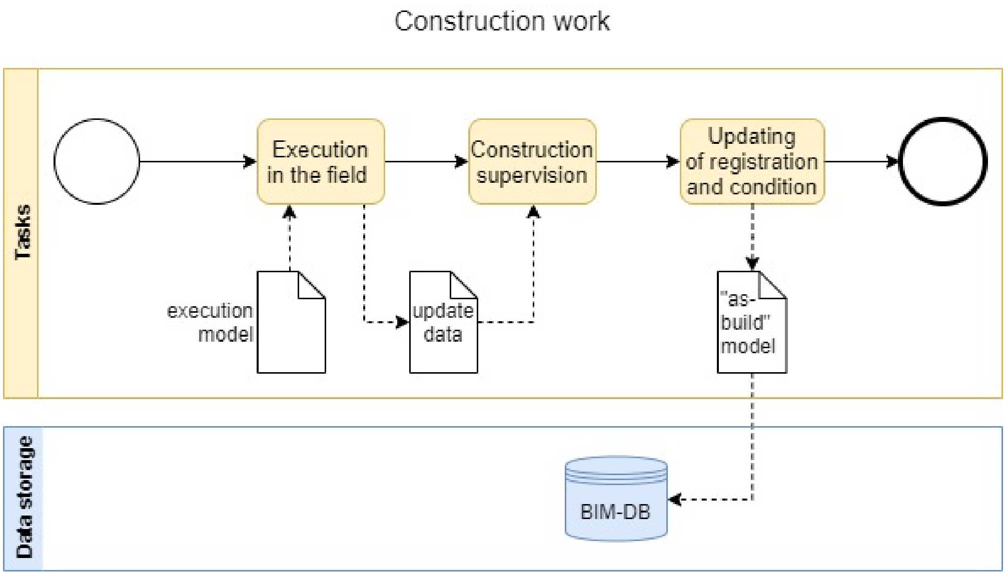

Figure 16: Sub-Process “Construction”

Handover of the as-built model delivers the update III as shown in Figure 17. The as built model contains these objects, which are renewed within the construction process. In this example a renewal of the existing pavement in a sub-section is shown. The update III is related to the asset data set.

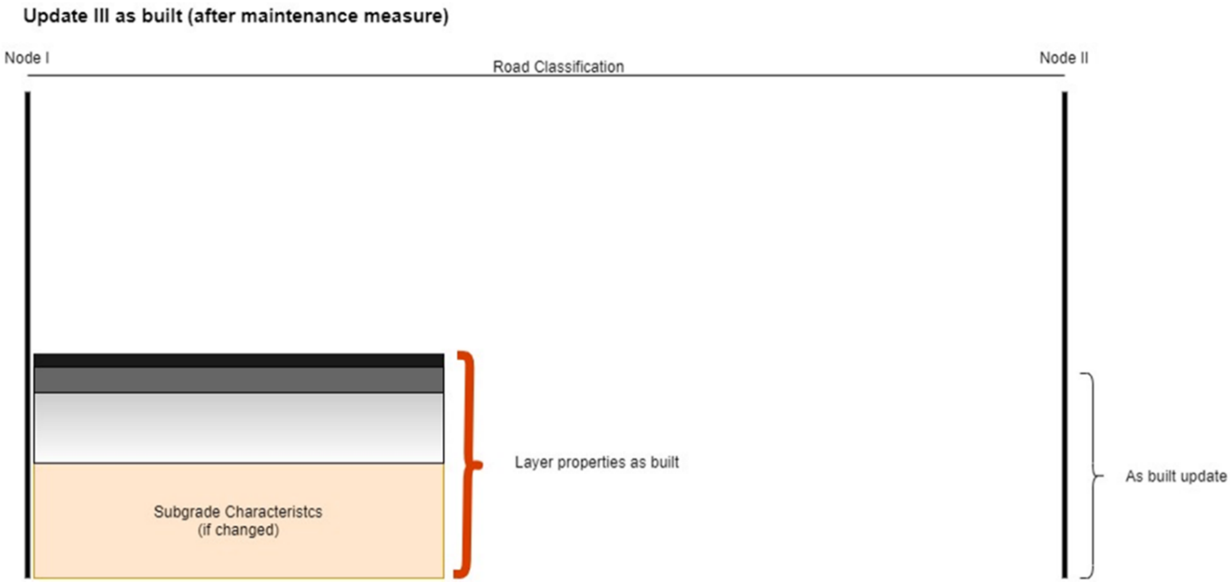

Figure 17: Data sets for update III; example for a pavement “as built model”.

Certain types of construction work within the maintenance of structures result in major changes of the asset’s geometry. The examples of these works are replacements or addition of elements (e.g. replacement of a prefabricated girder and widening of the bridge). These changes cannot be implemented using the proposed approach. More precisely, the information containers cannot store information on geometry changes. Nevertheless, there are other ways for addressing this issue. The approach which is straightforward and does not compromise the proposed use of information containers, is utilization of so called “time stamps” (Figure 18). This means that each time such a geometric change happens in reality, the asset would be associated with the new BIM model, representing the new geometry. Every model would be “time stamped”, so that the current state of the asset would be represented by the model with the latest time stamp. The initial model would be stamped with the commission date, or the date the first as-build BIM model is created and assigned to the asset.

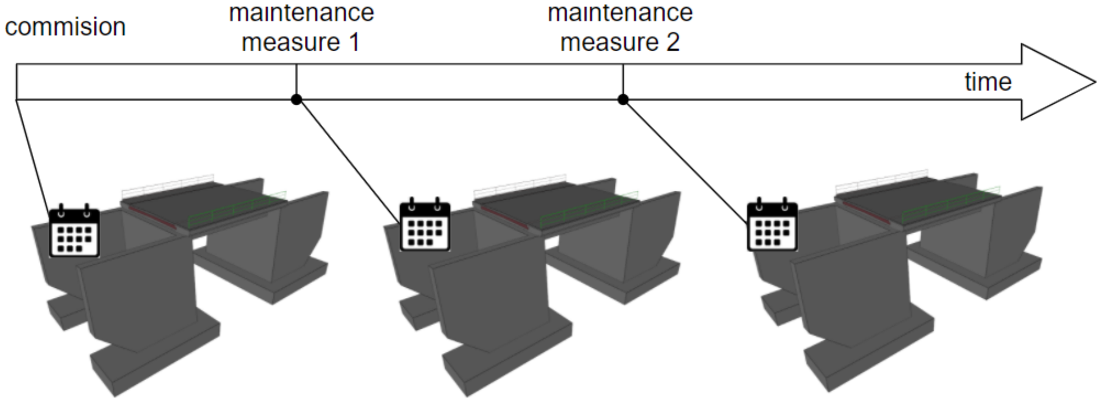

Figure 18. Possible implementation of Update III for structures: “time stamp” approach.

2.3 Required Data Overview

2.3.1 Data flow requirements

As written in the previous chapters, the data requirements for an AMS are primarily determined from sub-process 2 "Maintenance Planning". The algorithms and calculations to be performed within the different steps of Maintenance Planning represent the core requirement of the AMS, so all the data needed must be available. The data requirement should be derived from this sub-process, which will be supplied with condition data from sub-process 1 "Inspection and Survey" with update I as well as the as-built data supplied from the sub-process construction with the update III. Depending on the national approaches for maintenance planning, further data like traffic volume is needed. The described data flow, characteristic for pavement maintenance, can be seen in Figure 19. Update I provide the condition data, update III provides the as-built data, which is then required as part of the maintenance planning process. The maintenance program then provides the corresponding action lists for the AM measures.

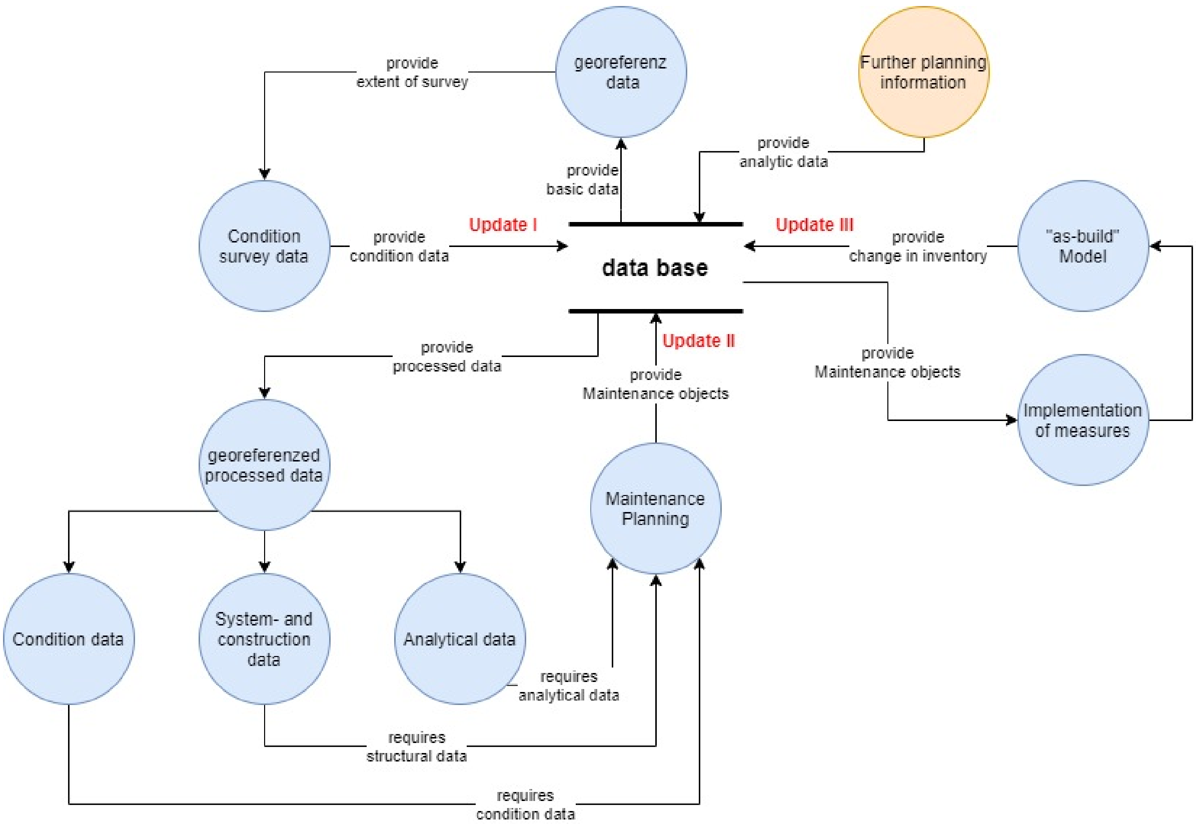

Figure 19: Data Flow Requirements for a generic Pavement Management System.

Condition assessment and maintenance of structures imply a slightly different data flow from the pavement condition assessment and maintenance. Unlike roads, bridges are not segmented based on the condition data. Bridge is represented in AMS as a composition of elements by default. Nevertheless, the update II includes the maintenance measure on these elements.

2.3.2 Required data for pavements

In order for a better understanding to describe the data requirements in an AMS, a broader study was carried out. For further European countries the procedures of condition survey and assessment as well as the further use of these results in an AMS were compared, focused on the scope of the project (Schlichter, 2020). With these results, it can be seen that the survey of the surface properties of road pavements is essentially carried out using the same groups of condition characteristics in most of the European countries. So, all countries survey and evaluate longitudinal and transverse unevenness, skid resistance as well as surface damages. Differences exist in the evaluation parameters and, namely, the surveyed parameters, or the type of surface damages. Significant differences can be found for the structural evaluation of road pavements. For example, methods for determining the bearing capacity as well as methods for determining the remaining service life of road pavements are applied and used differently in Europe. In addition, in different countries, there is an ongoing process to change or extend the assessment of pavement condition and pavement quality. As a general model, the process shown in Figure 20 can be outlined.

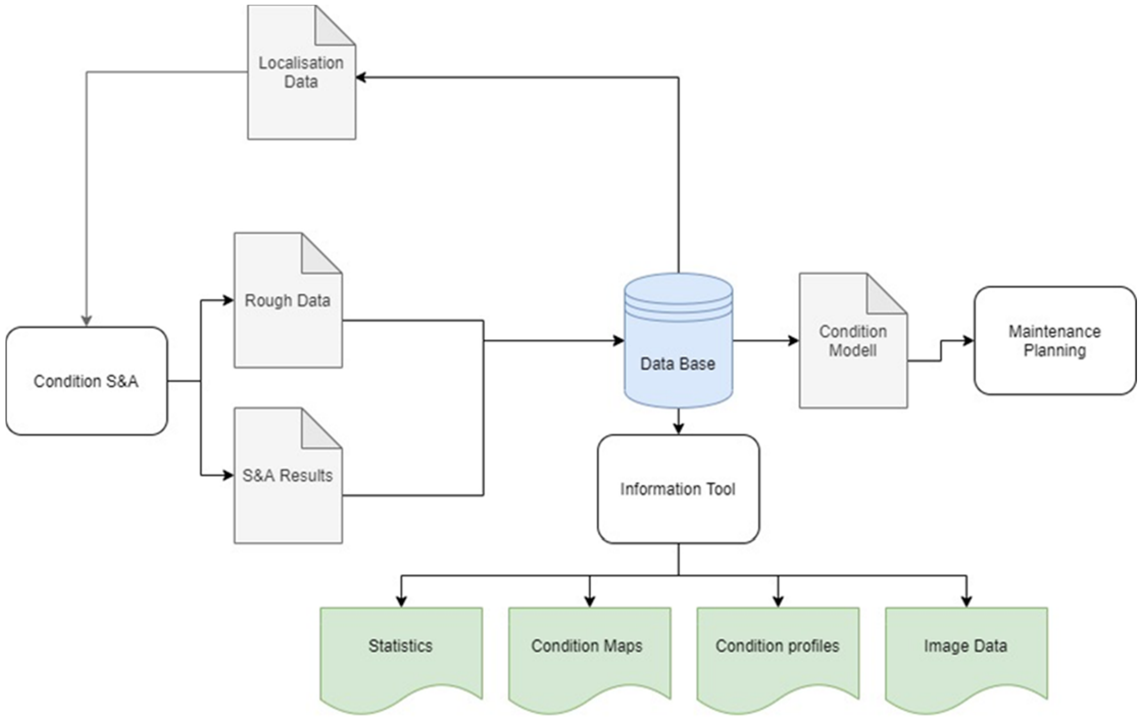

Figure 20: Common Model for Pavement S&A

Taking these results and also the considerations on the process analysis into account, a general model for describing the data need for maintenance planning of pavements was derived (see Figure 21). This will be regarded as a central request for the data model needed in sub-process 2 “Maintenance Planning”. This model comprises results from the condition assessment, from the structural evaluation, the evaluation of the load-bearing behaviour, further non-destructive examination methods such as the GPR and supplementary destructive examination methods, which are needed in special cases. It comprises data from both the as-built model and the condition model. The model will be scalable on a European level and can be adapted to national requirements accordingly.

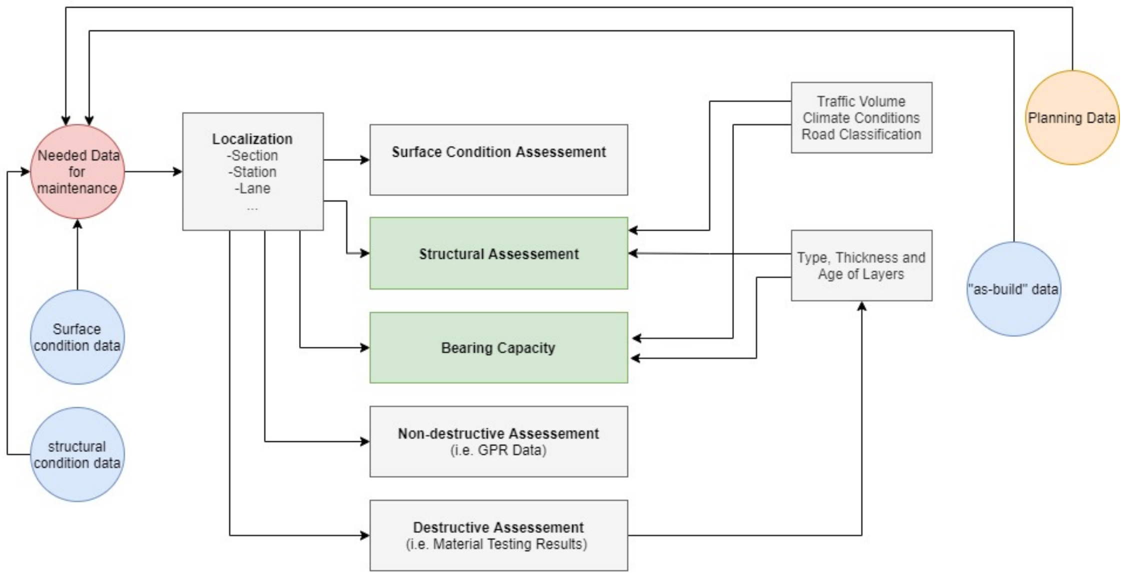

Figure 21: Model for Pavement Data Characterisation as input for maintenance planning

To a certain extent, European standards can help with the basic description of data requirements and properties. But these have to be in every case adapted at the national level according to the relevant technical regulations. The following standards can be found at the European level, which is used as a basis for the subsequent structuring of the database. These are in detail, without claim to completeness and as far as they are considered essential for the present context:

EN 13036-5: Road and airfield surface characteristics - Test methods -

Part 5: Determination of longitudinal unevenness indices

Part 6: Measurement of transverse and longitudinal profiles in the evenness and megatexture wavelength ranges

Part 8: Determination of transverse unevenness indices

CEN/TS 15901: Road and airfield surface characteristics;

Part 2: Procedure for determining the skid resistance of a pavement surface using a device with longitudinal controlled slip (LFCR**NL**): ROAR (Road Analyser and Recorder of Norsemeter)

Part 5: Procedure for determining the skid resistance of a pavement surface using a device with longitudinal controlled slip (LFCR**DK**): ROAR (Road Analyser and Recorder of Norsemeter)

Part 8: Procedure for determining the skid resistance of a pavement surface by measurement of the sideway-force coefficient (SFC**D**)

This includes the surface properties unevenness and skid resistance. No European specifications exist for the recording of surface damage, load-bearing capacity, structural evaluation and other destructive recording methods. Here, corresponding national regulations will be used.

Material related data should be available from the as-built model and include layer-related material data and material characteristics. Several European standards relating to construction methods are also available for this purpose. Examples are:

EN ISO 14688 ff	Geotechnical investigation and testing
EN 12697 ff	Bituminous mixtures - Test methods for hot mix asphalt
EN 13043	Aggregates for bituminous mixtures and surface treatments for roads, airfields and other trafficked areas
EN 13108 ff	Bituminous mixtures - Material specifications
EN 14023	Bitumen and bituminous binders
EN 13877	Concrete pavements

The basic material data properties are related to a European specification, which is then translated into national regulations. In principle, the general framework is well defined, but in detail, this leads again to different properties that have to be adapted in the model. This can be seen very clearly in the so-called performance properties of asphalt according to EN 12697, in which different test methods are specified to determine uniform properties. These naturally lead to a different catalogue of properties, since different parameters or even different designations are specified depending on the measurement method.

In order to create a common model based on these general preliminary considerations, the systems for Denmark, Germany and the Netherlands were first examined, and the data requirements were compiled in the form of the required data sets. For DK and GER, the specifications for the data input requirements for pavement are well documented. For DK the Appendix 02.d Location Reference Models and Appendix 02.e Data Model, vejman.dk /VIMS data and Paved Areas based on the Appendix 02 Customer's IT Environment and Situation Description from the actual DK tender documents were used. The analysis for the German Pavement AMS is based on the requirements for the data preparation tool PMS/IO (BASt, 2018), the project BIM4ROAD (König, et al., 2020) and a further research project (Stöckner, et al., 2020). Unfortunately, there is not much information from the NL System, so the results are based on publicly available sources.

As a result of these considerations, a rough overview is given in Figure 22 to Figure 24 for the pavement AMS. It can be clearly seen that different pavement condition models will be used. The generic model presented in Figure 21 will be able to cover both systems, so this has to work out with the national data sets. Based on these three results for DK, GER and NL, an attempt was made to present the data requirements in a general form. These national models contain a series of data sets, as currently specified in the systems, starting with network description, administrative data, condition data, structure data, cross-section data, and traffic data. For the description of the general data model, the geometric notation is omitted in the following, and only the data sets whose parameters must be assigned to an object and are important for the lifetime considerations are discussed. It will be outlined one more time that the difficulty here is that even if the data sets are nominally the same, different parameters must be defined later.

However, firstly different data sets and parameters can be predefined in the general model, which can be found more or less in all countries. The conversion of the parameter sets falls then into national responsibility. Secondly, some data sets are not found in all countries but are included for the scalability of the system. A third case are parameter sets that can be derived from the current technical development and are probably needed with the introduction of new evaluation methods.

The conclusion to be drawn from the actual results is, although the basic principles for a common process and data model can be described, an implementation in detail always means integrating national requirements. Therefore, a common framework can be described, but data content and parameters have to follow that assessment techniques and maintenance calculation algorithms, which are nationally used.

In the following steps, a data model based on the previous results will be further defined, which will then be used as an example to show how the national implementation can be carried out. The assumption is, as requested in the AMSFree project a vendor-free and IFC based data format. Therefore, in the next step, the property sets are derived based on the engineering-based requirements of the three countries. This can be seen which data should be included in detail in an AMS and – as an example - how this can be implemented. The result is a prototype for the data model that is scalable and can be adapted according to the procedures and requirements.

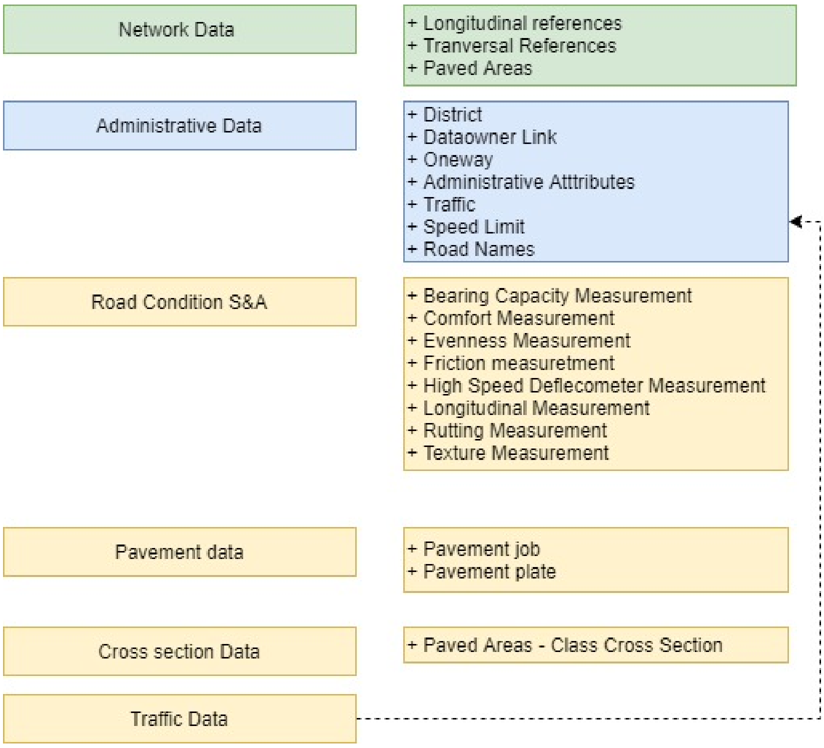

Figure 22: Required Data for DK Pavement AMS

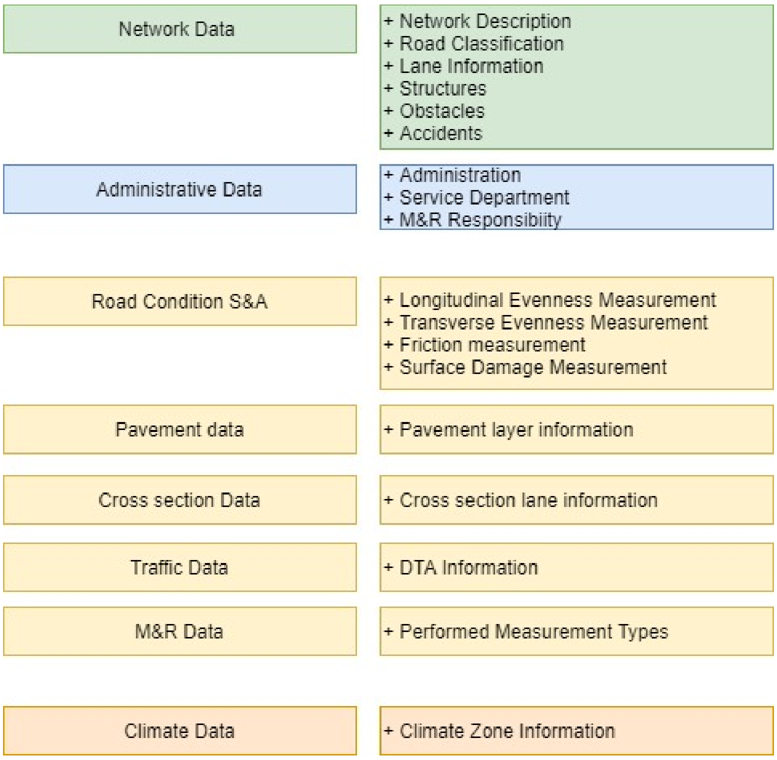

Figure 23: Required Data for GER Pavement AMS

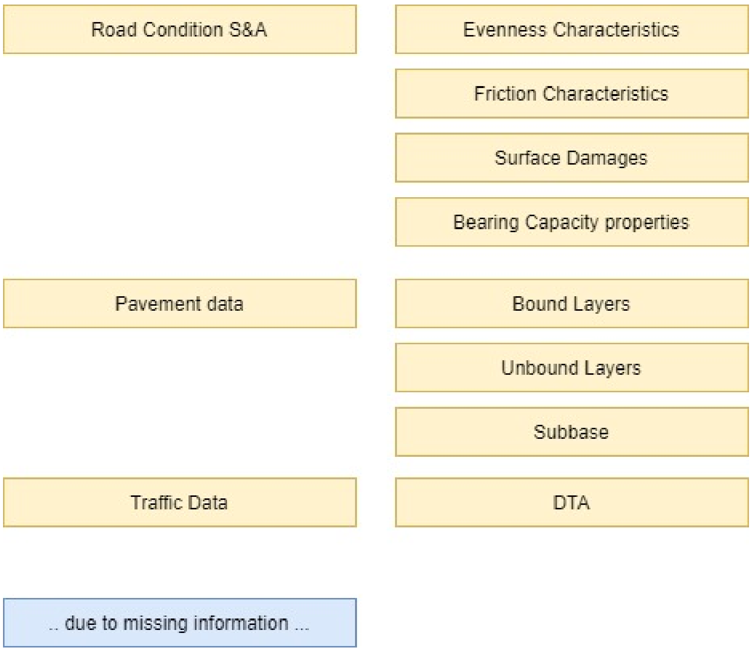

Figure 24: Required Data for NL Pavement AMS *(to confirm due to missing information)*

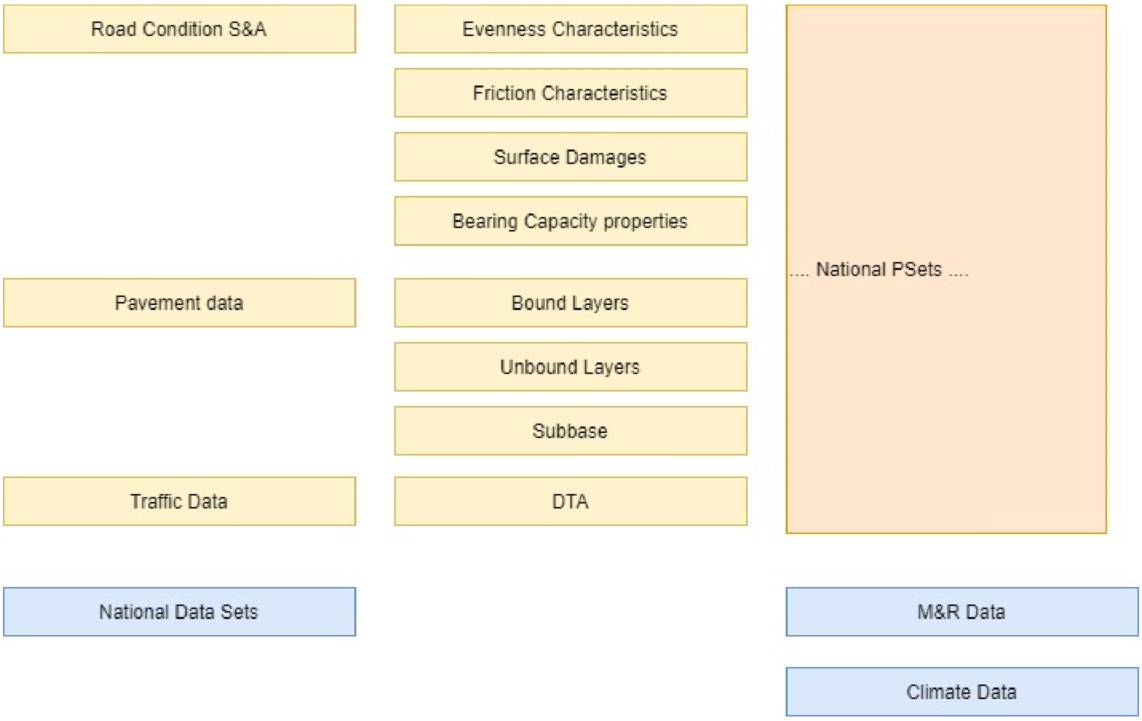

Figure 25: Required Data sets for Pavement AMS Model

2.3.3 Required data for structures

Being significantly more complex than roads, structures require more information to allow for efficient management. In this section, bridges are used as typical example of structure assets. It provides an overview of elements that need to be inspected, and the inspection methods used, whereas detail description of the assessed condition information is provided in the Report 4.2.

Bridges are inspected mostly visually. Visual inspection can further trigger an in-depth investigation, where non-destructive and/or destructive testing methods are used to measure the indirect performance indicators. Once identified, damage is classified and rated or are used to rate a bridge element affected by these damages. The rating can address damage occurrence, or element, depending on the national inspection guidelines.

German AMS for structures, SIB-Bauwerke (BASt, 2021), gives three rates to each element of the structure, according to the following criteria: stability (S), traffic safety (V) and durability (D). Damage classes are provided in the ASB-ING (BASt, 2013) database, which is described in detail in the report D4.2. As a help for visual damage classification, approx.1,700 assessed damage examples are provided in RI-EBW-PRÜF (BASt, 2021).

According to (Bundesministeriums für Verkehr, Bau und Stadtentwicklung, 2013), standard methods for in-depth testing of structures include:

- Knocking off concrete surfaces to determine cavities;
- Measuring cracks and comparing the results with preliminary measurements;
- Checking the tight fit of fastenings (screws, bolts);
- Measuring deformations (e.g. deflection) for possible conclusions on loss of bearing capacity;
- Measure displacements and gaps on bearings to detect irregularities;
- Chemical investigations (measuring the carbonation depth, determination of the chloride ion concentration) on concrete parts, to assess the risk of corrosion for the reinforcement;
- Testing of concrete strength using a rebound hammer.

According to (Bundesministeriums für Verkehr, Bau und Stadtentwicklung, 2013), non-destructive testing methods include:

- Electrochemical potential measurement for determination of active chloride-induced reinforcement corrosion in reinforced concrete structures;
- Ultrasonic echo and impact echo methods for detecting cavities in the concrete, for determination of separation zones of the reinforcement, or for localization of unpressed areas in ducts from tendons;
- Infrared thermography to localize moisture damage;
- Radar measurements, laser measurements for large-area preliminary investigation.

For a proper description of inspection findings, each classified damage occurrence needs to be assigned to a classified element. An example of the bridge inspection report with damages explicitly assigned to elements, in accordance to ASB-ING classification is provided in the Report 4.2. German NRA, BASt, does not specify which bridge elements are to be inspected, but suggests to examine all visible ones.

Danish NRA, Vejdirektoratet, also mandates the examination of all visible elements within the scope of routine inspection, whereas it strictly specifies the elements to be examined during the special inspection. According to (Vejdirektoratet, 2020), the following elements, or groups of elements, are observed:

- The entire structure
- Wings
- Slopes
- End supports
- Intermediate supports
- Bearings
- Load-bearing superstructure
- Waterproofing
- Edge beams
- Safety barriers / parapets
- Road surfacing
- Expansion joints
- Drainage structures
- Underpassing passage
- Other Elements

Figure 26 shows a part of the Danish AMS data model in order to describe condition information.

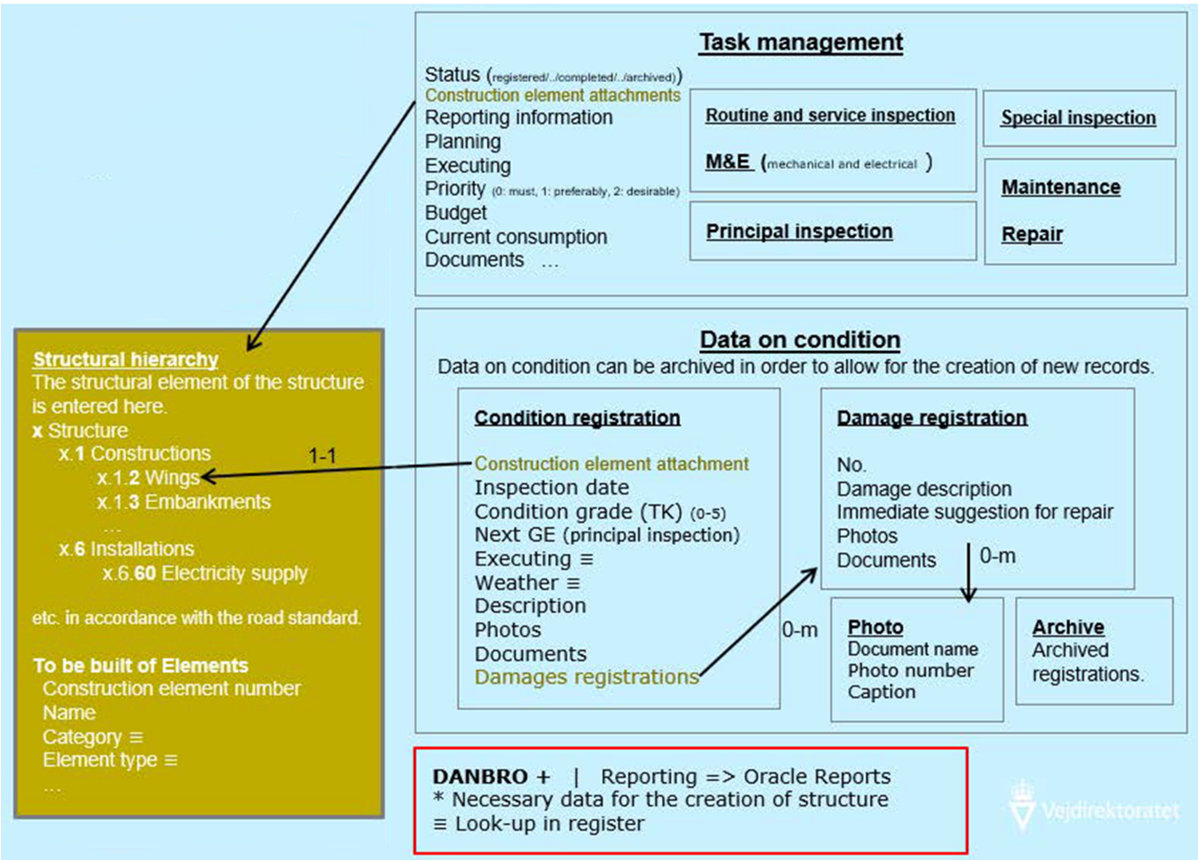

Figure 26. Part of the data model of Danish AMS, DANBRO, describing condition information. (Retrieved from (Vejdirektoratet, 2020)).

2.3.4 Data classification for pavements

The data used by the different NRAs in the AM are collected and stored using different methods. This disparity, due to different guidelines applied, results in inconsistent descriptions of parameters, different units recorded, and different characteristics. Despite all the differences, the data expresses similar conditions and are used for the same purpose in AM. To unify the data from different fields required for the AM, the data were grouped, and data sets were created. By using these data sets, the data from the NRAs can be compared and classified.

The data sets must contain data from different NRAs to be usable by all of them. Each agency must be able to map its own data requirements using the data sets. This allows contractors to populate and use the unified data sets as required by the NRAs. The classification of the data sets allows all NRAs to provide and receive the infrastructure data via the same exchange format. Some examples for structure of the exchange format are described in the next Deliverable 4.2.

The calculations performed for the maintenance planning process step require, in addition to general layer properties, input data for calculating predictive maintenance algorithms. For each layer, the type, material properties and the condition assessment are regarded as main input variables for IAMS assessment processes. A basic system for the required material properties is shown as an example in Figure 27, but without assignment to the IFC model. These data belong to the asset data set. For an asphalt layer, these are the characteristic quantities determined during type testing as well as the results of the subsequent quality control of the executed service. Such characteristic descriptions can be found, for example, in (König, et al., 2020), (Radenberg, et al., 2020) and are also currently being developed in the BIM4AMS project. These are based on European standardization and can be integrated comparatively easily into a general data model. In addition, with the performance (fatigue, deformation, stiffness and cold behaviour) potential for service life considerations, so that it is proposed to integrate these characteristics within an AMS data model. For asphalt layers, these are the following parts of EN 12697:

Part 22: Wheel tracking

Part 24: Resistance to fatigue

Part 25: Cyclic compression test

Part 26: Stiffness

Part 46: Low temperature cracking and properties by uniaxial tension tests

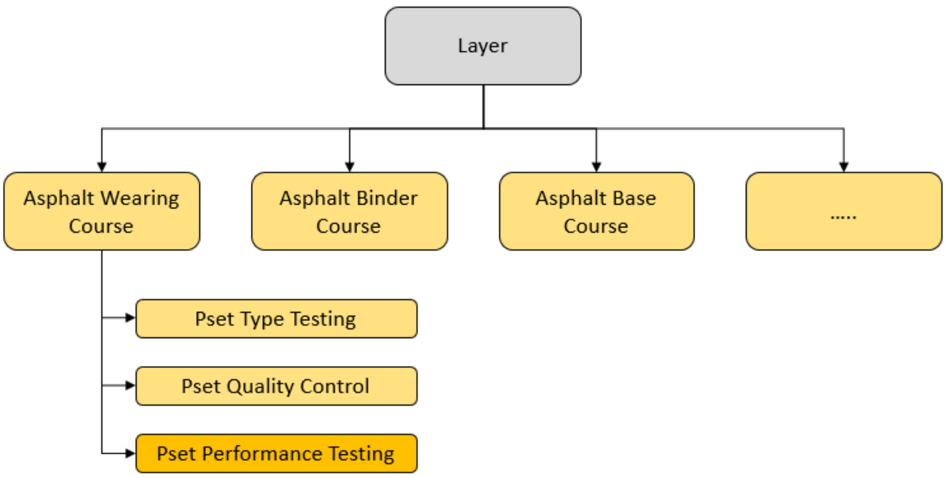

Figure 27: Example for Asphalt Layer Properties

These properties offer considerable potential for future life cycle considerations. For example, back-calculated layer-related Young's moduli are used in the Danish model, which are based on bearing capacity measurements (Vejdirektoratet, 2020). The integration of performance properties can improve the procedure. The possibility of using performance-related characteristics to determine remaining service life in the German PMS was demonstrated successfully for asphalt pavements (Stöckner, et al., 2020). For concrete pavements, performance characteristics are also to be considered, although further development is still to be awaited here. So, they will also be proposed. Further fundamental input variables for service life analyses as well are of course, the condition data as they come from update I. The characteristic groups of the condition data are also separated in asphalt and concrete pavements.

For the project and the development of the extensible prototype, which shows the implementation of a uniform exchange format, therefore five data set proposals are worked out for pavements. These five proposals contain the data mainly used by Germany, Denmark and the Netherlands and form a basis that can already be used in this form and extended if necessary. The five data sets describe asphalt and concrete performance, asphalt and concrete condition, and structural information. Although not all agencies, distinguish between asphalt and concrete in the application, for others this is an important distinction and leads to different collection methods and input data, so it was decided to separate asphalt and concrete.

The data set "Performance Asphalt" belongs to the asset data set describes the material properties of asphalt, which shows effects on lifespan, durability and application. The four examples of asphalt performance are fatigue, deformation, stiffness and low-temperature performance. Different test methods are used to determine these properties. For fatigue, these are the four-print flexural test and the dynamic indirect tensile test. For deformation the wheel tracking, the uniaxial compressive strength test, the triaxial compressive strength test and the dynamic indenter test. For stiffness, the dynamic indirect tensile test and the four-print flexural test. And for low-temperature performance, the cooling test, the uniaxial tension test, and the uniaxial dynamic tensile test (Figure 28). The test procedures have different effects on the evaluation of the material, depending on the national approach, so that certain test procedures are not used at all in other NRAs. Each test procedure results in parameters with specific symbolism and, if applicable, a unit of measurement data. The detailed properties can be found in the appendix to this report, as well as for all data sets.

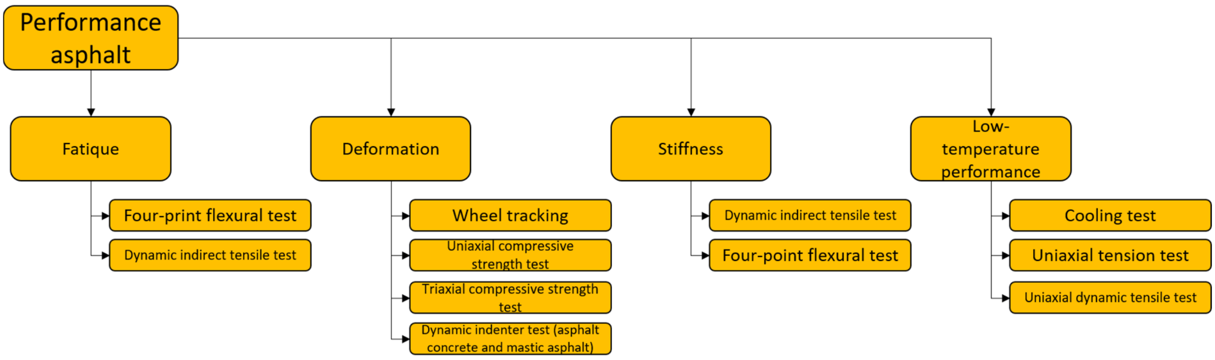

Figure 28: Structure of the Asphalt Performance data

The data set "Performance Concrete" belongs to the asset data set and describes the material properties of concrete that have an impact on service life, durability, and application. The three examples of concrete performance are fatigue, ageing/resistance, and cracking. For these, properties are given and corresponding test methods. These are for the group fatigue test with cyclic determination of stiffness, splitting tensile strength, resonance frequency and elastic modules, static E-modulus, and sonic run time. For ageing/ resistance, the time coefficient of road paving concrete (subsequent hardening) is given. For the third group of cracks, the wedge splitting test is used (Figure 29). Since concrete is only treated individually by some NRAs, fewer different test methods are listed than for asphalt. The in-depth characteristics of the test results and units can be found in the appendix too.

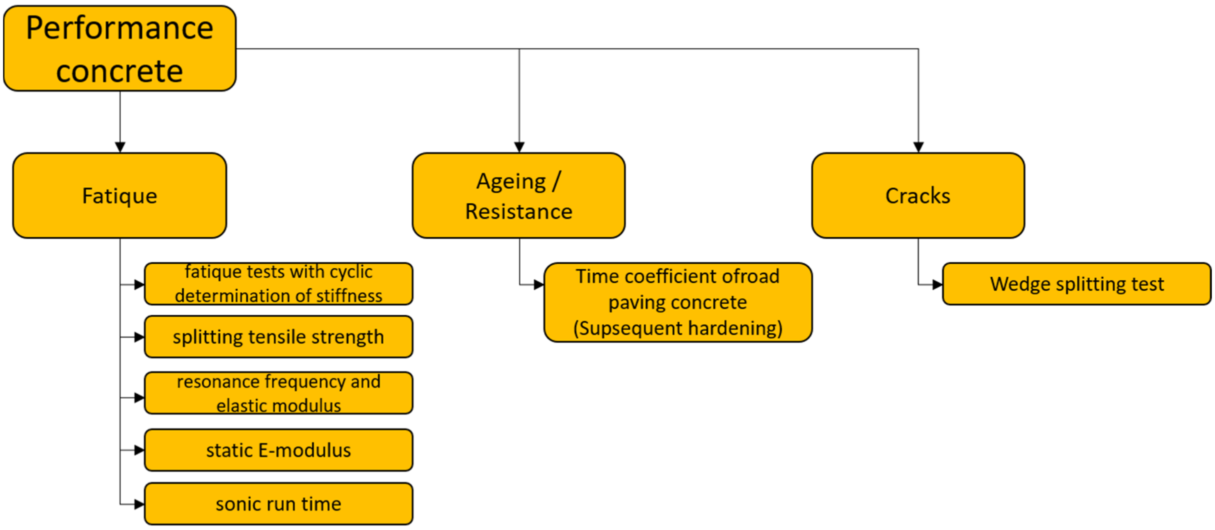

Figure 29: Structure of the Concrete Performance data

Condition assessment plays a central role in AM to check the current value of assets and to be able to react to deficiencies in order to coordinate asset maintenance. The most important input data for condition assessment comes from the data set "Condition asphalt". The evaluation parameters longitudinal evenness, transverse evenness, roughness, bearing capacity, texture, acoustic properties, reflection properties, and surface with the sub-parameter's cracks, cracks in joints, patches, outbreaks, deformation, structural damages, surface smoothness, surface damages are assigned to this data set (Figure 30). As the individual NRAs rely on different assessment methods for the properties, it can be, that the same properties are assessed with different indicators. Therefore, the differences are listed in the property set, since the assignment of values from different measurement methods to the same property, does not apply to other national AMs. The classification, however, allows the use of the same exchange format considering the source and target guidelines.

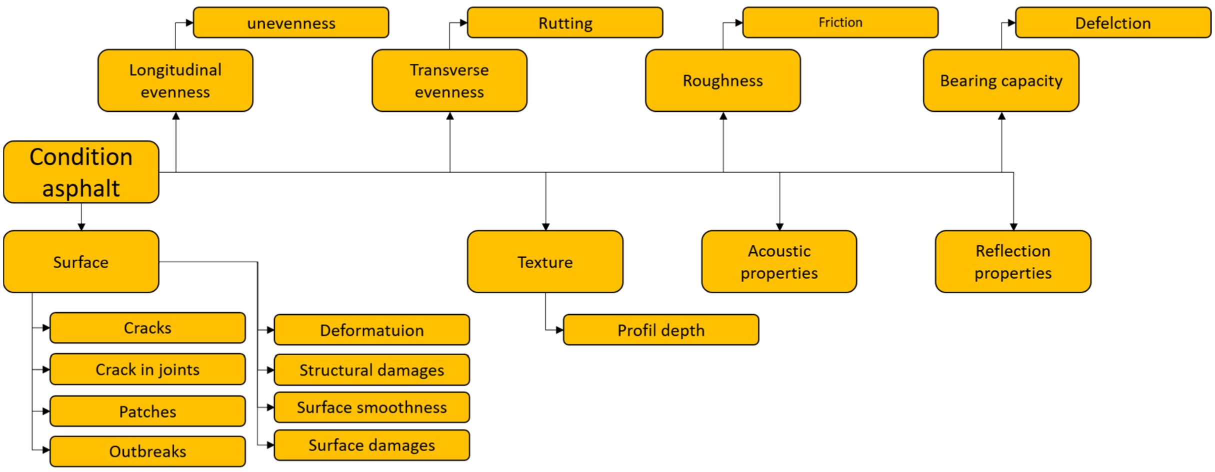

Figure 30: structure of the Asphalt Condition data

Similar to the condition assessment of asphalt, comparable methods are used for concrete wearing surfaces. However, the various methods can be grouped into the data set "Condition concrete". This consists of the following evaluation parameters: longitudinal evenness, transverse evenness, roughness, bearing capacity, texture, acoustic properties, and surface with the sub-parameter's longitudinal cracks, corner demolition, edge damage, bursting, fractures, surface damage, surface slickness, material deficiencies, joint damage, vertical shifting, and patches (Figure 31). The units and indicators belonging to the sub-parameters are given in detail in the appendix to this report. This detailed list is used for further processing of an exchange format in the project.

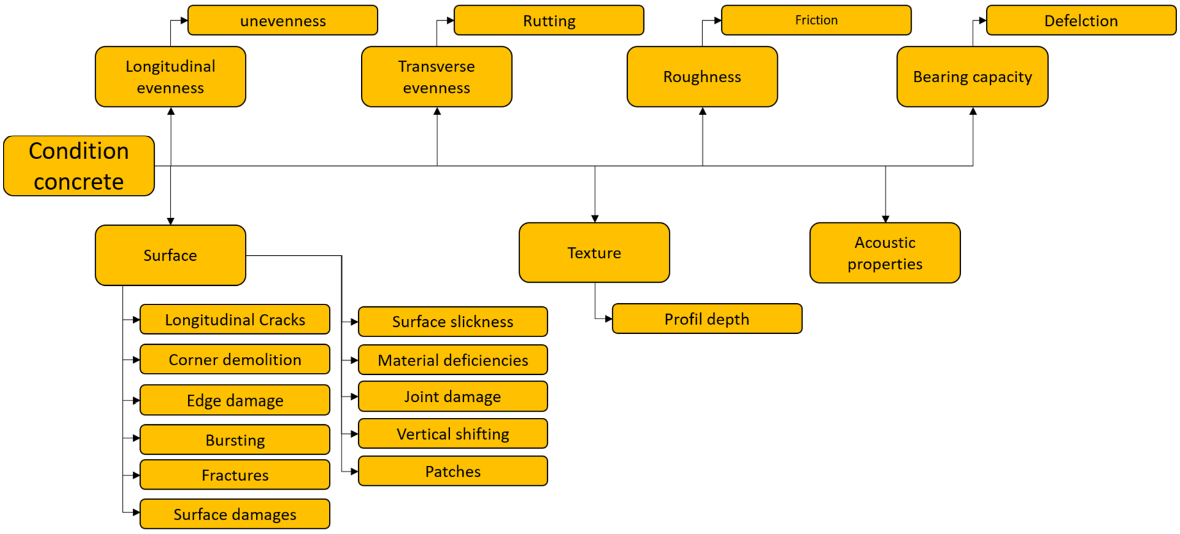

Figure 31: structure of the Concrete Condition data

The fifth data set considered contains the structural information of the pavement assets. Here, properties for asphalt construction as well as for concrete construction are taken into account. As an example, the following property groups are defined for this purpose: Concrete surface layer, mixing material, temperature resistance, base layer, binder, solidification, compaction, and planum.

The predefined data sets make it possible to provide data from different measurement methods and sources for different NRAs by clearly assigning them. By defining the properties in relation to each other, further incorrect assignments of the same property with different guidelines and methods can be avoided. By means of the property sets, the specifications for the further data containers of the exchange format are prepared.

2.3.5 Data classification for structures

For bridges, the properties are focused only in terms of damage description and condition assessment. The information requirements of each country (DE, DK, NL) for structural element, damage and condition rating of a bridge are presented in Report 4.2. With the narrowing down data scope, a clear demonstration of data capturing and integration for sub-process inspection can be performed. Based on this, the required sematic information for inspection is created or extended in the appropriate format as ontology, which are presented for the information container described in Report WP3.2

3 Conclusion

This report describes the AMS process and defines the data requirements so far, that national similarities and differences can be seen. This includes the process flow, which was merged into a generic process model in which the data exchange is structured by the three important data updates. In addition, requirements for the needed date sets were defined.

4 Bibliography

BuildingSMART Finland. (2019). *Common InfraBIM requirements YIV.* Von BuildingSMART Finland: https://buildingsmart.fi/wp-content/uploads/2019/08/YIV_main_document_ENG_DRAFT1.pdf abgerufen

Andersson, H. (2019). *Data och dokumentation till förvaltande system – Väg.* Trafikverket.

BASt. (2013). *Anweisung Straßeninformationsbank für Ingenieurbauten, Teilsystem Bauwerksdaten (ASB-ING) Erhaltung.* Berlin: BASt.

BASt. (2018). *Meeting Information from Department Road Construction, 6/2018, unpublished.*

BASt. (25. February 2021). Von SIB-Bauwerke: https://sib-bauwerke.de/ abgerufen

BASt. (25. February 2021). *Bauwerksprüfung RI-EBW-PRÜF*. Von Bundesanstalt für Straßenwesen (BASt): https://www.bast.de/BASt_2017/DE/Ingenieurbau/Fachthemen/b4-Bauwerkspruefung-RI-EBW-PRUEF/b4-Bauwerkspruefung-RI-EBW-PRUEF.html abgerufen

Beetz, J., & Borrmann, A. (2018). Benefits and Limitations of Linked Data Approaches for Road Modeling and Data Exchange. *Advanced Computing Strategies for Engineering. EG-ICE 2018* (S. 245-261). Cham: Springer.

Bernard, E., Marschal, C., & Hajdin, R. (2015). *Forschungspaket Nutzensteigerung fuer die Anwender des SIS: EP6: Schnittstellen aus den Auswertungssystemen SIS (SIS-DWH).* Bern.

Bundesministeriums für Verkehr, Bau und Stadtentwicklung. (2013). *Bauwerksprüfung nach DIN 1076 Bedeutung, Organisation, Kosten.* Berlin: Bundesministerium für Verkehr, Bau und Stadtentwicklung.

Hårrskog, C. (2017). *Trafikverkets strategi för digitalisering.* Trafikverket.

Helmerich, R., Niederleithinger, E., Algernon, D., Streicher, D., & Wiggenhauser, H. (12 2008). Bridge Inspection and Condition Assessment in Europe. *Transportation Research Record, 2044*, 31-38. doi:10.3141/2044-04

Hoeber, J., Alsem, D., & Willems, P. H. (2015). The management of information over the life-cycle of a construction project using open standard BIM. *Proc. of the 32nd CIB W78 Conference 2015* (S. 295-301). Eindhoven: CIB W78.

Ingemar, L. (2017). *Trafikverkets strategi för BIM.* Trafikverket.

INTERLINK. (12. November 2020). Von Basic European Road OTL: https://www.roadotl.eu abgerufen

Isailović, D., Stojanovic, V., Trapp, M., Richter, R., Hajdin, R., & Döllner, J. (2020). Bridge damage: Detection, IFC-based semantic enrichment and visualization. *Automation in Construction, 112*, 103088. doi:https://doi.org/10.1016/j.autcon.2020.103088

Jackson, P. (2018). *Infrastructure Asset Managers BIM Requirements.* buildingSMART International. Von https://www.buildingsmart.org/wp-content/uploads/2018/01/18-01-09-AM-TR1010.pdf abgerufen

König, M., Borrmann, A., Stöckner, M., Radenberg, M., Hagedorn, P., Jaud, S., . . . Müller, D. (2020). *BIM-basiertes Erhaltungsmanagement im Straßenbau Endbericht zum Forschungsprojekt FE-Nr. 04.0299/2016/MRB, unpublished.*

Kusar, M., Linneberg, P., Amado, J., Masovic, S., Tanasic, N., & Hajdin, R. (2019). *Quality control for road bridges – overview of COST Action TU1406 WG3 final report.* (4. I. Symposium, Hrsg.) Guimaraes, Portugal.

O’Keeffe, A., Alsem, D., Corbally, R., & van Lanen, R. (2017). *Information Management for European Road Infrastructure using Linked Data - Investigating the Requirements.* CEDR.

Radenberg, M., Müller, D. König, M., Hagedorn, P., Geistefeldt, J., Hohmann, S., & Heinrichs, J. (2020). *Anwendung der Methode BIM in Konformität mit den Regelwerken der FGSV und des IT-Ko, Entwurf Schlussbericht zum FE 02.0427/2018/ARB.*

Rijkswaterstaat Ministerie van Infrastructrur en waterstaat. (2018). *Functionele specificatie voor een RWS.*

Sacks, R., Kedar, A., Borrmann, A., Ma, L., Brilakis, I., Hüthwohl, P., . . . Muhic, S. (2018). SeeBridge as next generation bridge inspection: Overview, Information Delivery Manual and Model View Definition. *Automation in Construction, 90*, 134-145. doi:https://doi.org/10.1016/j.autcon.2018.02.033

Schlichter, P. (2020). *Vergleich von Verfahren zur Zustandsprognose der Straßenbefestigungen im europäischen Vergleich.* Karlsruhe: unveröffentlicht.

Stöckner, M., Sagnol, L., Brzuska, A., Wellner, F., Blasl, A., Sommer, V., . . . Komma, C. (2020). *Abschätzung des Restwerts im PMS am Ende des Bewertungszeitraums. Schlussbericht zum Forschungsprojekt FE-Nr. 04.0207/2007/MGB, unpublished.*

Vejdirektoratet. (2020). *Appendix 02.b - Danish Road Directorate Asset Management Strategy Version 1.1.* DK-2640 Hedehusene: Ministry of Transport, Building, and Housing.

Vejdirektoratet. (2020). *Appendix 02.e - Data Model, vejman.dk / VIMS data.* DK-2640 Hedehusene: Ministry of Transport, Building, and Housing.

Vejdirektoratet. (25. February 2020). Appendix 02.o Structures - Paradigm for Special Inspection. Copenhagen, Denmark.

Vejdirektoratet. (25. February 2020). Appendix 2.f Data Model Structures (Danbro). Copenhagen, Denmark.

Vejdirektoratet. (2020). *Danish Road Directorate Asset Management Strategy Version 1.1.* Hedehusene: Ministry of Transport, Building and Housing.