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Applications of Rail View, Sky View and Maintenance Go – digitalisation within railway asset management

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ABSTRACT

The work presented in this paper is performed in connection to the research project "Reality Lab Digital Railway" (VDJ). The paper contains a description of three parts of the project, i.e. "Rail View", "Sky View", and "Maintenance Go". Infrastructure data was collected through railway vehicle and helicopter, while user needs was collected through interviews, workshop, observations, and document studies. The analysis of qualitative material is mainly based on international dependability standards, e.g. the IEC 60300-series. The result encompass a description of some use cases as well as some specific user needs in relation to a generic maintenance process. Finally, the paper concludes with a discussion of some results and their application, but also their extension with Artificial Intelligence (AI) as part of digitalised asset management. A tentative analysis model is also described to support the positioning of different digitalisation initiatives within asset management and support their implementation.

Keywords: Railway; digitalisation; laser scanning, 360 pictures, Reality Lab, Augmented Reality (AR), asset management, planning, Sweden

1. Introduction

As all parts of society, the railway is experience a paradigm shift due to digitalisation. The railway infrastructure is digitalised through new systems such as the European Rail Traffic Management System (ERTMS), but also Internet of Things (IoT), where traditional systems such as Switches & Crossings (S&C) are becoming connected. Hence, asset management of the railway system also have to change due to new possibilities and challenges to manage the system throughout its lifecycle. In fact, Trafikverket (the Swedish Transport Administration), as all other authorities in Sweden, is required to be managed efficiently, take care of the state's resources, obey present laws and obligations, and present its performance in a reliable and fair manner; see SFS(2007:515) at [1]. Hence, to fulfil these requirements, Trafikverket as national railway infrastructure manager has to adapt to the digitalisation. However, even though the technology is changing very fast, a successful implementation requires changes also of more slow changing areas such as individuals and organisation, but also of regulations (see, e.g., Martec's Law).

The work presented in this paper has been carried out in connection to the research project "Reality Lab Digital Railway" (VDJ) [2]. Within VDJ, research and development is conducted to promote the digitalisation of railway maintenance. One of the project's goals is to find new areas of application for existing technologies, while simultaneously considering existing organisation and regulations. For example, data about the railway infrastructure has been collected through railway vehicles, drones, helicopters and satellites, see Figure 1. This data has in turn been analysed by a wide range of approaches spanning from manual analysis to advanced statistical approaches and AI. This paper describes three parts of the project, i.e. "Rail View", "Sky View" and "Maintenance Go".

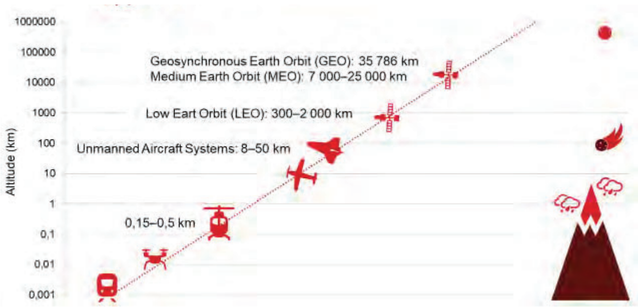

Figure 1. Examples of vehicles used to monitor the railway infrastructure. From [2].

"Rail View" is an application of 360-degree images of railway infrastructure. A similar technology is used by, for example, Google in their service "Street View". Images are positioned using GPS. In parallel with the photography, the railway infrastructure has also been laser scanned. Hence, the results can be used to, for example, measure the position, size and distance of infrastructure objects and surrounding objects in relation to each other.

"Sky View", is an application of helicopter 3D photography and laser scanning of the railway infrastructure. This corresponds to technology currently used by Trafikverket for inspection of infrastructure for non-linear power. The applied technology has similar possibilities for measuring objects as in "Rail View".

"Maintenance Go" is an application of Augmented Reality (AR) in the management of railway infrastructure assets and is an extension of "Rail View" and "Sky View".

2. Method and material

Based on systematic selection criteria [3] (i.e. type of research question, no required control over behavioural events, and focus on contemporary events, but also criticality and extremeness of the case) a single case study of the Swedish Iron ore line was chosen as an appropriate research strategy. The choice was also supported by accessibility and available resources, since the Iron ore line is part of the physical assets of the project "Reality Lab Digital Railway". The choice also enabled the use of action research (see discussion in, e.g. [4] and [5]).

Qualitative data was collected through interviews, a workshop, document studies, and observations. Information about the railway infrastructure that constitute the basis for Rail View and Sky View was collected by railway vehicle and helicopter respectively. The analysis of qualitative data is mainly based on theories from the dependability area, e.g., international dependability standards within the IEC 60300-series. Finally, the paper has been reviewed by key informants and roles to verify its content.

2.1. Overall case study – the Iron ore line

The Iron ore line is about 500 kilometres long and runs between Narvik in Norway in the north-west and Luleå in Sweden in the south-east. The largest ore deposits and refining plants are located in-between, at Kiruna, Gällivare/Malmberget and Svappavaara. The iron ore is transported around the clock throughout the year in an extreme subarctic climate. Large temperature differences and weather changes are demanding both for the infrastructure and the rolling stock. The Iron ore line allows a train weight of 8,600 metric tonnes and an axle load of 32.5 metric tonnes. This are the heaviest train transports in Europe, and within some years, the aim is to increase the axle load to 40 metric tonnes. Hence, asset management of the Iron ore line is crucial and continuous dependability improvements are necessary to meet ever increasing operational requirements.

2.2. Collection of infrastructure data

The vehicles and equipment used for collection of data used in Rail View and Sky View can be seen in Figures 2 and 3 respectively. Collected data for Rail View was stored, analysed and provided in the application "Orbit 3DM Publisher". To manage data for Sky View in a similar way, the application "DPM 3D Inspection" was used. To enable a qualitative inspection of the infrastructure, it was desirable to collect data after the snow had melted and before the leaves on trees start to grow, but also to have good weather and lighting conditions.

The original assignment for Rail View included laser scanning and photography of 360 degree images, with the purpose to aid projecting of ERTMS at the Iron ore line. The requirement for data collection was that it should be carried out under lighting and weather conditions so that sign texts, cabinet designations etc. could be identified. Furthermore, additional requirements were [6]:

- The data positioning accuracy of +/- 0.05 m in plane and height.
- At least two scanners should be used, rotating 135 degrees relative to the driving direction, to minimize shadow effects.
- The spot density for laser data would be at least 1,000 points per square meter.
- The images should have a 360-degree coverage and no part of the image should be covered by equipment and vehicles.
- The images should have a resolution of at least 30 Megapixels and a colour depth of at least 12 bits.
- Distance between images should be 5-10 m.

However, in order to be able to evaluate whether the opportunities for inspection could be improved by changing the requirements, which Trafikverket traditionally uses in procurement of mobile data collection, supplementary data were used where the density of laser data and resolution in downward images were significantly improved. [6]

Complementary data consisted of comprehensive images photographed with downward-facing cameras with a ground resolution of about 1 mm. As well as directed line scanners with an approximate point distance in the line of 0.5 - 1 mm, each rail was covered and with a distance between each line of about 10 mm. [6]

Figure 2. Picture of locomotive with measuring equipment used for 360 photography and laser scanning of the Southern iron ore line.

Sky View data was collected through a Hughes 500:a helicopter. The helicopter is turbine-powered and the system for image collection and laser scanning is EASA certified to be installed on the model. The applied measurement system consists of:

- GPS / GLONASS L1L2
- Inertial navigation sensor
- Two 3D-cameras that create a 3D-image of the power line and its surroundings.
- Two cameras that take pictures for documentation and possibly inspections, one is aimed forward and one backward to get pictures of, e.g., posts, on both sides.
- Laser scanners that generate between 30-80 points per square meter.
- Multiple echoes
- Camera for orthophoto

2.3. Collection of user needs

To identify various applications of Rail View, Sky View and Maintenance Go in the management of Trafikverket's railway infrastructure a number of activities have been conducted. The approach has been both inductive (starting from user needs and identifying contribution of available solutions) and deductive (matching available solution to user needs).

A deductive approach was to perform individual demonstrations of Rail View and Sky View for various stakeholders within Trafikverket and maintenance entrepreneurs. Examples of internal stakeholders are: project managers railway maintenance; maintenance engineers; project engineers; railway system representatives; asset data managers; and claims manager.

Included stakeholders from maintenance entrepreneurs are site managers, supervisors, and technicians.

Another deductive approach was to conduct a workshop focusing on Rail View and Sky View solutions. At the workshop, representatives from Trafikverket, maintenance entrepreneurs and the suppliers of respective solution discussed their functionality and usability. Examples of participant stakeholders are maintenance districts, measuring units, asset data, railway systems, business management, technology and environment, inspectors, and maintenance contractors

Figure 3. Picture of helicopter with measuring equipment used for 3D photography and laser scanning of the Iron ore line.

The inductive approach was based on three smaller case studies. These case studies were initiated by needs in the ongoing operations, where employees at Trafikverket had to study the railway infrastructure and its surroundings, and Sky View or Rail View was judged to give valuable support.

In addition to the above activities, a meeting with SL (Stockholm local traffic) was conducted since they are an infrastructure manager that has their own application of Rail View. This meeting was used as a validation of the findings of the case studies at Trafikverket.

3. Results

The results of the study can be divided in two parts depending on the applied approach for collection of user needs, and if it was inductive or deductive.

The results related to the inductive approach is described in the context of the three subcases where needs emerged in the organisation and valuable support was judged to be available through Rail View and Sky View. The results based on the deductive approach, where Rail View and Sky View were presented for potential stakeholders to judge its usefulness, is related to some of the phases of a generic maintenance process.

3.1. Results from subcases

Roles related to the management of Trafikverket's road maintenance contracts, make frequent use of services such as Google Maps and Street View. These are valuable tools for road project managers who may be responsible for assets that can be up to 2,000 km long. Hence, a person cannot possibly have a total local knowledge about these assets. The tools are used to quickly get information about the area and its surroundings (e.g., geographical positioning and an overview of how it looks in the immediate nearby area), which can save Trafikverket and the taxpayers considerable money. For example, regarding working time, vehicles and fuel when field visits can be carried out at the office instead of out in the field. The tools can support a person to quickly get a picture of the asset and its surroundings, e.g., regarding fences, railings, water sources, ground conditions, and slope conditions. In different types of consultations with stakeholders, the tools are also valuable. For example, in contact with the public the responsible person can quickly get an idea of what it looks like in and around the road area that is adjacent to the property owner concerned, e.g., the school or the sports ground.

In a similar manner, project roles related to the management of railway maintenance contracts from time to time use Google Earth, and to some extent Street View (in cases where the railway is visible). Common applications are, e.g., control of intersections between road and rail (level crossings, bridges, and tunnels), planning of field visits, and the identification and localisation of connecting roads. However, as indicated above, the usability of these commercial solutions for rail purposes are very limited compared to the road applications.

3.1.1 Timber terminal

One case was consultation related to modifications of the timber terminal in Murjek. This consultation involved two external stakeholders, i.e., railway operator and paper manufacture (SCA). Internal stakeholders at Trafikverket that participated were representatives from the unit responsible for strategical and tactical management of the railway infrastructure, the unit responsible for long-term planning, and the unit responsible for operational management of the railway infrastructure and the maintenance contract.

The paper company SCA wanted to improve their logistic solution by using longer timber trains and thereby reduce the number of trains from three to two per day. However, to achieve this, the timber terminal has to be modified. Trafikverket's contact with SCA goes through the unit of Planning (who is responsible for external contacts), which prepared a consultation meeting with the primary external stakeholders (SCA and the railway operating company Hector-Rail) together with the unit responsible for the operational infrastructure maintenance. The consultancy meeting was performed via Skype and used Google Earth and Rail View as main information sources. In addition to the internal and external stakeholders mentioned above, the unit at Trafikverket responsible for strategic and tactic maintenance of the infrastructure asset also participated.

The physical constraints of the infrastructure and its surroundings could easily be identified. The information was even better than would be obtained through a field visit since the consultancy meeting was performed during winter and snow was covering the area. Two different scenarios could be evaluated through the available information, i.e., extension of the terminal in the far end (limited by water) or loading of train in two parts from two sides of a crossing road, followed by a coupling of the train.

The Skype meeting based on information from Google Earth and Rail View took about one hour. A field visit would take roughly eight hours. The distance from Luleå to Murjek is about 300 km. the labour cost of the five participating persons are about SEK 24,000 (SEK 650 per person and hour) for a field visit compared to about SEK 3,000 for a Skype meeting. In addition, each participant can use seven hours for other activities, i.e., 35 hour in total saved for all participants.

3.1.2 Snow protection and avalanche warning

Another case was the investigation of measures in avalanche areas, where Sky View was used to investigate local conditions in the immediate area where avalanches have emerged. The purpose of this investment project was to build avalanche protection and to investigate the location of avalanche warning devices. From a work environment point of view, it would be beneficial to avoid building the systems to far into the terrain, as it in many cases is very hilly with steep slopes. Figure 4 illustrates an avalanche area, which is identified through an area with fallen trees in one direction. In Figure 5, the user can move around in the laser point cloud, and identify the topology of an area, e.g. in this case steep slopes at the position of a cross section (white line in Figure 5). Figure 6 illustrates the cross section at the white line in Figure 5. This is a valuable tool in this case to assess steepness. In other cases it can be used for mass calculations and other assessments of areas where work is to be executed.

By using Sky View it was possible assess the characteristics of the terrain, to identify, position, and measure, e.g., buildings, roads, walking trails, water, existing avalanche systems, and areas of earlier avalanches.

The investigation of the area took about one hour by the use of Sky View. A field visit would take about one week to achieve the same result. The quality of information from Sky View was judged to be of much higher quality than services available from, e.g., Google, Eniro or Favy (a GIS system within Trafikverket).

Figure 4. Fallen trees used to identify an avalanche area.

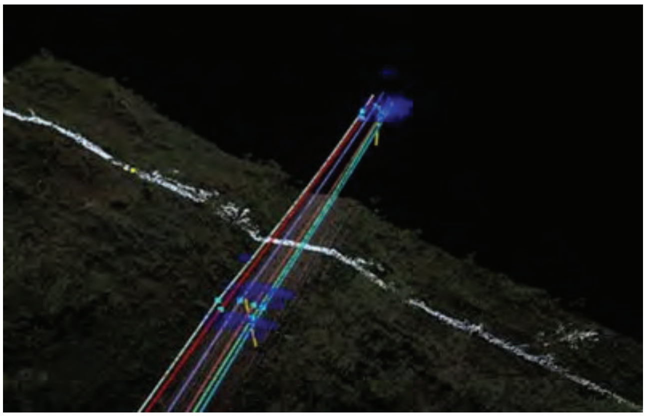

Figure 5. Laser point cloud, including position of cross section (white line).

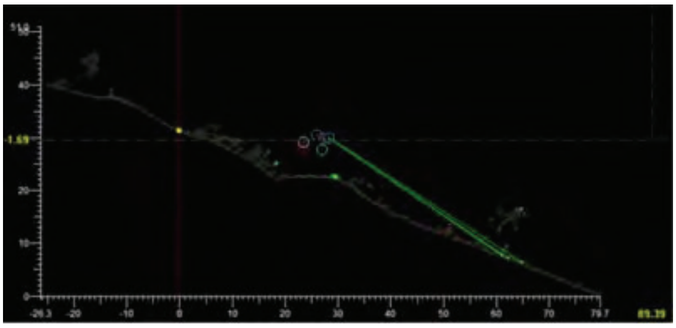

Figure 6. Cross section of terrain, correlating to white line in Figure 5.

3.1.3 Accident investigation

When an accident occurs, it may be possible to use Rail View or Sky View to gather some of the necessary information. One example of this is the third case, which was an accident investigation, where visibility conditions at a level crossing was studied in relation to an accident with one fatality. Since the information in Rail View was gathered shortly before the accident, it was possible to establish that the line of sight was according to the requirements at the time of the accident. Hence, vegetation clearance was performed as it should and some other contributing factors to the accident had to be identified. In addition, it was possible to verify that the project manager and the entrepreneur had fulfilled their responsibilities even though their internal communication had been informal and not documented.

3.2. Results related to user needs in the maintenance process

The generic maintenance process is an extension of the improvement cycle and adapted for maintenance practice. However, the findings are also relevant for other asset management activities such as operation and investment.

3.2.1 Asset information management

One central part of asset management is the asset register. The reason being that it is at the core of Trafikverket's systems for management of safety and dependability. For example, the asset register gives input to the system "Inspection plan" that manages the status of both safety and maintenance inspections. Hence, the system makes it possible to follow up that the right objects are inspected in a correct way regarding type, frequency, time and place. The asset register also gives input to the inspection protocol, which is used by the inspection personnel to ensure that the right inspection points are included for individual items in the infrastructure depending on its unique features such as configuration and model. Besides the inspection systems, the fault reporting system is also dependent on the asset register to connect faults to individual parts of the infrastructure. The data from the inspection and fault reporting systems, are in turn used to follow up the safety and dependability performance of the asset or the related organization and make decisions about appropriate actions within, e.g., maintenance, reinvestment or investment.

Today, errors regarding asset register data is manually reported by personnel using the data in their work, e.g. for inspections. The follow up of these error reports are time consuming and the quality of the reports may in turn be rather low adding to the burden. Field visits to measure and position objects take time, and the use of alternative sources of information such as film from measurement wagons or commercial map services have limited usability. The measurement wagons only provide film as a secondary service, which makes the quality heavily depending on daylight, weather, season, and direction of travel. The commercially available information services have limited usability with regard to evaluate individual objects within the railway infrastructure.

Hence, information about the asset from Sky View and Rail View can be used to update and improve the quality of information in the asset register, e.g., missing, extra or erroneous objects as well as their position. The inventory of existing items of a specific type (e.g. bird spikes) in the asset may also be supported by the use of Sky View and Rail View. This management of information can be performed through a system interface instead of field visits, which improves the efficiency tremendously.

3.2.2 Planning of actions in the infrastructure

Rail View and Sky View can be used to support the planning of actions in the infrastructure in a strategical, tactical and operational perspective, e.g., regarding maintenance, reinvestment and investment. By providing information about the infrastructure and its surroundings, it is possible to:

- Plan safety measures.

- Plan the use of machinery, e.g. which type, access paths, and working sites.
- Plan material logistics, e.g., which material shall be used, where should it be stored and loaded, and how to manage disposed material.
- Combined planning of multiple actions that are beneficial to coordinate at a specific site and time.
- Amount of work that is necessary depending on the assets condition and the characteristics of the surroundings.

From a maintenance perspective, the actions can be single major actions such as felling of risk trees, vegetation clearing, and drainage or fencing works. However, also the planning of additional work, e.g. when replacing component in Switches & Crossings (S&C), it is possible to investigate the surroundings. Hence, it might be possible to coordinate the component replacement with replacement of broken or missing equipment in other asset types (e.g. ducting caps) or removal of disposal that are on the site.

Another example is coordination of multiple actions that requires railway vehicles and are to be performed in the infrastructure at about the same time and place. Two examples of this type of actions are the changing of sleepers and mechanical vegetation clearance.

3.2.3 Inspection

Inspection is a central part of condition-based maintenance in railway. Rail View can be used for many visual inspections where the perspective is similar to a train driver. Hence, Sky View is a good complement to visual inspections with the view of a helicopter pilot. To perform inspections through an interface to Rail View and Sky View has a number of benefits compared to inspections in the field, e.g.:

- Time savings, the time for traveling to and in the infrastructure changes from hours to minutes or seconds.
- Improved work environment, it is more safe and comfortable for the personnel to perform the inspections at an office than out in the field.
- Improved capacity for traffic, since the time in field for maintenance activities is reduce there are more time for traffic.
- Improved effectiveness and efficiency of maintenance, the number of inspectors may be reduced and they can focus on yards instead of on lines.
- Assessment of performed work, depending on the relation in time between different maintenance actions and gathering of information as input to Rail View and Sky View.

With regard to inspection, data from Rail View was evaluated with regard to Trafikverket's regulation for safety inspection (TDOK 2014:0240). The possibilities for off-site inspection were calculated for each asset type. The greatest opportunities for inspection was related to track, where approximately 85% of the inspection was judged possible. Automation were most developed in some cases where it is possible to see changes between images from different data collections, for example missing or damaged fasteners and sleepers, damaged signals and signs, but also cracking on various construction objects. [6]

Other areas where automation of inspection proved to be possible based on analysis of Rail View laser data were, for example, wear on rail heads, deviating track geometry, control of ballast levels, erosion and damage to the embankments, free space, and control of catenary system. [6]

Much of the inspection points according to TDOK 2014: 0240 was carried out by use of Rail View. The application showed that the completeness could be improved by adding high-resolution laser data and track images. Inspection of tracks, switches, bank, intersections, platform, signals, boards, and fences showed a special suitability with completeness of 50-100% at inspection. [6]

4. Discussion

To achieve the potential benefits with Rail View and Sky View, the geographical positioning of data and integration with the asset register is fundamental. Hence, this is an integration with the spatial and the system domains. In addition, it would be beneficial to have an integration with the time domain, where past, present and future actions or asset condition can be visualised. Hence, the time domain also supports a life cycle perspective where maintenance, reinvestment and investment actions can be considered simultaneously. By a combination of spatial, system and temporal domains, both coordination and optimisation of actions in the infrastructure from a line (instead of subsystem) perspective is enabled. However, the need for actions may very well be initiated from a subsystem perspective, e.g., track, catenary, or signalling systems. However, from a practical point of view, the bottleneck is the physical asset, where all these actions have to be performed in coordination with each other and with the railway traffic.

Virtual Reality (VR) can be used as an enhanced interface in order to move around in the infrastructure while being off site. In this way it may be possible to perform all the actions described in this paper, but in a more vivid way than through a screen. In addition, education and training may also be supported in a safe, effective and efficient way. However, with or without VR, both Rail View and Sky View provides the possibility to gain local knowledge about the infrastructure and its surroundings. This local knowledge is fundamental for performing actions in the infrastructure both effectively and efficiently.

There are technologies to combine information in Rail View and Sky View with other information to enable Augmented Reality (AR) when being out in the field. The most famous application of AR is probably Pokémon Go (see Figure 7), where a similar application for maintenance purposes could be named Maintenance Go. For example, inspection remarks generated off site by inspection personnel using Rail View or Sky View can be visualised through goggles for the personnel in field when they are acting upon the remarks. Hence, the remarks can be superimposed on the asset type concerned, which facilitates identification of the right action to perform on the right object. However, the time constraints of this study limited the demonstration of any solution for Maintenance Go.

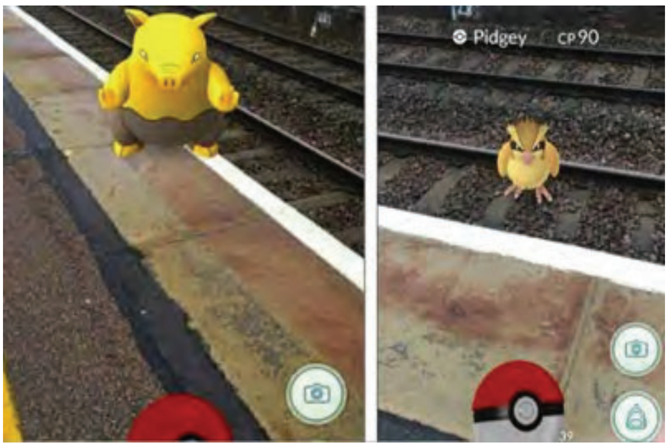

Figure 7. Example of Pokémon in the track area.

The data in Rail View and Sky View can be used as parts of a digital twin. For example, in Sky View, the catenary system have been digitalised and classification of laser data has been performed of, e.g., land, buildings, road, water, and vegetation. In Rail View, multiple asset types have been digitalised. When digitalisation of objects are done, Artificial Intelligence (AI) can be used to automatize many analyses, e.g., identification of risk trees, vegetation in the track area, estimation of line of sight, volume of ballast, volume of vegetation, and tilted or missing objects (e.g., fasteners, sleepers, and poles). Additional benefits with AI in combination with machine measurement are increased objectivity compared to manual inspection. The digital twin can also be used to predict the future condition of the asset (e.g. degradation of items) or its surroundings (e.g. when individual trees becomes a risk) based on different scenarios. However, this prediction requires consecutive measurement occasions. [6] [7]

Hence, the frequency of measurement related to Rail View and Sky View becomes central. Based on the study, the recommendation is to update Rail View twice a year, once in the fall (after defoliation) and once in the spring (after snow melting and before leaves budding). Besides the conditions for performing measurements, it is good to have a view of the asset after winter and summer respectively. In the spring, it becomes possible to judge if there are any damages in the infrastructure due to winter actions by comparing with the autumn images. In the autumn, it is possible to evaluate some of the work performed during summer by comparing with the images from spring. Regarding Sky View, the measurement for update could be carried out every other year, for example to harmonize with the catenary system maintenance carried out every second year.

The application of commercial system platforms facilitates integration of different systems. For example, the platform for Rail View, Orbit 3DM Publisher, has been successfully integrated with asset management systems, such as IBM Maximo, by other infrastructure managers. Sky View is also provided to users in Trafikverket and externally by an agreement, which gives access to DPM 3D Inspection through “My page” at Trafikverket’s web page (see Figure 8). It is necessary to review specifications when purchasing mobile data collection if the purpose is inspection instead of projecting. Mainly with regard to high-resolution data of the track, both so that the outside and inside of the rail are visible. As well as ensuring that the visibility is good in panoramic images both forward and backward, to avoid that the image is covered by the locomotive in one direction and that there is backlight in the other. [6]

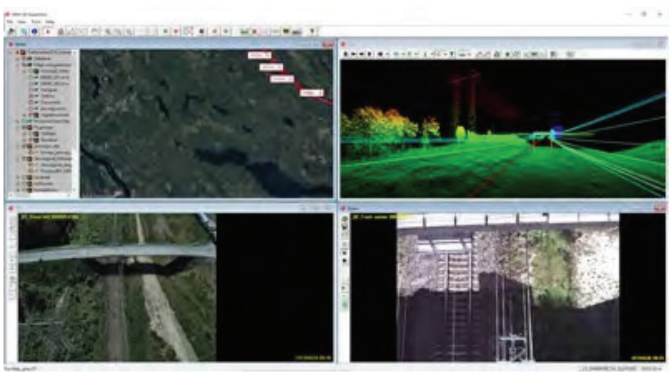

Figure 8. Example of interface to digital twin of the Iron ore line based on "Sky View". Upper left corner - town photo with distance and km-marking, upper right corner - laser point clouds with digitized catenary system, lower left corner - overview photo, lower right corner - detailed photo. From [2]

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As indicated above, due to requirements on image quality, collection of data for Rail View and Sky View is performed during nice conditions. Existing collection approaches (e.g. traditional measurement wagons) and applications (e.g. projecting instead of inspection) have lower requirements and hence lower quality.

There are many similarities between Rail View and Sky View. However, there are also some differences. One obvious difference is the perspective. Rail View provides the perspective of a train driver, while Sky View provides the perspective of a pilot. Hence, they provide complementary perspectives on the infrastructure and its surroundings. Sky View enables a wider view of the infrastructure’s surroundings and the possibility to view assets from above (e.g. roofs on buildings, top of poles, wirings and cables). Another difference is that collection of data for Rail View requires time in track, while Sky View does not. Other differences of the present applications depends mainly on the sensors installed on the measurement vehicles, which in turn depend on the present use and related requirements. The functionality of Rail View is mainly based on requirements related to projecting, with some additional functionality for inspection purposes. The functionality of Sky View is optimised for inspection of non-linear power infrastructure (e.g., high resolution and overview cameras, identification of warm objects by infrared camera and dead or dry trees by near-infrared camera). However, if inspection of railway infrastructure is becoming a common practice, sensors and functionality will be adapted for both Rail View and Sky View.

Inspection by use of Rail View and Sky View can currently be seen as a complement to ordinary manual inspection activities, where it can be used to plan and optimize existing resources. Furthermore, where it is possible to apply automation, an increased objectivity and an opportunity to register remarks at an earlier stage are achieved without increasing the effort. However, one limitation with Rail View and Sky View is that it is not possible to perform inspections points that include functional tests where the inspector, for example, should feel that screws and bolts are tightened. On the other hand, you can get an indication of a risk for inspection remarks, which is not captured by the statistics, e.g., by an indication of a loose fastener if there are, e.g., large cracks in a sleeper, the base plate is oblique, or the bolt is tilted.

When working with digitalisation of railway asset management it is possible to use different models to support implementation. One way is to relate different levels of analysis to the model of organisational learning and its three loops of learning , see [8]. One first level of analysis may be seen as related to “doing things the right way” (efficiency), or “following the rules” (single-loop learning). Hence, independent of what kind of maintenance that is applied (i.e., corrective, preventive or improvement), it can be enhanced by the use of digitalisation. However, the development is performed within single boxes of Figure 9. This practice might be exemplified with the comprehensive work related to Rail View, where the new technology was evaluated with regard to each inspection point (about 600 in total) in the existing regulation (see [6]). Even though new technology is used to enhance the maintenance, the regulation itself is not questioned to any large extent. Here it is worth noticing, that even though the focus is on the application of AI within condition-based maintenance, digitalisation can be applied to increase the efficiency also of corrective maintenance (see Figure 9).

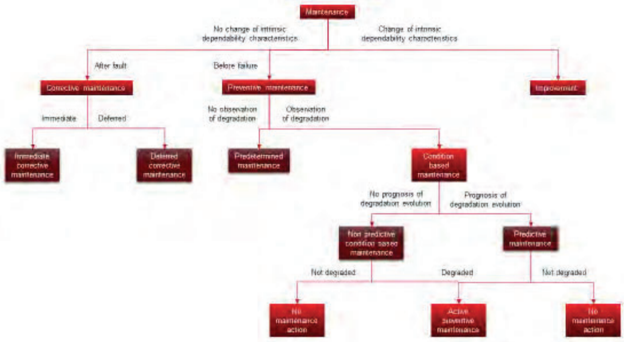

Figure 9. Different types of maintenance. Inspired by EN 13306:2017 (Maintenance – Maintenance terminology).

Another level of analysis may be seen as related to "doing the right things" (effectiveness), or "changing the rules" (double-loop learning). Here, the regulation itself is questioned and an analysis may be performed to evaluate new technologies and change the current practice. In this way, it is possible to achieve a more dynamic, or "living", regulation. One example of this is to apply an infrared camera to inspect the function of heating systems in S&C (i.e. obtain a certain temperature in the S&C to melt snow and ice), instead of using snow or water to indicate the temperature in combination with measuring the resistance in cables powering the heating elements (see, e.g., Granström et al., 2019). On this level of analysis, it is also possible to change between different types of maintenance (i.e., which box to select in Figure 9), where digitalisation often tends to be used as a means to strive towards predictive maintenance. This may be due to new technologies that makes monitoring (cf. Figure 1) and analysis more accessible to detect degradation or faults that earlier were hidden or performed manually (cf., first level of analysis). However, as mentioned earlier, digitalisation can be used to improve any type of maintenance (see Figure 9).

A third level of analysis is to reflect upon the methodology used to decide upon which the right things are (i.e., how to select the right box of Figure 9) by a systematic use of best practise, historical data and expert judgement. This level of analysis might be related to "learning about learning" (triple-loop learning). Examples of this third level is to apply Failure, Modes, Effects & Criticality Analysis (FMECA) or Reliability-Centred Maintenance (RCM) in combination with barrier-analysis to achieve a more dynamic maintenance regulation, see, e.g. [9] and [10] respectively. Design of Experiments (DoE) is another useful methodology to evaluate what the right things to do are. See, e.g., [11] for a description of DoE and [12] and [13] for applications within a railway context. As mentioned earlier, corrective maintenance might be the right (effective) choice and digitalisation might be one way to make it more efficient.

On a more aggregated level, the third level of analysis may be illustrated by the "Four-step principle", which is an approach that Trafikverket applies to identify the most efficient and sustainable solutions in the transport system (cf. the dependability standard SS-EN 441 05 05 – Dependability terminology, and its description of relationship between stakeholder requirements, operation, maintenance, and modification). The first step is to rethink, e.g., if it is possible to transport things in a different way, or to use another mode of transport (cf. stakeholder requirements). If the rethinking does not result in any valuable solution, the next step is to see if it is possible to make more effective use of existing infrastructure (cf. operation and maintenance). For example, if it is possible to control the traffic or adjust the installations that currently control the traffic. In the third step, it is evaluated if it is possible to resolve the issue by making some minor alterations, e.g., add a track, redesign a level crossing (cf. maintenance and modification). It is not until the fourth and final step that the most expensive solution is considered, i.e., carrying out a major rebuild or extension, or investing in new infrastructure (cf. modification).

The performed study and related experiences indicate that the technology is available and develops very fast. However, to support an implementation it is necessary to at least consider the related regulations, but also organisation and roles. The regulations may be considered on any of the described three levels of analysis. However, only providing a technical solution without relating it to user needs and linked regulations is only one of the very first steps towards an implementation. The supplier should many times take a larger responsibility to provide mature user-centred solutions instead of requiring the user to adapt technical solutions with low or no integration in practice. The three levels of analysis related to digitalisation of asset management can be compared to the four business requirements that all Swedish authorities should fulfil; see SFS (2007:515) at [1]. Hence, digitalisation initiatives related to asset management should fulfil the following requirements:

- objectives that are aligned with and support the mission (effectiveness, i.e., to do the right things);
- operations with an efficient use of resources (efficiency, i.e., to do things the right way);
- reliable operational and financial reporting (i.e., the data and information included in the technical solution, e.g. Rail View and Sky View, but also the management of a more dynamic maintenance regulation through the use of FMECA, RCM and barrier analysis);
- compliance with applicable laws and regulations (e.g., the maintenance regulations as part of the safety management system).

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