VALIDATIONS CROSS ANALYSIS & PRACTICE DEVELOPMENT

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Project full title: Development of a Smart Framework Based on Knowledge to Support Infrastructure Maintenance Decisions in Railway Corridors
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Executive Summary

The final task in WP6 will perform an evaluation of the overall effectiveness of the validation processes as a whole. With the results from this analysis evaluation and initial development of validation practices will be performed and documented to be utilized in later efforts within the railway sector. Also some chapters with the lessons learnt is displayed, in order to help to future projects in the same domain.
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## Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>IM</td>
<td>Infrastructure Manager</td>
</tr>
<tr>
<td>CMMS</td>
<td>Computerised Maintenance Management System</td>
</tr>
<tr>
<td>RAMS</td>
<td>Reliability, Availability, Maintainability and Safety</td>
</tr>
<tr>
<td>ICT</td>
<td>Information and Communication Technologies</td>
</tr>
<tr>
<td>RCM</td>
<td>Reliability Centred Maintenance</td>
</tr>
<tr>
<td>RUL</td>
<td>Remaining Useful Life</td>
</tr>
<tr>
<td>LCC</td>
<td>Life Cycle Cost</td>
</tr>
<tr>
<td>MDSS</td>
<td>Maintenance Decision Support System</td>
</tr>
<tr>
<td>TRV</td>
<td>Trafikverket</td>
</tr>
<tr>
<td>GPR</td>
<td>Ground Penetrating Radar</td>
</tr>
<tr>
<td>DSS</td>
<td>Decision Support System</td>
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1. EVALUATION OF THE OVERALL EFFECTIVENESS OF THE VALIDATION PROCESSES AS A WHOLE.

The concept of Living Labs was described in D6.1. This creative concept was introduced to the research community as a possible research methodology for testing, validating, and realising product and service prototypes and redefining complex solutions in a real environment undergoing continuous evolution. OPTIRAIL has considered the Living Lab from the beginning of the project when the work was first described. It has been showed the success of the pilot tests and provides feedback from the end users of the case studies to suggests further improvements of the developed tool.

Living Labs extend the previous concept of innovation to incorporate the end user at all stages of design and validation. The Living Labs used in OPTIRAIL introduced services and platforms, diverse users and a variety of interfaces and communication protocols. In the validation of the developed tool in the pilot tests in Sweden and Spain, the Living Lab methodology became the central point of the process.
1.1 THE ROLES OF SWEDEN AND SPAIN CASES IN OPTIRAIL LIVING LAB APPROACH

The Living Lab has been the centre point and methodology for the validation. The Living Lab method has helped ADIF and Trafikverket deploy the prototype and evaluate their services and other aspects.

The components of a Living Lab are ICT and infrastructure, management partners and users, research and approach. At the centre is innovation.

- **ICT & Infrastructure**: ICT technology can facilitate new ways of cooperating and co-creating new innovations among stakeholders. In this regard, existing maintenance systems will be integrated for data collection with the OPTIRAIL tool.
- **Management**: This includes ownership, organisation, and policy aspects. A Living Lab can be managed by, for example, consultants, companies or researchers. In the case of OPTIRAIL, the IMs will deploy the software supported by the researchers and companies to get useful feedback.
- **Partners & Users**: Each brings a specific wealth of knowledge and expertise to the collective, helping to achieve boundary spanning knowledge transfer.
Research: This represents the collective learning and reflection that take place in the Living Lab. In addition, technological research partners can provide direct access to research that can benefit the outcome of a technological innovation. In OPTIRAIL, as in many cases in maintenance research, the main issue has been to combine real scenarios with academic innovation, since real life needs and R&D do not always run parallel.

Approach: Methods and techniques for Living Lab practices which are necessary for professional and successful Living Lab operations.

Any Living Lab should have access to multi-contextual environments, as well as high-end technology and infrastructure that can support the processes of user involvement and technology development and tests.

A Living Lab needs organisation and methodologies suitable for its specific circumstances. These circumstances were a concern, as European railways and maintenance practices are entirely different across countries with a tremendous lack of harmonisation. Therefore, the multi Living Lab approach was selected, with several Living Labs running simultaneously and two case studies (Sweden and Spain).
Finally, a Living Lab needs access to a diversity of expertise in terms of the partners who contribute to the activities. Equally important are the key principles of the approaches applied in Living Lab activities.

Sweden and Spain have been selected to deploy the OPTIRAIL tool. They are different in terms of characteristics of the track, context (weather conditions, use of the track, age etc.), as explained in previous deliverables, for example, 1.1 and 1.3. They also use different maintenance management systems.

1.1.1 SWEDEN MALMBANAN LULEÅ – NARVICK

The Iron Ore Line (Malmbanan) in northern Sweden starts in Luleå and ends in Narvik, Norway. Both passenger and freight trains use the Line. The freight traffic consists primarily of heavy haul trains with axle loads of 22.5 tonnes and more. Running heavy-haul railway traffic in a mountainous area north of the Arctic Circle is a challenging task. The trains operate in harsh climate conditions, including snow in the winter and extreme temperatures ranging from -45ºC to +25 ºC. There are many tight curves along the track that experience high wear.

Today the Line transports iron-ore with an axle-load of 30 tonnes at speeds of 60 km/h.

Weather and climate
Sweden experiences temperatures below freezing most years. In the southern parts, it might only be for a few days. In the north, it is usually below zero for up to seven months of the year.
Operating trains

Malmbanan mostly has heavy-haul trains from LKAB mining company. These trains consist of two IORE locomotives with 68 wagons; the trains are 750 metres long and have a total weight of 8,500 tonnes. But Malmbanan also has passenger, freight, steel-slab and copper-ore trains. The freight trains consist of lighter wagons up to 18 tonnes of axle load, the copper-ore trains have an axle-load of 22.5 tonnes, and the steel-slab trains have an axle-load of 25 tonnes.

Train speeds vary from 50-60 km/h for loaded iron ore trains, to 60-70 km/h for unloaded ones and 80-135 km/h for passenger trains.

1.1.2 SPAIN: THE MEDITERRANEAN CORRIDOR

The Mediterranean Corridor (MEDCORR) is a rail line connecting the South of Spain (Algeciras/Seville) to the eastern French border through Valencia and Barcelona (Figure ).

This is one of the major transport routes of the Iberian Peninsula, connecting four Spanish autonomous communities: Andalusía, Región de Murcia, Comunidad Valenciana and Cataluña. Economic links are particularly robust, especially between Comunidad Valenciana and Cataluña, which together represent almost 30% of the Spanish Gross Domestic Product (GDP), a share that has remained fairly constant since the 1990s.
The location of the MEDCORR, stretching from western to eastern Spain and crossing some of its most highly populated and developed regions, makes it an important multimodal axis to connect Spain to the rest of Europe through the Pyrenees and the world via the numerous ports. Algeciras and Valencia are two of the most competitive ports for Western Mediterranean traffic.

For the purpose of this case study, the unit of analysis is not the MEDCORR as a whole (almost 1,500 km), but the section line between Oropesa and Vandellós (100 km).
FIGURE 5. CURRENT STATE OF MEDCORR RAIL INFRASTRUCTURE IN THE REGIONS OF CATALUÑA AND COMUNIDAD VALENCIANA.
At the moment, the MEDCORR line is focused on providing services for passengers, particularly short and medium-distance; freight traffic represents a minor share (discussed in the following section). Besides tourists, passengers include commuting students and workers.
1.2 FULFILLMENT OF LIVING LAB KEY PRINCIPLES IN OPTIRAIL

In Living Lab activities, five key principles should guide all operations:

- Value
- Influence
- Sustainability
- Openness
- Realism

These key principles provide the foundation for the design of Living Lab operations. They also define what counts as a Living Lab and determine how the value of Living Lab operations can be assessed.

1.2.1 KEY PRINCIPLE: VALUE

Living Lab processes have created value for OPTIRAIL partners in terms of business value. It is not the purpose of this deliverable, but the OPTIRAIL open platform may be suitable for expansion to other IMs and maintenance actions, resulting in a much more ambitious software with a high dissemination level.
To determine the benefit or value for the presumed customer or user of the developed innovation in terms of user value, it has been performed a benchmarking process. This principle is aligned with current interpretations of maintenance as having value rather than the traditional approach which defines maintenance as a cost centre. Research centres and companies (especially transportation assets) now realise the value created by the maintenance function has a strategic role in achieving company goals.

As stated in previous deliverables along WP6, the tool is evaluated based on benchmarking analysis. To determine item categories, we will use the “Likert” scale. Each statement is followed by an estimate scale (rating scale) comprising a graduation from "strongly agree" to "strongly disagree" and including intermediate grades. It should be noted that while Turnstone’s scale asks subjects to respond to only those items they consider relevant, in a Likert-type scale, subjects must express their opinion on all items.

**TABLE 1. THE ESTIMATE SCALE INCLUDES A NUMERICAL VALUE ASSIGNED TO EACH GRADUAL INTERVAL.**

<table>
<thead>
<tr>
<th>Score</th>
<th>Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Strongly disagree</td>
</tr>
<tr>
<td>1</td>
<td>Disagree</td>
</tr>
<tr>
<td>2</td>
<td>Indifferent, indifferent or neutral</td>
</tr>
<tr>
<td>3</td>
<td>Agree</td>
</tr>
<tr>
<td>4</td>
<td>Totally Agree</td>
</tr>
</tbody>
</table>

Each item is scored according to the formula shown in the following table.

**TABLE 2. LIKERT SCALE EVALUATIONS DEPENDING ON THE SCORE.**

<table>
<thead>
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<th>Score</th>
<th>Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>An optimal situation: 100 % of the time the activity is performed as defined in the question.</td>
</tr>
<tr>
<td>3</td>
<td>A good situation but with caveats: most of the time the activity is done as defined in the question but sometimes is not – either voluntarily or</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Score</th>
<th>Assessment</th>
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<tr>
<td>4</td>
<td>An optimal situation: 100 % of the time the activity is performed as defined in the question.</td>
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<td>3</td>
<td>A good situation but with caveats: most of the time the activity is done as defined in the question but sometimes is not – either voluntarily or</td>
</tr>
</tbody>
</table>
Can maintenance employees get initial training in OPTIRAIL MDSS?

<table>
<thead>
<tr>
<th>Likert scale rating</th>
<th>Number of responses per rating</th>
<th>% rating</th>
</tr>
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<tbody>
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<td>6</td>
<td>17.1</td>
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<tr>
<td>1</td>
<td>1</td>
<td>2.9</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>17.1</td>
</tr>
<tr>
<td>3</td>
<td>13</td>
<td>37.1</td>
</tr>
<tr>
<td>4</td>
<td>9</td>
<td>25.7</td>
</tr>
</tbody>
</table>

The information provided with the software has evidently been satisfactory for most people. Videos and installation guides have been greatly appreciated. The tool does not require long training, and the attached information is sufficient, as the language and terminology are the same as those used in the daily maintenance work.
Is there an ongoing OPTIRAIL MDSS training program for maintenance employees?

<table>
<thead>
<tr>
<th>Likert scale rating</th>
<th>Number of responses per rating</th>
<th>% rating</th>
</tr>
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<tbody>
<tr>
<td>0</td>
<td>7</td>
<td>20.6</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>14.7</td>
</tr>
<tr>
<td>3</td>
<td>18</td>
<td>52.9</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>11.8</td>
</tr>
</tbody>
</table>

Most of the users had a short training session or read the documents and watched the videos in order to use the tool. The existence of this short training session was helpful to identify the right niche of the tool. Those who did not take the training found it more difficult to assess it.

In railway maintenance, business value is an intangible term that includes all forms of value coming from the maintenance function. The value of maintenance has not been always clear and for many years was considered a necessary evil that should be minimised in terms of cost, with no thought of it as possibly adding value. Although maintenance value is now a quantified reality, it is seldom transferred to IT tools. In addition, even though the value of maintenance in terms of cost reduction and asset utilisation is clear to most researchers and asset managers, certain sectors still lag behind. Therefore, the value of our approach is quantified in terms of cost and KPIs; users appreciate this.
Are the labour, parts and vendor support costs related to the work order charged and accounted for in an asset history file?

<table>
<thead>
<tr>
<th>Likert scale rating</th>
<th>Number of responses</th>
<th>% rating</th>
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<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>2.9</td>
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<tr>
<td>2</td>
<td>13</td>
<td>38.2</td>
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<td>3</td>
<td>20</td>
<td>58.8</td>
</tr>
<tr>
<td>4</td>
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</table>

Users definitely appreciate the cost estimation. It gives them a rough idea of expenditures, even though they may change slightly. The combination of a tool assessing degradation with planning and cost estimation is appreciated by most maintenance workers.
Are deferred maintenance and repairs identified during the budgeting process?

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<th>% rating</th>
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<tbody>
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<td>0</td>
<td>1</td>
<td>2.9</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>26</td>
<td>76.5</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>20.6</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0</td>
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</tbody>
</table>

Deferred maintenance is the worst enemy of OPTIRAIL deployment. The tool does not consider opportunistic maintenance performed for the convenience of the different stakeholders, i.e. deferred maintenance. This less than ideal situation makes predictions consistent but different.
1.2.2 KEY PRINCIPLE: INFLUENCE

Maintenance is a heterogeneous domain with users, asset manufacturers and contractors constituting a complex triangle supervised by strong regulations in some sectors, such as transportation.

IMs must have an influence on innovation and development processes. This means utilising the creative power of Living Lab partners in OPTIRAIL by facilitating their right to influence innovations. These partners include both IMs and regulators. In fact, regulators and the market have a strong presence in the railway transportation sector, something OPTIRAIL has respected throughout – from the conceptual phase to the pilot phase.

The influence of IMs and regulators has been successfully transferred to the tool considering the constraints and regulations of the railway across Europe along with the uniqueness of the various IMs.

Are hierarchies of systems/subsystems used for equipment/asset numbering in the database?

<table>
<thead>
<tr>
<th>Likert scale rating</th>
<th>Number of responses per rating</th>
<th>% rating</th>
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</thead>
<tbody>
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<td>0</td>
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<td>0</td>
</tr>
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<td>1</td>
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<td>0</td>
<td>0</td>
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<td>0</td>
</tr>
<tr>
<td>4</td>
<td>34</td>
<td>100</td>
</tr>
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</table>
All users agree that information segregated by hierarchies is included and works well for tailored predictions. Different components of the track like sleepers, fastnings, and type of ballast are included, and visualisation and decisions are classified according to the different asset levels.

As the above figure shows, taxonomies and ontologies of railway administrators are understood and successfully integrated in the platform.

In addition, OPTIRAIL has analysed other transportation sectors and linear assets to assess the adaptability and transferability of successful technologies in other domains to the railway. It has deployed RUL estimation of other types of assets, both linear and conventional, and new prognosis techniques from disparate sectors where information has different granularity and nature.

Responses to the question below show the successful integration of prognosis capabilities in the tool as requested by the IMs.

Does OPTIRAIL MDSS provide MTBF, MTTR, failure trends and other reliability data?

<table>
<thead>
<tr>
<th>Likert scale rating</th>
<th>Number of responses per rating</th>
<th>% rating</th>
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<tbody>
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<td>0</td>
</tr>
<tr>
<td>1</td>
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<td>2</td>
<td>4</td>
<td>11.8</td>
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<td>8.8</td>
</tr>
<tr>
<td>4</td>
<td>27</td>
<td>79.4</td>
</tr>
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</table>
All users agree with the reliability capabilities of the OPTIRAIL tool in terms of RUL estimation and predicting degradation and time to failure. RAMS capabilities, especially reliability capabilities, are greatly appreciated by the respondents. New capabilities for maintainability and availability should be explored, however.

### 1.2.3 KEY PRINCIPLE: SUSTAINABILITY

Sustainable transportation is a key factor of European development and a central component on the European agenda. Railways are becoming more dominant in the economy, as freight traffic crosses borders and connects people from west to east and south to north. This expansion means the impact of transportation on the environment is an increasingly important issue.

Creating a sustainable environment includes economical, ecological and social aspects, making it a complex and multi-faceted task. Maintenance is a relative newcomer to sustainability issues. It has been neglected for many years as a residual activity, but many authors now recognise the importance of maintenance on the environment and safety.

Bad maintenance practices may increase a company’s KPIs but degrade the environment. Operational practices that maximise an asset’s ROI but ignore the consequences are no longer accepted, however. Recently approved standards like ISO 55000 claim sustainability as a key value in asset management. This principle is new but is important now and in the future. Maintenance will play a key role, as long lasting infrastructure have less impact than new ones constructed every ten or twenty years, increasing emissions and waste.

The OPTIRAIL tool pays attention to maintenance performance by tracking downtime information, a main point for sustainability, as downtime implies aggressive maintenance intervention and a waste of resources, including energy. As indicated below, OPTIRAIL successfully integrates information from downtime as KPIs.
Is downtime (equipment/asset availability) due to maintenance measured and documented?

<table>
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<th>% rating</th>
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<td>35.3</td>
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<tr>
<td>4</td>
<td>15</td>
<td>44.1</td>
</tr>
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</table>

Users agree downtime can eventually be used to predict maintenance actions. This may be of interest to availability predictions based on track possession time for tamping, but the lack of connectivity with OFELIA and other systems makes this downtime visualisation very limited.

OPTIRAIL attempts to achieve optimum maintenance by using new technologies to maximise capacity and meet other goals of IMs whilst minimising the impact of aggressive maintenance actions on the environment. In this regard and to fulfil ISO 55000 principles of continuous improvement, maintenance must track KPIs and keep a record of the changes. Unfortunately, this is missing in the OPTIRAIL tool as a stand-alone option, as seen below, but has connectivity to other railway applications.
Are maintenance service levels measured and documented and have improvements occurred?

Unfortunately, most users note a lack of control over the quality of the tamping or other maintenance actions. TFV and other IMs need to integrate contractor information if most of the work is outsourced and there is a real need of control.

### Likert scale rating

<table>
<thead>
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<th>per</th>
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</table>

1.2.4 KEY PRINCIPLE: OPENNESS

In the present European railway scenario, in order to cooperate in a multi-stakeholder milieu, different levels of openness are required between stakeholders because information will flow in different way from some actors to others. Although the regulators must be open in all aspects, the companies or end users may limit the information flowing to protect certain economic interests, for example, the reliability or safety aspects of equipment, RUL (Remaining Useful Life), LCC (Life Cycle Cost), etc.
As the term suggests, the openness principle emphasises creating an innovation process that is as open as possible with the stakeholders. To move forward in the maintenance area, especially in the railway, sharing information is a MUST. At the same time, this is a concern for companies who perceive it as a threat to their business.

In the OPTIRAIL Living Lab, railway stakeholders can meet to support commercialisation and to bring maintenance products and services to market. This openness respects the economic interests of the actors and supports the needs of all by sharing information. The OPTIRAIL tool is data driven, with strong input from a number of different IMs. Information is shared by stakeholders in different domains and also by stakeholders in the same domain.

The e-maintenance cloud acts as a data repository, allowing data to be shared and providing security for stakeholders. For the OPTIRAIL e-maintenance cloud, we first defined a data integration architecture, specifying the interaction of services within the architecture. The resulting Service Oriented Architecture (SOA) aims to enhance the agility, efficiency and productivity of an enterprise’s system. SOA is implemented using web services, particularly WCF (Windows Communication Foundation). Because WCF can communicate using web service standards, interoperability is straightforward with other platforms that also support SOAP (Simple Object Access Protocol). Therefore, interoperability is gained through a set of XML-based open standards, such as WSDL (Web Services Description Language), SOAP, and UDDI (Universal Description, Discovery and Integration). These standards provide a common approach for defining, publishing, and using web services.

The software services comprising the e-maintenance cloud as described above will run on virtualised hardware, provided for the project by LTU for validation by end users. The underlying physical hardware and virtualisation technology can be selected or changed as needed but should support Microsoft Windows as a guest system.
For the client systems used by end users, the goal is to provide platform-independent access to the e-maintenance cloud using browsers and dynamic web content and avoiding the need for special client software. Target systems and hardware capable of rendering modern, dynamic web content range from desktop systems running Windows, Mac OS, Linux or other operating systems to smartphones and tablets based on Android or iOS.

In general, the ambition of the OPTIRAIL tool was to be open, easily connected to other platforms to leverage knowledge from existing data sources through simple connections and eventually being scaled up to include other functionalities.
As an open platform, OPTIRAIL has avoided proprietary systems requiring tailored gateways and costly deployment. The goal is to avoid architectures like those shown below.

Multiple perspectives bring power to the development process, so the OPTIRAIL project has emphasised a process that is as open as possible with the various railway stakeholders. Through openness, we are able to gather and use a multitude of perspectives to develop an innovative and attractive tool. In summary, sharing knowledge and data is crucial to the OPTIRAIL Living Lab and the developed OPTIRAIL tool.
1.2.5 KEY PRINCIPLE: REALISM

The goal of realism needs to be addressed on different levels and for different elements, including contexts, users, use situations, technologies, and partners. This principle does not distinguish between physical and online contexts. Rather, activities carried out in both contexts are real and realistic. Inspired by online reality, we argue that IT based tools and methodologies can function as twin-world mediators (Attasiriluk et al., 2009) to facilitate the interconnection between real-world devices and their virtual counterparts.

Living Labs take two approaches to realistic use situations. In the first approach, environments for testing and evaluating products or services are created in ways that are similar to the real world. To this end, OPTIRAIL takes real data from real case scenarios for training and validation to give realism to the tool.

Second, different stakeholders face different realities. What is important for one stakeholder is not necessarily important for another. For this purpose, to test the OPTIRAIL tool, there has been selected two main scenarios, Sweden and Spain. The tool is designed to provide realism from both perspectives.

Note that we accommodated the possible differences in realities across situations, by involving end railway users and other stakeholders in the development process rather than relying on representative theories.

1.3 THE LIVING LAB METHODOLOGY AND ITS DEPLOYMENT IN OPTIRAIL

1.3.1 EVALUATING THE TOOL: FIRST ITERATION

The Living Lab has guided the whole project and comprises many iterations, cycles and phases. Now on the final stage before commercialisation, the focus has been on encouraging users to express their thoughts about the concepts being developed. Does the developed tool meet their needs?

Concept evaluations should be iterated until the concepts answer relevant user needs and no new insights about user needs can be identified. The aim is to identify how the concepts should be related and refined to answer to the needs identified in previous inquiries. In what follows, we describe one
of the iterations to demonstrate how the needs of the users were met. We also note the potential work to be done, i.e., what the tool may require in later versions.

The Benchmarking System for IT maintenance tools is a universal benchmarking methodology. It provides the framework for an improvement process for better use of a company’s information technology for maintenance. This benchmarking tool was developed for a number of reasons:

1. To evaluate the effectiveness of the current MDSS.
2. To define functional gap.
3. To define how to enhance present use.
4. To upgrade functional gaps.
5. To serve as a methodology to develop and justify a replacement strategy.

Generally speaking, a benchmarking system is a means to evaluate the effective use of maintenance applications to define functional gaps and suggest how to enhance current use. Effective benchmarking should start with a total evaluation of current maintenance practices and procedures and lead to the development of a plan for improvement. A benchmarking system will also help to develop and justify a replacement strategy if necessary. It is adaptable and should be specifically tailored to the existing software and its intended application.

The OPTIRAIL tool is an internal benchmarking monitor. Internal benchmarking starts locally within the maintenance operation at the shop floor. It focuses on measuring the successful execution of best practices such as preventive and predictive maintenance, maintenance planning and scheduling and effective maintenance storeroom operations. Internal benchmarking develops explicit internal metrics or performance indicators. It determines progress from an internal baseline or starting point and measures progress toward a performance goal specific to a maintenance operation. For example, an internal benchmark could be the current level of maintenance related downtime hours for a critical asset or the maintenance cost per unit of output.

The information provided by benchmarking may be fused to create composite indexes.

Internal benchmarking shows how well existing ICT tools are used to enhance maintenance best practices. In this sense, the proposed OPTIRAIL benchmarking system is an important internal benchmarking tool to help achievement maximum value from an existing MDSS or from the implementation of a new system for computerised maintenance management Peters(2006).
1.3.2 USABILITY EVALUATION

The focus is to encourage users to express their thoughts about the OPTIRAIL tool.

Can maintenance leaders use OPTIRAIL MDSS to manage maintenance as an internal business?

<table>
<thead>
<tr>
<th>Likert scale rating</th>
<th>Number of responses per rating</th>
<th>% rating</th>
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<tbody>
<tr>
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<tr>
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<td>32.4</td>
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<tr>
<td>4</td>
<td>6</td>
<td>17.6</td>
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OPTIRAIL can be used on three levels: strategic, tactical and operational. On the tactical level, knowing the accumulated cost of maintenance actions versus the cost of degradation constitutes a huge advantage for managers seeking to convert maintenance spending into asset integrity. The question above elicits a generally positive answer about the tool’s ability to improve maintenance. In essence, the innovation is positive.
1.3.3 USER EXPERIENCE EVALUATION

Users’ experiences are primarily subjective; they can have a positive or negative, an enjoyable or a frustrating experience.

Do operations staff understand and use OPTIRAIL MDSS for better maintenance service?

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<thead>
<tr>
<th>Likert scale rating</th>
<th>Number of response per rate</th>
<th>% rating</th>
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<tbody>
<tr>
<td>0</td>
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<td>1</td>
<td>13</td>
<td>38.2</td>
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<td>2</td>
<td>5.9</td>
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OPTIRAIL degradation tools are appreciated and create expectations of better and more accurate predictions. They are less appreciated for maintenance planning because of the lack of configuration options.
1.4 OPTIRAIL: A SWEDISH AND A SPANISH LIVING LAB LEARNING IN ACTION

The OPTIRAIL research project is developing and demonstrating approaches to introducing innovations into the railway sector using two Living Labs. As mentioned, these Living Labs are in Spain and Sweden.

![Map of Europe highlighting Sweden and Spain](image_url)

**FIGURE 9. IM’S FOR THE CASE STUDIES.**

Sweden and Spain represent concrete railway real-life settings in which technology prototypes have been developed, used, observed, and refined.

Training in the use of the tool has been intensive for the end users. The information provided with the software has been satisfactory for most users. Videos and installation guides have been highly appreciated. The tool does not require long training and the attached information is sufficient since the language and terminology is same as used in the daily maintenance work.

The two research environments are complex, comprising IM managers, contractors and regulators. They sometimes interact, at times being cooperative and at other times becoming more competitive and less willing to compromise.

Each Living Lab is an open system, directly influenced by the actions of the various stakeholders. Regulators can consist of many national agencies, international agencies, institutions, associations...
etc. This complexity is especially pronounced in the railway arena, and the aim of OPTIRAIL is to develop harmonised and accepted/adopted maintenance practices and technologies in a sector where the regulators and companies have traditionally been local stakeholders.

1.4.1 THE ISSUES OF CROSS BORDER RESEARCH

This project has developed a conceptual design for the next generation of decision support tools to manage and coordinate cross-border railway infrastructure maintenance operations. The completion of the project deliverables will allow the railway industry to take concrete steps in replicating the integration of the new tool with lower risk and fewer warranty issues. The Living Labs employ both qualitative and quantitative research.

By providing industry and researchers tools (open code) to work with, we are contributing to the appearance of new players with innovative ideas that could be used by the main railway companies and operators, looking for new ideas and opportunities to improve without major investments or risks.

Dissemination activities related to this project will help policy-makers become aware of the needs of the transportation market.

At the same time, the project management will consider other parallel R&D projects dealing with complementary issues, at European and national levels, to avoid overlapping efforts and to take full advantage of synergies between projects.

1.4.2 OPTIRAIL: A CASE STUDY & USABILITY TESTING SELECTION

Usability testing to capture the opinions of users measures how well people can use the products or services for their intended purpose. The main characteristic of this selected method in the OPTIRAIL context is that it focuses on a particular object or small set of objects, whereas general human-computer interaction studies attempt to formulate universal principles.

Why use benchmarking? What does not get measured, does not get managed. Therefore, benchmarking should be used to measure what is to be managed. Benchmarking is required for better management of a facility’s return on its assets. In most cases, the higher the quality of the
maintenance, the greater the return. To optimise a facility’s return on its assets, it is useful to compare that facility’s numbers to the rest of the industry through benchmarking. If any problem areas exist, benchmarking can detect them, and these problem areas can be eliminated or minimised.

The MDSS benchmarking system was developed to support getting maximum value from an investment in MDSS by evaluating how well existing MDSS functionality is being used. The benchmarking system provides a methodology for developing an overall benchmark rating of the MDSS implementation as the baseline for determining how well MDSS is supporting best practices within the total maintenance operation. It can also be used as the baseline to measure the success of a future MDSS utilisation.

Effective resource management and reliable equipment are essential to optimise railway performance. Both depend up on accurate timely management of massive amounts of data and on the effective use of maintenance resources. Maintenance Decision Support System (MDSS), is designed to fulfil these needs. The system can provide a cost-effective way to manage a massive amount of data generated by maintenance. In addition, the system can provide the means to manage effectively both human and capital resources in railway.

The MDSS benchmarking system is introduced as a means to validate the effective and efficient deployment and use of the OPTIRAIL MDSS implementation to define functional gaps and enhance current use. Its results measure the level of services and practices; it develops its own unique benchmarking criteria with high standards for maintenance excellence, always in a qualitative way.

Effective benchmarking should start locally with a total evaluation of existing maintenance practices and procedures and lead to the development of ways to improve. It is a challenge to isolate the validation of the OPTIRAIL tool, making this process independent from assessing the excellence of the ongoing maintenance practices.

The MDSS benchmarking system is adaptable and should be specifically tailored to the existing MDSS and its intended application. This will provide a unique opportunity to benchmark the goodness of OPTIRAIL with other tools using the same validation methodology.
Living Labs represents a research methodology for sensing, validating and refining complex solutions in multiple and evolving real-life contexts. Innovations such as new services, products or application enhancements, are validated in empirical environments within specific regional contexts. In this case, Optirail will provide a new product in a mature market with the expectation of going beyond the regular products the companies already offer. The focus is on the customers, in this case, two different railway administrators (TRV and ADIF). This focus requires an emphasis on interface designs and ergonomics; users are part of the design process to ensure user acceptance. The result will be the creation of a service or product.

Value is captured on an individual level and on an organisational level through a close analysis of emerging value distribution and changes of existing value chains. Site-specific features are identified when the applications are transferred across borders into diverse contexts and cultures. The participation not only of the potential customers but of all other stakeholders along the value-chain is a necessary element of a Living Lab. According to [Niitamo et al. 2006] a Living Lab needs to bring access to state-of-the art technology, not simply one kind but often competing technologies delivered through different business models.

The core advantage of the Living Lab concept over traditional user-centric methodologies is its multi-contextual sphere in which product and service development and evaluation take place. The ability to interact with users distinguishes the Living Lab approach from other supplier-customer partnerships or previous cross-disciplinary approaches. Users are incorporated at the end of classical field trials to test final products. In contrast, users are involved in all stages of R&D and all stages of the product development life cycle in the Living Lab approach.

The validation of OPTIRAIL tool by benchmarking is qualitative. In the first stage, we examine the respondent’s point of view on MDSS implementation. The aim is to create awareness in the research community of MDSS and its different activities. Its emphasis on the effective use of scientific knowledge and its level of abstraction guide researchers in the development of new maintenance technologies.

For the validation process among railway stakeholders, a structured interview is carried out using a well-designed questionnaire. This will give answers to the research questions and shed more light on the topic. The empirical study gathers information about the MDSS implementation and initiatives.
For the usability test, the aim is to observe people using the developed product in as realistic situation as possible (pilot cases in Spain and Sweden) to discover errors and areas of improvement.

Usability testing involves a controlled experiment to determine how well people can use the product, as well as watching people trying to use something for its intended purpose i.e. the usability of OPTIRAIL product in the two pilot sites. Intensive training was provided to enable this type of testing.

The most commonly used technique to gather data during a usability test is a Think-aloud protocol; it measures responses from users in four areas: time, accuracy, recall, and emotional response.

1. Time on Task determines how long takes people to complete basic tasks and OPTIRAIL product should be able to speed up maintenance decision making process by the means of data fusion and data mining techniques used for that purpose. In question below, one can see that time to complete tasks is not recorded and must be incorporated in further versions of the tool and evaluated again in later iterations

Has performance been measured against estimated repair times and have improvements occurred?

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<thead>
<tr>
<th>Likert scale rating</th>
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<tbody>
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<td>88.2</td>
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<tr>
<td>1</td>
<td>4</td>
<td>11.8</td>
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</table>
Users agree that performance of the maintainers is not measured and not visualised in the tool. Unfortunately, there is no chance to check how long a maintenance action takes; therefore, track possession time is critical for IMs.

2. Accuracy counts the total number of mistakes people make; the new tool should increase accuracy as decisions relying on multiple data sources may be more trustworthy and reliable. Reliability improvements through better maintenance decisions have been validated and crossed checked as seen in the question below.

Are failure and repair codes used to track trends for reliability improvement?

<table>
<thead>
<tr>
<th>Likert scale rating</th>
<th>Number of responses per rating</th>
<th>% rating</th>
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<tbody>
<tr>
<td>0</td>
<td>1</td>
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<tr>
<td>1</td>
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<td>26.5</td>
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<td>38.2</td>
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<td>4</td>
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</table>
Most users agree on this point. As the degradation model is based on databases, standards, catalogue of failures etc., the user can monitor the track status and forecast its future state. The visualisation of reliability improvement after maintenance actions and the recovery of the track quality is a plus for the OPTIRAIL tool versus existing ones.
1.5 OPTIRAIL ADAPTION OF LIVING LAB METHODOLOGY

The method designed for the OPTIRAIL project, ‘OPTIRAIL adoption of Living Lab,’ is based on the established Living Lab methodology, FormIT. The results of the questionnaires are gathered and analysed, based on the above mentioned methodologies, and are set into an eight step pyramid.

Step 1. Planning the pilot.

ADIF (Administrador de Infraestructuras Ferroviarias) is a Spanish state-owned company under the responsibility of the Ministry of Public Works and Transport, charged with the management of most of Spain’s railway infrastructure, that is the track, signalling and stations. It was formed in 2005 in response to European Union requirements to separate infrastructure management from train services.

ADIF is responsible for administrating rail infrastructures (tracks, stations, freight terminals, etc.), managing rail traffic distributing capacity to rail operators, and collecting fees for infrastructure, station and freight terminal use.

The Swedish Transport Administration (Trafikverket) is a government agency in Sweden. It is responsible for long-term infrastructure planning for all kinds of transport: road, rail, shipping and aviation. It owns, constructs, operates and maintains all state-owned roads and railways and operates a large number of ferry services.

Step 2. Generating and understanding users’ needs.

OPTIRAIL will contribute to higher levels of safety and service in railway infrastructures, ‘optimal’ life cycle for the management of railway infrastructure maintenance, better quality of service, higher level of client satisfaction, and improved availability of the railway infrastructure. OPTIRAIL will ensure more effective planning of the management and activities of infrastructure maintenance.
based on expert knowledge accumulated over years of experience and on information stored in the monitoring and maintenance management systems.

Step 3. Concept design.

All collected data are clustered in different ways and viewed from different perspectives to construct concepts representing users’ needs.

Trafikverket (TRV) is using the systems shown in the table below for maintenance inspection systems used in case studies.

<table>
<thead>
<tr>
<th>System</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basun</td>
<td>Traffic information system. One application is the registration of faults in the railway track.</td>
</tr>
<tr>
<td>BESSY</td>
<td>Program used for registration of safety and maintenance inspections in track with the possibility of using a PDA (Personal Digital Assistant) or a mobile phone (TRV 2011c).</td>
</tr>
<tr>
<td>BIS</td>
<td>Railway engineering assets register. Every time an asset is changed in some way, it has to be registered in BIS, e.g. component replacements.</td>
</tr>
<tr>
<td>Duvan</td>
<td>A tool for maintenance analysis. It is possible to search for reports with data assembled from Ofelia, BESSY, BIS and train delays.</td>
</tr>
<tr>
<td>LUPP</td>
<td>The successor to Duvan, it has the old functions of Duvan, plus some additional ones, such as searching for data on train delays and the reasons for the delays (TRV 2011h).</td>
</tr>
</tbody>
</table>
**Step 4. Concept evaluation and pre-trial evaluation.**

Evaluations ensure that a sound understanding of users occurs throughout the whole development process.

The OPTIRAIL project has developed a comprehensive tool, based on Fuzzy and Computational Intelligent techniques, to manage some elements crucial for track maintenance, predicting future conservation needs. It allows a better understanding of complex infrastructure behaviour; as a consequence, it extends the lifecycle and durability of networks and reduces the environmental impact. Furthermore, the ability to integrate the tool into existing commercial platforms and pilot tests ensures it will meet all the requirements of the rail sector.

**Step 5. Final design.**

This ensures that the gained knowledge from earlier stages is considered in the final design.

The final design is implemented

The OPTIRAIL research project develops and demonstrates approaches to introducing innovations in the railway sector and its multiple stakeholders, including infrastructure managers, operators, constructors, maintenance contractors and transport authorities. At the core of the OPTIRAIL research agenda is the design of information infrastructures encompassing document standards, systems interoperability, process modelling and network redesign for maintenance optimisation purposes.

The EU’s vision for railway innovation provides the empirical context for the OPTIRAIL research project. The developed methodology aims to transform a broad range of maintenance practices in different European regions. OPTIRAIL started this process in defined regions with limited resources but with the goal of continued development through self-sustaining momentum beyond the funding period. The project started collecting data from only a few European countries, but during the execution, Poland and UK joined as contributors, increasing the chances of success.
The contributors have been involved in the stages previous to the prototyping. The outcome of these Living Labs will be deployed in two of the contributors: Spain and Sweden.

![Map of Europe highlighting Spain and Sweden](image)

**FIGURE 10. IM’S FOR THE CASE STUDIES.**

**Step 7 and Step 8. Pilot evaluation and Cross pilot evaluation.**

These stages represent the evaluation of the whole pilot and between the pilots respectively.

![Diagram of appreciation opportunities and case definition planning the pilot](image)

To learn about the user experience and acceptance of the OPTIRAIL tool, the pilots collected quantitative and qualitative feedback from users during the test phases and cycles by deploying the methods shown in the table below.
Each method was selected to elicit a particular kind of data and enabled a full end-to-end analysis of the pilot services. All pilots used questionnaires, interviews and demonstrations. Questionnaires allowed us to gather quantitative feedback from a large number of end users about their experience and acceptance. They also provided more qualitative feedback by means of open questions where testers could express the negative aspects, positive aspects and recommendations for design purposes. In the evaluation phase, interviews and focus groups allowed a deeper understanding of meaningful themes, practices and relationships from the interviewee’s point of view.

The findings will be circulated among different potential users from TRV.
2. PROGRESS BEYOND STATE OF THE ART

2.1 REVIEW OF PREVIOUS RESEARCH IN THE SAME DOMAIN

In 1987, Committee D161 of ORE (Office for Research and Experiments) conducted a comprehensive study of track geometry degradation based on historical data; it concluded that with the exception of certain sections with high deterioration rates, track quality deteriorates linearly with tonnage or time between maintenance operations after the first initial settlement (Esveld, 2001). However, a more recent study has revealed that the track quality deteriorates exponentially (Veit, 2003).

Some researchers have examined the effect of speed and axle loads on track deterioration. Earlier studies concluded the speed of the train has a significant effect on track geometry deterioration (Kearsley and Vanas, 1993; Ferreira and Muray, 1997). More recently, Sadeghi and Askarinejad (2007) have noted the influence of axle load, speed, rail type, subgrade condition, rail pad stiffness and sleeper spacing on the average growth of track irregularities. Sato (1997) proposed a degradation model in which degradation depends on tonnage, speed, types of rail connection (jointed or continuously welded) and quality of the subgrade. Bing and Gross (1983) presented a model to predict how the track quality, measured in terms of track quality indices (TQIs), changes as a function of causal parameters, such as traffic, track type and maintenance. Nurmikolu (2013) identified factors affecting the performance of track substructures subjected to cold climates. Finally, Audley and Andrews (2013) analysed the effects of tamping on track geometry degradation.

The European project INNOTRACK (2008) has specified the key parameters for monitoring turnouts using the FMECA (Failure Mode Effects and Criticality Analysis) method. It has also advocated the optimisation of turnouts by optimising the geometry and track stiffness (INNOTRACK, 2010).

Some researchers have examined the dynamic interaction between the train and the turnout to simulate wear, rolling contact fatigue (RCF) and plastic deformation in turnout components (Nicklisch et al., 2010; Kasa and Johansson, 2006). Others have evaluated the effects of the switch
angle and frog angle on the wear rate. For instance, Elkins et al. (1989) concluded wear at the switch could be reduced by decreasing the switch entry angle.

In addition, several attempts have been made to optimise track geometry maintenance in terms of planning and cost efficiency. Markow (1985) applied a demand-responsive approach to the life cycle costing method, creating a model to estimate the total costs for different maintenance alternatives. Chrismer and Selig (1993) combined a mechanistic method of timing ballast maintenance with an economic model to identify the life cycle cost of different maintenance methods. Higgins (1998) proposed a model to determine the best allocation of maintenance activities and crews to minimise maintenance costs whilst keeping the track condition at an acceptable level. By using track geometry historical data, Miwa et al. (2000) developed a degradation model and a restoration model and applied these models within a mathematical programming model to determine an optimal maintenance schedule for a multiple tie tamper. Jovanovic and Esveld (2001) presented ECOTRACK, an objective condition-based decision support system developed by ERRI’s D 187 Committee and 24 European railways between 1991 and 1998. The aim of this system is to provide solutions to the problems of restoring track at the required quality level with minimum cost and resolving a trade-off between maintenance and renewal. Zhao et al. (2006) developed a life cycle model to optimise ballast tamping and renewal. Their model incorporates the track deterioration model proposed by Riessberger (2001), and the tamping model. It uses three algorithms to obtain the optimal tamping and renewal strategy for three policies of fixed intervention level, constant interval of tamping and optimal non-constant intervals of tamping. Vale et al. (2010) developed a model for scheduling tamping on ballasted tracks by considering the track degradation, the track layout, the dependency of track quality improvement on the quality of track at the time of maintenance operation and the track quality limits that depend on train speed. Larsson- Kråik (2012) used cost benefit risk analysis to evaluate future maintenance and reinvestment activities which lead to risk reduction of avalanches and wet slush flow. Finally, Famurewa et al. (2013) proposed a methodology to optimise tamping scheduling by minimising the total maintenance cost.

In the optimisation of track geometry inspection, more attention has been paid to optimising the inspection procedure by correlating geometry irregularities to dynamic responses at wheel-rail interface. Given the inability of track standards to account for the performance of different vehicle types or deal with combinations of track geometry perturbations, in the last few years, operating railroads have shifted their focus to performance-based track geometry (PBTG) (Liu
and Magel, 2009). Li et al. (2009) noted that current standards and assessment methods do not consider dynamic responses at the wheel-rail interface and may not be adequate for track maintenance and train speed setting; they proposed a dynamic model to assess vertical track geometry quality based on simulation of dynamic track-vehicle interaction. More recently, Silvast et al. (2013) studied the use of integrated track geometry data and ground penetrating radar (GPR) data analysis to locate problem sections and identify the root causes of faults.

Advances in the optimisation of track geometry inspection intervals remain limited. An exception is Lyngby et al. (2008) who studied the optimisation of track geometry inspection intervals on the Norwegian railway network and showed that by optimising inspection intervals, about 20000 NOK (Norwegian Krone) per year could be saved on a specific track.
2.2 LESSONS LEARNT IN OPTIRAIL PROJECT.

Track geometry is an important aspect of railway construction (Esveld, 2001) for the following reasons, as indicated by Jovanovic (2004):

- The degradation of many other track components is closely related to the track geometry condition;
- Track geometry is often used to trigger the entire range of track maintenance and renewals.

Track with good inherent quality provides a good ride and needs little maintenance; conversely, track with poor inherent quality results in poor ride comfort and requires much maintenance (Selig and Waters, 1994). For example, Karttunen et al. (2012) show the influence of lateral geometry irregularities on the mechanical deterioration of freight tracks.

Track maintenance consists of inspections and interventions (Lyngby et al, 2008). Inspections are carried out to ensure track safety by monitoring track condition and obtaining the information necessary to set up maintenance scheduling. Inspections are manual or automated using a vehicle. Intervention refers to preventive and corrective maintenance, as well as renewal actions carried out to improve track quality.

In the past, railway maintenance procedures were usually planned based on the knowledge and experience of the infrastructure owner. The main goal was to provide a high level of safety, and there was little concern for economic issues (Lyngby et al,2008; Carretero et al, 2003). Today, however, the competitive environment and budget limitations are forcing railway infrastructures to optimise operation and maintenance procedures. The primary goal is to reduce the operation and maintenance expenditures whilst still assuring high safety standards (Lyngby et al., 2008; Carretero et al., 2003).

Optimising maintenance requires estimating track degradation and the consequence of this degradation, often in the form of cost (Lyngby et al., 2008). Obtaining knowledge about degradation helps a company estimate the right time for inspection, maintenance and renewal.

Track geometry degradation is a complex phenomenon affected by dynamic loads (Esveld, 2001). The rate of degradation is a function of time and/or usage intensity (Lyngby et al., 2008). According to Lichtberger (2001), the initial track quality, the initial settlement and the
deterioration rate are the major parameters of track quality deterioration. The monitoring and evaluation of track geometry allow the infrastructure administration to control safety and plan track maintenance (Berggren et al., 2008).
3. THE ADDED VALUE OF OPTIRAIL TOOL

The railway setting changes rapidly. Since the 1980s, many countries have introduced market forces; North America and Japan led the way in the 1970s and 1980s, and the EU followed suit in the 1990s. The European model separates infrastructure departments from other departments; in many countries, this transition is still in progress. The new infrastructure managers (IMs) are being given an entirely new responsibility: transport operators and governments increasingly ask them to deliver specified performance levels in terms of infrastructure availability and reliability. At the same time, they have to negotiate such input factors such as government funding; performance-based costing regimes, or ‘performance payment regimes’, may ultimately result from these changes.

Effective and efficient maintenance management, like that proposed in OPTIRAIL, is essential to ensure a competitive and attractive transport system. Furthermore, with the increasing focus on sustainability, the railway sector is being called upon to ensure a green transportation process. Maintenance issues are central to sustainability, as good maintenance ensures lower energy consumption, lower resource consumption, less noise and less pollution than other modes of transport.

The new IMs have to deal with a number of obstacles to meet expectations. First, despite much research, not all infrastructure deterioration processes are well enough understood to ‘translate’ them into quantitative relationships between investment and maintenance decisions and infrastructural quality effects; this might result in longer-term effects being underestimated.

Second, the long-term capital-intensive nature of rail infrastructure conflicts with the preference of many governments and shareholders for short payback periods on investments and fast performance improvements. Decisions have a high degree of irreversibility. And the consequences of bad decisions (e.g. low construction qualities or insufficient preventive maintenance) must be dealt with for a long time.

Third, although the IM should be the actor who considers long-term effects, many factors in the organisational structure urge him/her not to do so; e.g., historic organisational and institutional boundaries, such as allocated budgets, standard operating procedures, established relations with other actors, and regulations.
These obstacles have prompted IMs to review, among other things, present maintenance practices, information systems and tools.

The maintenance concept is the centrepiece in a proactive approach to asset maintenance. It defines the appropriate tasks and activities in relation to the importance of particular assets (i.e. criticality of failures). It steers the maintenance planning process and must be updated regularly on the basis of new information.

ICT and computerised maintenance management systems (CMMSs) can support the practical use of such maintenance concepts on complex, linear assets such as railway networks because components in different railway assets, such as track segments, are economically and structurally interdependent. Scale effects are involved in their maintenance and renewal, and their degradation is often structurally related. Moreover, because operations have to continue on the rail network during maintenance and because budgets are often restricted, all kinds of constraints must be considered in the planning of infrastructure maintenance.

Because rail infrastructure components, particularly tracks, are expensive and have a long life span, cost effectiveness of design and maintenance decisions over the long term should be explored. Life Cycle Costing (LCC), an engineering economics technique, can lead to design and maintenance strategies with minimised life cycle costs, whilst meeting functional specifications (e.g. required capacity and reliability of the system). LCC can be defined as ‘an economic assessment of an item, system, or facility and competing designing alternatives considering all significant costs over the economic life.’

With LCC, design and maintenance options can be tested on the total costs of ownership and operation, including the additional costs or revenues lost due to failures or planned maintenance. Decision options to be considered should, however, comply with the minimal functional requirements, e.g., design speeds, axle-loads and curve radii.

An early example of a decision support system for LCC is the North American TRACS, which estimates track maintenance and renewal costs as a function of route geometry, track components, track condition and traffic mix.
In Europe, some efforts have been made to use railway CMMSs and decision support systems (DSSs). In 1991, the UIC started a research project; in 1997, the project delivered a rule-based expert system, named EcoTrack, which should enable IMs to plan M&R on the basis of well-defined technical and financial rules; see Zaalberg (1998).

The lack of empirical data may be a reason why CMMS research and implementation are not yet widespread. Relatively more attention has been given to the development of DSS for Life Cycle Costing. OPTIRAIL aims to integrate degradation models and decision support systems, thereby bridging the traditional gap. The optimisation of LCC through proper maintenance decisions based on accurate degradation predictions is a key aspect of the OPTIRAIL tool; according to end users, it is a unique maintenance DSS. Other condition monitoring tools and degradation models have not been scaled up to include maintenance DSS by integrating specific maintenance tasks like tamping.

Researchers from a range of European countries recently reported the development of tools for LCC aspects for their national IMs. Several of these tools try to use statistical analysis on the basis of historic MBR work lags, and most attempt to include, in more or less detail, estimates of the costs of traffic disruptions caused by the infrastructure. OPTIRAIL is a rara avis in the sense that it successfully combines a degradation model with maintenance decisions in a unique mixture of RAMS parameters and LCC optimisation. Traffic is not considered but could be in the near future by integrating OPTIRAIL track possession with the deployed TMS.

The EU has prioritised this area and has initiated many projects directly or indirectly related to the maintenance of the railway system. With the wide application of ICT (Information and Communication Technologies) in maintenance, it has been easier to manage different stakeholder requirements and also make optimal decisions. The application of ICT offers many opportunities to implement e-maintenance solutions in the context of the rail industry. e-maintenance also facilitates the creation of maintenance databases that allow more accurate information on repair costs and the costs of preventive maintenance and facilitate the development of a Life Cycle Costing approach to rail infrastructure. OPTIRAIL has integrated data from disparate sources and of differing nature by understanding the existing taxonomies and ontologies. However, a seamless integration of harvested data remains a future project.

Outcomes from several of R&D Framework projects related to the railway have provided the high speed market with a set of specifications that allow better inter-changeability of key components for
maintenance and a higher level of standardisation at the interfaces of the main train subsystems. This was achieved by identifying the main interfaces subject to possible standardisation and drafting the related standards. The concept of modularity aims to create economic advantages for both railway suppliers and operators, including reduced manufacturing cost and economies of scale, increased productivity of new rolling stock, and increased reliability based on an increase in the proportion of service-proven components used in new rolling stock designs.

Despite the desire to achieve better decision making, the maintenance management process at the ‘work floor’ level of the infrastructure manager remains in an early phase. A significant problem is that information is still mainly collected for the purpose of accountancy (labour hours and budgets), not for maintenance management and engineering. Therefore, the estimation of life-cycle impacts of design and maintenance decisions is often difficult. Moreover, current asset information systems are frequently based on inaccessible, unreliable or incomplete data systems.

We cautiously conclude that railway maintenance is slowly moving from a ‘craftsmanship’ phase, in which maintainers follow historic, rigid work instructions and (subjective) experience, to an ‘engineering’ phase, in which quantitative assessments play a key role. Projects like OPTIRAIL are proof of this evolution. Yet much R&D remains to be done, and there are many obstacles. For example, there is a need for maintenance optimisation tools that will facilitate cross-border coordination of railway infrastructure maintenance activities. European Standard 50126, which prescribes the testing, commissioning, monitoring and auditing of railway systems and maintenance services, could serve as an important vehicle for this research journey.
4. REFERENCES

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