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# Innovative Monitoring and Predictive Maintenance Solutions on Lightweight Wagon

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## DELIVERABLE D5.2

## INTEGRATION OF CARGO MONITORING AND PREDICTIVE MAINTENANCE SOLUTIONS ON THE LIGHTWEIGHT WAGON CONCEPT

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| Prepared by: | Lukas Hejzlar (VUZ) |
| Contributors: | Cristian Ulianov, Paul Hyde, Petr Voltr (UNEW)<br>Mihai Marin-Perianu (INE)<br>David Vincent (PER)<br>Stefano Bruni, Adalberto Polenghi (POLIM)<br>Dachuan Shi (TUB) |
| Verified by: | Cristian Ulianov, Paul Hyde (UNEW) |

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## The INNOWAG project consortium

| No | Partner organisation | Short Name | Country |
|---|---|---|---|
| 1 | NEWCASTLE UNIVERSITY | UNEW | UK |
| 2 | INERTIA TECHNOLOGY B.V | INE | Netherlands |
| 3 | HAVELLANDISCHE EISENBAHN AKTIENGESELLSCHAFT | HVLE | Germany |
| 4 | LUCCHINI RS SPA | LRS | Italy |
| 5 | NEW OPERA AISBL | NEWO | Belgium |
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| 7 | POLITECNICO DI MILANO | POLIM | Italy |
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| 9 | UNION DES INDUSTRIES FERROVIAIRES EUROPEENNES | UNIFE | Belgium |
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| 11 | VYZKUMNY USTAV ZELEZNICNI | VUZ | Czech Republic |

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# 1 Table of Contents

# *Executive Summary*

The overall aim of the INNOWAG project was to develop intelligent cargo monitoring and predictive maintenance solutions integrated on a novel concept of lightweight wagon. This was intended to respond to major challenges in relation to rail freight competitiveness, specifically the increase of transport capacity and logistic capability, improving RAMS, and lowering LCC.

This document presents in its first section a brief description of methodology that was used for assessing the integration issues.

Chapter 2 gives a more detailed description of the methodology, including the structure of the matrix for evaluation of issues related to integration and of how data was gathered from the partners and processed.

Chapter 3 - Integration of innovative solutions - is divided into four sections dealing with the most significant aspects that have been identified through the methodology described in Chapter 2, i.e.:

- Relevance of *condition monitoring systems for lightweight freight wagon structures*, which includes elements from WS1 and WS3 with respect to WS2;
- Relevance of *health assessment of lightweight freight wagon structures* which includes elements from WS3 with respect to WS2, e.g., diagnosis and prognosis solutions;
- Relevance of *reliability and LCC modelling of lightweight freight wagons* that includes "Reliability analysis and LCC model" from WS3 with respect to all relevant topics from WS2; this includes issues related to dealing with reliability of structures that have not been traditionally used in railway industry and the use of LCC assessment to support novel design solutions;
- Relevance of *integration of on-board monitoring and communication solutions* that includes elements from WS1 with respect to WS3.

It should be mentioned that the assessment process showed that some items that are of high interest in relation to their implementation are not necessarily relevant when considering difficult problems of integration presented by this project.

The final Chapter 4 draws conclusions and summarises the essential recommendations for further work that would be required to address the identified critical integration issues.

## List of abbreviations

| | |
|---|---|
| EN | European Norm |
| ERA | European Union Agency for Railways |
| ERTMS | European Rail Traffic Management System |
| GNSS | Global Navigation Satellite System |
| GSM-R | Global System for Mobile Communications – Railway |
| HSS | High Strength Steel |
| LCC | Life Cycle Cost |
| LTE | Long Term Evolution |
| PHM | Proportional Hazards Model |
| RAMS | Reliability, Availability, Maintainability and Safety |
| RFID | Radio Frequency Identification |
| TRL | Technology readiness levels |
| TSI | Technical Specification for Interoperability |
| TSI WAG | TSI relating to the subsystem ‘rolling stock — freight wagons’ |
| UHF | Ultra-High Frequency |
| WLAN | Wireless Local Area Network |
| WS | Work Stream |

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# 1 INTRODUCTION

This innovative wagon development project has generated outputs in highly complementary areas of freight wagon design, reflecting the need for diverse and strategic improvements in performance to improve competitiveness of rail freight. During the project, development of the Work Streams (WS) has occurred independently. The purpose of this deliverable is to consider the opportunities and challenges of integration offered by these innovative technical developments.

This deliverable investigates the potential for integration of WS1, WS2 and WS3 outcomes into a single intelligent wagon concept, both from a technical point of view (with respect to certification issues, further homologation, conformity with standards, etc.) and from an opportunity point of view (the features of one Work Stream enhancing the benefits of another), highlighting the difficulties involved in making further progress. The first step is to identify the critical aspects related to the integration of innovations with respect to both technical challenges and regulatory restrictions. The task will further propose a set of recommendations for further integration of the innovative solutions, considering both technical issues and regulatory aspects in relation with the certification of the novel solutions, interoperability, etc.

In order to make conclusions regarding the integrated solutions that will lead to valid recommendations, this deliverable proceeds first with an evaluation of the relevance of the INNOWAG innovations with respect to criteria relating to their integration through assessment matrices. The multi-criteria methodology that was used for assessing the integration issues used evaluation matrices for this scope; further, based on results of the matrices, the integration issues with highest relevance are further analysed and discussed.

# 2 ASSESSMENT OF INTEGRATION OF INNOWAG INNOVATIONS

## 2.1 Assessment Approach and Method

The activities in the project INNOWAG were divided into three Work Streams, dedicated to cargo condition monitoring, wagon design and predictive maintenance.

In each Work Stream, a number of innovative solutions were developed. The relationships among the innovations within each Work Stream were clear, but integration of innovations from different Work Streams was not discussed continuously. Hence, a specific task dealing with integration of all solutions was set up in the final Work Package 5.

Some innovations of the INNOWAG project were quite independent of each other. There were others where additional benefits – or additional technical problems – would be expected if implementing them at the same time. To fulfil the task of *integration of innovative solutions on lightweight wagon concept* and produce a consistent conclusion to the INNOWAG project, assessment of the complex potential relationships between the individual innovations is necessary.

The most relevant innovations and/or technical solutions in each Work Stream were selected for assessment. These are as follows:

- **WS1 – Cargo condition monitoring innovations & challenges**:
    - Energy harvester on carbody
    - Energy harvester below the primary suspension
    - RFID applications
    - Onboard data communication solutions
    - Data communication to central server and processing
- **WS2 – Wagon design innovations & challenges**:
    - Implementation of HSS in the bogie structure
    - Implementation of HSS in the carbody structure
    - Implementation of composite materials in the carbody structure
    - HSS welds
    - Hybrid joints (steel-composite)
    - Non-standard wagon dimensions and/or tare
- **WS3 – Predictive maintenance**:
    - Condition monitoring systems (sensors)
    - Models and algorithms for wagon health assessment
    - PHM-based tool for prognostics assessment
    - Reliability analysis and LCC model

Each of these innovations and/or technical solutions was matched with all others from the other Work Streams, and the potential relationship between each pair was evaluated. First, a quantitative approach (scoring system) was used to identify the most relevant combinations – this approach is further described in sections 2.2 to 2.4. Then, qualitative evaluation of the most important issues was carried out, along with discussion and recommendations relating to the critical integration aspects – this is presented in section 3.

## 2.2 Assessment tool

A multi-criteria method for assessing the critical integration aspects has been developed; the method uses qualitative criteria that have been proposed and defined, which are further assessed through quantitative indicators. The quantitative assessment tool has the form of three matrices:

a) Relevance of WS 1 with respect to WS 2;

b) Relevance of WS 2 with respect to WS 3;

c) Relevance of WS 1 with respect to WS 3.

An example of an empty matrix (table) is given in Figure 1.

| | | WS1 Cargo Condition Monitoring Innovations & Challenges | | | | |
|---|---|---|---|---|---|---|
| | | Energy harvester on carbody | Energy harvester below the primary suspension | RFID applications | Onboard data communication solutions | Data communication to central server and processing |
| WS3 Predictive Maintenance | Condition Monitoring systems (sensors) | | | | | |
| | Models and algorithms for wagon health assessment | | | | | |
| | PHM-based tool for prognostics assessment | | | | | |
| | Reliability analysis and LCC model | | | | | |

| | |
|---|---|
| A | B |
| C | D |
| total | |

Figure 1 Example empty assessment matrix

At the intersection of each row and column, there is a group of four cells for assessing four different aspects of integration:

A – Relevance of WS *X* innovation to WS *Y* one (and vice versa);

B – Technical issues/barriers relating to the integration of the WS *X* and WS *Y* innovations;

C – Standardisation/homologation issues relating to the integration of the WS *X* and WS *Y* innovations;

D – Compatibility & interoperability issues relating to the integration of the WS *X* and WS *Y* innovations.

Each cell would be populated with a quantitative indicator, in the range from 0 to 3 with the following meaning:

0 – The issue relating to the cell (A, B, C or D) is irrelevant (or N/A) to the integration of the WS *X* and WS *Y* innovations;

1 – The issue relating to the cell (A, B, C or D) is low-relevant to the integration of the WS *X* and WS *Y* innovations;

2 – The issue relating to the cell (A, B, C or D) is medium-relevant to the integration of the WS *X* and WS *Y* innovations;

3 – The issue relating to the cell (A, B, C or D) is high-relevant to the integration of the WS *X* and WS *Y* innovations.

The fifth cell below each group contains the total score, which is a sum of the four values and can therefore range from 0 to 12. Higher score means higher relevance; it does not express the nature of this relationship (what criterion), but allows identification of the issues that are most relevant for further discussion. In this context, where the integration of two outcomes is selected as relevant for further integration it reflects the combination of an innovation that is both relevant to delivery of another innovation as well as technically challenging and therefore worthy of further discussion. Some innovations that are highly relevant to enhancing other innovations but present no challenges for further integration (if the solution is already well developed) have a low score, reflecting that little further work is required.

## 2.3 Assessment methodology

The evaluation was done independently by experts from the relevant INNOWAG partner organisations (both industry and academia/research) through the tool described in section 2.2. The inputs were averaged to produce final assessment matrices for all Work Streams. These matrices included a value in the range of 0–3 for each of the cells A, B, C, D illustrated in Figure 1, and a total value in the range of 0–12 for each combination of considered innovations.

The priorities were identified based on the total score with the following relevance grades:

| | |
|---|---|
| 0–2 | *Irrelevant* – not to be discussed further |
| 3–5 | *Low-relevant* – not to be discussed further |
| 6–8 | *Medium-relevant* – not to be discussed further |
| 6–8 | *Medium-relevant with at least one highly-relevant component* – **to be discussed further** |
| **9–12** | *Highly-relevant* – **to be discussed further** |

As a guide, the integration issues with high relevancy (score 9–12) or medium relevancy (score 6–8) were marked as priorities for further discussion in section 3.

## 2.4 Assessment results and critical integration issues

In the first matrix, relevance of **WS1** (Cargo condition monitoring innovations & challenges) solutions with respect to **WS2** (Wagon design innovations & challenges) solutions, no issue has been identified as highly relevant. In the averaged table, a few cells reached the medium-relevant score. This was somehow expected, as there is, indeed, little relationship between the cargo condition monitoring innovations of WS1 (energy harvesters, data communication etc.) and the lightweight solutions of WS2 (wagon design, materials and their joints, etc.).

It should be noted that the technologies and solutions that were developed, implemented and tested for cargo condition monitoring systems may be relevant to new wagon design and construction methods or materials, because they may be also partially employed within systems that would be necessary to monitor the physical condition of the wagon as part of the risk mitigation strategy for the implementation of new designs with novel features. Many of these monitoring systems typically present no homologation or integration challenge, therefore are not considered interesting for further (low TRL) development.

The results of the quantitative assessment are shown in the following tables (Table 1 and Table 2).

*Table 1 Assessment matrix for integration of WS1 and WS2 innovations – detail view*

| | | **WS1 Cargo Condition Monitoring Innovations & Challenges** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **MEAN VALUES** | Energy harvester on carbody | | Energy harvester below the primary suspension | | RFID applications | | Onboard data communication solutions | | Data communication to central server and | |
| **WS2 Wagon Design Innovations & Challenges** | HSS implementation in bogie structure | 0.4 | 0.7 | 1.2 | 1.0 | 0.8 | 0.9 | 0.8 | 1.2 | 0.8 | 1.2 |
| | | 0.4 | 0.5 | 0.8 | 1.1 | 0.9 | 0.9 | 1.0 | 0.8 | 1.0 | 0.8 |
| | | **1.9** | | **4.1** | | **3.6** | | **3.7** | | **3.7** | |
| | HSS implementation in carbody structure | 0.7 | 1.3 | 0.8 | 0.9 | 0.8 | 0.7 | 0.8 | 1.0 | 0.6 | 1.0 |
| | | 1.0 | 0.9 | 0.6 | 0.8 | 0.4 | 0.4 | 0.8 | 0.6 | 0.8 | 0.6 |
| | | **3.8** | | **3.0** | | **2.3** | | **3.2** | | **3.0** | |
| | Composite implementation in carbody structure | 1.3 | 1.9 | 1.0 | 0.7 | 1.8 | 1.4 | 1.2 | 1.4 | 0.6 | 1.0 |
| | | 1.3 | 1.3 | 0.5 | 0.8 | 1.4 | 1.2 | 1.0 | 0.8 | 0.8 | 0.6 |
| | | **5.7** | | **2.9** | | **5.6** | | **4.4** | | **3.0** | |
| | HSS welds | 0.5 | 0.9 | 0.7 | 1.3 | 0.3 | 0.3 | 0.6 | 1.0 | 0.6 | 1.0 |
| | | 0.6 | 0.6 | 1.0 | 0.6 | 0.3 | 0.3 | 0.8 | 0.4 | 0.8 | 0.4 |
| | | **2.5** | | **3.5** | | **1.0** | | **2.8** | | **2.8** | |
| | Hybrid joints (steel-composite) | 0.7 | 1.1 | 0.5 | 0.7 | 0.8 | 0.8 | 0.6 | 1.0 | 0.6 | 1.0 |
| | | 0.6 | 0.6 | 0.4 | 0.4 | 0.8 | 0.8 | 0.8 | 0.4 | 0.8 | 0.4 |
| | | **2.9** | | **1.9** | | **3.2** | | **2.8** | | **2.8** | |
| | Non-standard wagon dimensions and/or tare | 0.9 | 0.9 | 0.9 | 0.9 | 1.5 | 0.7 | 0.9 | 0.7 | 0.7 | 1.0 |
| | | 0.7 | 0.4 | 0.7 | 0.4 | 0.8 | 0.7 | 0.5 | 0.4 | 0.8 | 0.4 |
| | | **2.8** | | **2.8** | | **3.7** | | **2.4** | | **2.8** | |

*Table 2 Assessment matrix for integration of WS1 and WS2 innovations – summary results*

| | | **WS1 Cargo Condition Monitoring Innovations & Challenges** | | | | |
|---|---|---|---|---|---|---|
| | **MEAN VALUES** | Energy harvester on carbody | Energy harvester below the primary suspension | RFID applications | Onboard data communication solutions | Data communication to central server and processing |
| **WS2 Wagon Design Innovations & Challenges** | HSS implementation in bogie structure | 2 | 4 | 4 | 4 | 4 |
| | HSS implementation in carbody structure | 4 | 3 | 2 | 3 | 3 |
| | Composite implementation in carbody structure | 6 | 3 | 6 | 4 | 3 |
| | HSS welds | 2 | 3 | 1 | 3 | 3 |
| | Hybrid joints (steel-composite) | 3 | 2 | 3 | 3 | 3 |
| | Non-standard wagon dimensions and/or tare | 3 | 3 | 4 | 2 | 3 |

The second matrix, relevance of **WS2** (Wagon design innovations & challenges) solutions with respect to **WS3** (Predictive maintenance) solutions identified many relevant integration issues with the average summary score of 6 and higher. These are discussed in section 3. Among the assessment criteria (A, B, C, D in section 2.2), the highest scores were in A – relevance of integration of both assessed innovations. The main reason is that materials and joints that are non-traditional in wagon design will have significant impact on maintenance and reliability. Advanced monitoring (see WS1) and maintenance solutions can be expected to provide benefits in connection with novel materials with which the railway industry does not yet have extensive experience with.

The results of the quantitative assessment are shown in the following tables (Table 3 and Table 4).

*Table 3 Assessment matrix for integration of WS2 and WS3 innovations – detail view*

| | | WS3 Predictive Maintenance | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **MEAN VALUES** | Condition Monitoring systems (sensors) | | Models and algorithms for wagon health assessment | | PHM-based tool for prognostics assessment | | Reliability analysis and LCC model | |
| WS2 Wagon Design Innovations & Challenges | HSS implementation in bogie structure | 2.1 | 1.0 | 2.4 | 1.6 | 2.3 | 1.4 | 2.7 | 2.1 |
| | | 1.1 | 1.3 | 1.6 | 0.9 | 1.4 | 1.2 | 1.8 | 1.1 |
| | | **5.4** | | **6.5** | | **6.2** | | **7.7** | |
| | HSS implementation in carbody structure | 1.9 | 1.0 | 2.1 | 1.6 | 2.1 | 1.4 | 2.5 | 1.8 |
| | | 1.3 | 1.1 | 1.6 | 0.8 | 1.4 | 1.2 | 1.5 | 0.8 |
| | | **5.3** | | **6.1** | | **6.0** | | **6.5** | |
| | Composite implementation in carbody structure | 2.6 | 1.1 | 2.6 | 1.8 | 2.5 | 1.9 | 2.9 | 2.0 |
| | | 1.4 | 1.3 | 1.6 | 1.1 | 1.4 | 1.2 | 1.6 | 1.0 |
| | | **6.4** | | **7.0** | | **7.0** | | **7.4** | |
| | HSS welds | 2.8 | 1.6 | 2.9 | 2.1 | 2.7 | 2.1 | 2.9 | 2.3 |
| | | 1.5 | 1.3 | 1.8 | 1.3 | 1.7 | 1.4 | 1.6 | 1.0 |
| | | **7.1** | | **8.0** | | **7.8** | | **7.7** | |
| | Hybrid joints (steel-composite) | 2.6 | 1.6 | 2.7 | 2.3 | 2.5 | 2.3 | 2.7 | 2.4 |
| | | 1.6 | 1.5 | 1.8 | 1.1 | 1.4 | 1.2 | 1.9 | 1.1 |
| | | **7.3** | | **7.9** | | **7.4** | | **8.2** | |
| | Non-standard wagon dimensions and/or tare | 1.7 | 1.0 | 0.4 | 0.6 | 0.6 | 0.4 | 1.7 | 0.8 |
| | | 1.3 | 1.1 | 0.4 | 0.4 | 0.4 | 0.4 | 1.0 | 0.8 |
| | | **5.0** | | **1.6** | | **1.9** | | **4.2** | |

*Table 4 Assessment matrix for integration of WS2 and WS3 innovations – summary results*

| | | WS3 Predictive Maintenance | | | |
|---|---|---|---|---|---|
| | **MEAN VALUES** | Condition Monitoring systems (sensors) | Models and algorithms for wagon health assessment | PHM-based tool for prognostics assessment | Reliability analysis and LCC model |
| WS2 Wagon Design Innovations & Challenges | HSS implementation in bogie structure | 5 | 7 | 6 | 8 |
| | HSS implementation in carbody structure | 5 | 6 | 6 | 7 |
| | Composite implementation in carbody structure | 6 | 7 | 7 | 7 |
| | HSS welds | 7 | 8 | 8 | 8 |
| | Hybrid joints (steel-composite) | 7 | 8 | 7 | 8 |
| | Non-standard wagon dimensions and/or tare | 5 | 2 | 2 | 4 |

The third matrix, relevance of **WS1** (Cargo condition monitoring innovations & challenges) solutions with respect to **WS3** (Predictive maintenance) ones, identified some relevant issues. Although there are numerous synergies between technologies for monitoring the condition of cargo and those for monitoring the vehicle health (which is a prerequisite for predictive maintenance), the challenges and issues relating to their integration were not considered to be highly critical Most of these technologies are mature, therefore, their integration into commercial products is feasible. According to the guideline in section 2.3, three items were identified as relevant for further discussion. The most important was integration of condition monitoring systems (sensors) and on-board communication solutions, which is not surprising.

The results of the quantitative assessment are shown in the following tables (Table 5 and Table 6).

*Table 5 Assessment matrix for integration of WS1 and WS3 innovations – detail view*

| | | WS1 Cargo Condition Monitoring Innovations & Challenges | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **MEAN VALUES** | Energy harvester on carbody | | Energy harvester below the primary suspension | | RFID applications | | Onboard data communication solutions | | Data communication to central server and | |
| WS3 Predictive Maintenance | Condition Monitoring systems (sensors) | 2.3 | 2.1 | 2.8 | 1.6 | 2.2 | 2.1 | 3.0 | 1.9 | 2.7 | 1.6 |
| | | 1.2 | 1.3 | 1.0 | 1.2 | 1.5 | 1.5 | 2.1 | 1.9 | 1.5 | 1.9 |
| | | **6.9** | | **6.4** | | **7.3** | | **8.9** | | **7.6** | |
| | Models and algorithms for wagon health assessment | 1.9 | 1.7 | 1.7 | 1.5 | 1.1 | 1.7 | 2.1 | 1.6 | 2.1 | 1.7 |
| | | 0.6 | 0.6 | 0.6 | 0.6 | 0.9 | 1.1 | 1.2 | 1.0 | 1.2 | 1.2 |
| | | **4.7** | | **4.3** | | **4.8** | | **5.8** | | **6.1** | |
| | PHM-based tool for prognostics assessment | 1.3 | 0.8 | 1.7 | 0.7 | 1.1 | 0.8 | 1.1 | 1.1 | 1.8 | 0.9 |
| | | 0.6 | 0.6 | 0.6 | 0.6 | 0.8 | 1.3 | 1.3 | 1.0 | 1.1 | 1.3 |
| | | **3.2** | | **3.5** | | **3.9** | | **4.4** | | **5.1** | |
| | Reliability analysis and LCC model | 1.7 | 0.9 | 1.7 | 0.9 | 1.1 | 0.8 | 1.9 | 1.1 | 1.9 | 0.9 |
| | | 0.6 | 0.6 | 0.6 | 0.7 | 0.9 | 0.7 | 1.1 | 1.1 | 1.1 | 1.0 |
| | | **3.7** | | **3.8** | | **3.4** | | **5.2** | | **4.8** | |

*Table 6 Assessment matrix for integration of WS1 and WS3 innovations – summary results*

| | | WS1 Cargo Condition Monitoring Innovations & Challenges | | | | |
|---|---|---|---|---|---|---|
| | **MEAN VALUES** | Energy harvester on carbody | Energy harvester below the primary suspension | RFID applications | Onboard data communication solutions | Data communication to central server and processing |
| WS3 Predictive Maintenance | Condition Monitoring systems (sensors) | 7 | 6 | 7 | 9 | 8 |
| | Models and algorithms for wagon health assessment | 5 | 4 | 5 | 6 | 6 |
| | PHM-based tool for prognostics assessment | 3 | 3 | 4 | 4 | 5 |
| | Reliability analysis and LCC model | 4 | 4 | 3 | 5 | 5 |

The most relevant integration issues that have been identified by using the assessment methodology developed for this scope, and which were summarised above, are further discussed in the following section.

# 3 INTEGRATION OF INNOVATIVE SOLUTIONS

The integration issues that were identified through the assessment carried out and presented in the previous section, have been further analysed by the INNOWAG partners.

This section presents a qualitative assessment of the most relevant aspects relating to the integration of the different INNOWAG innovations, including both comments and recommendations.

## 3.1 Condition monitoring and health assessment systems for lightweight freight wagon structures

**Relevance of RFID applications with respect to implementation of HSS in bogie/carbody structure**

Ultra-high frequency (UHF) radio frequency identification (RFID) tag antenna based sensors could be used for monitoring of structural integrity, such as monitoring cracks/strain, by attaching a patch antenna on the conductive surfaces. Therefore, UHF RFID antenna sensors could be used for monitoring of HSS structures. The deliverable D1.1 and D1.2 reviewed the applications of the passive RFID tag antenna-based sensors. RFID sensors have a dedicated antenna design for indirectly sensing. This means no additional sensors are needed and no power on the tag-side is required. They are commonly used for monitoring structure integrity, where the tags should be attached to the conductive material. The technical feasibility was experimentally studied in UNEW laboratory (Zhang et al., 2017). The proposed UHF passive RFID sensor (around 915MHz) system was able to detect the presence of a crack and differentiate between cracks of different sizes.

The challenges of this application lie in the reading distance and environmental interference. The test of the onboard RFID solution in Task 2.4 showed that the wireless communication using RFID technologies is strongly affected by the metallic environment. In that test, RFID was only used for communication, rather than sensing. In case of sensing, the measured backscattered power and phase versus frequency could vary in response to the variation of the metallic environment, potentially affecting the values measured by the sensor. To tackle this issue, new emerging materials and structures, i.e., meta-material based super-lens, dielectric resonant antennas, or cavity-back slot antennas are required. The variation of measurement results due to the environment could also be solved by calibration. In terms of the application of RFID technologies within a wireless sensor network, the difficulties could be the restricted reading distance, sourcing enough power on the wagon to energise the sensors, or arranging enough trackside readers to produce meaningful data. Another issue is the homologation of RFID technology with regard to selecting a standard communications protocol and wavelength so that all communications hubs can interrogate the sensors. However, a RFID sensor could be developed for the application of low-cost NDT inspection of vehicle structures, where a hand-held reader is used for reading and measurements (an example being shown in Figure 2).

**Relevance of implementation of composites in wagon design with respect to RFID applications and onboard data communication**

The use of composite materials in wagon design could help reduce the limitations of applying RFID technologies and other wireless communication technologies in the context of freight wagons. Metals, which most wagons are constructed from, have radio wave shielding properties, which results in radio interference in wireless communication; this is especially significant in the case of RFID technologies. On the other hand, the electrical characteristics of composite materials are anisotropic and the influence on the radiation pattern is dependent on the manufactured structure.

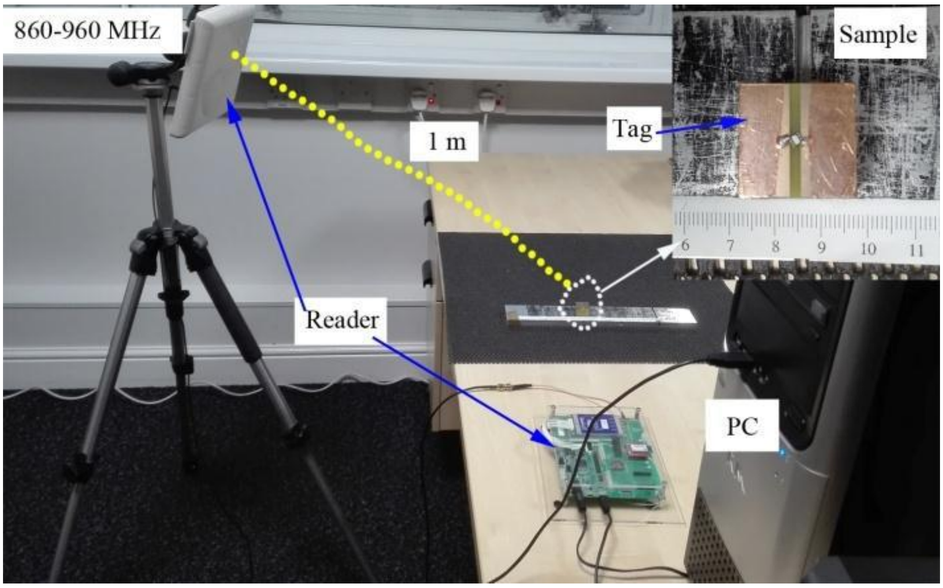


Figure 2 Test setup of the RFID sensor system for crack detection

In order to investigate how the RFID tag readability changes when tags are attached to the composite material, several experiments have been conducted by other researchers (Gorski et al. 2019). In these tests, the effect of composites containing Carbon fibres, linen fibres and fibreglass on a UHF RFID system were tested. When the RFID tag was placed behind a composite material, the tag could not be read due to the very strong radio frequency attenuation characteristic of the composite material. On the other hand, when the composite material was placed behind the tag, the reflected RF signal was strengthened due to strong RF reflection characteristic of the composite. This means that the implementation of composite materials to freight wagons could enhance the use of RFID technologies in freight wagon applications since the composite material has less of a negative effect on the performance of the RFID technologies than the metals. In the INNOWAG application of RFID technology based on trackside RFID reader, a trackside reader reads data from a tag on a passing wagon. In this scenario the RFID tags could be placed between the reader and the composite material as in the second test case described above. RFID enabled sensor tags can also be used for composite structures, and present the same challenges as RFID tags on HSS structures, except that there might be an improvement with respect to some of the issues relating to performance of the RFID technologies (such as measurement range) when the tags are applied to composite materials or in an environment where composite materials are more prevalent. Both applications present the opportunity to reduce the risk of introducing new materials into the rail environment.

**Relevance of energy harvesting with respect to implementation of advanced materials (composites and HSS)**

Where HSS and composite materials are used in freight wagon structures, those structures are intended to have the same strength as traditional structures for the same purpose. However, they can have lower stiffness, can be subject to different fatigue mechanisms, or the manufacturing methods used are less well understood than traditional manufacturing methods for freight wagon structures. An instance of this was observed in the test of torsional stiffness of the HSS bogie frame. Vibration energy harvester powered sensors mounted above and below the suspension can report on the dynamic response of the new structures, as well as reporting on the absolute levels of impact and vibration going into the structure from the wheels. This data may be used to monitor the condition of the structure and show whether vibration is inside or outside design limits for the wagon. Changes to the dynamic behaviour as a result of the vehicle being of lighter weight, particularly in unloaded condition, may also be monitored, ensuring that the vehicle design and suspension system capable of achieving safe running characteristics in all load conditions.

**Relevance of condition monitoring systems with respect to implementation of advanced materials (composites and HSS)**

Integration of WS3 methodologies for condition monitoring and WS2 innovations related to measuring parameters associated with condition are also highly relevant in terms of monitoring the health of HSS welds. It is known from past studies that the quality of HSS welds and their resistance to fatigue is highly sensitive to the welding process, and this was borne out by the results of INNOWAG. Therefore, it is extremely useful to consider the opportunities to devise methods for the structural health monitoring of welded connections in a bogie or carbody made of HSS; this could take advantage from the health monitoring methods developed in WS3. For instance, in Task 4.2 *Integration of Data and Development of Analytical Models* a method was developed for the continuous monitoring of structural integrity of railway axles. Although the method cannot be directly applied to the monitoring of HSS welds, there are parts of the monitoring hardware (sensors and data processing unit) and also part of the fault detection algorithm (in particular, the method used for detection of outliers) which could be used. Similarly, the method for monitoring the health of suspension components, also developed in Task 4.2, is based on detecting a loss of symmetry in the vibration of the bogie; this could be adapted to detect local changes in the stiffness of the bogie frame resulting from structural failure of the bogie frames, possibly due to fatigue cracks initiating at welds. In summary, vibration monitoring above and below the suspension should be sensitive to small yet significant changes to the dynamic response of the wagon that may indicate a failure of a structural element.

The challenge for integration and homologation is to ensure that a common interface is used for radio communication from the sensors and data presentation to the user is employed and to ensure that the system is sensitive enough to detect structural defect before they become safety critical. This will enable interchangeability and compatibility of communication hubs and sensor systems from different manufacturers, and ensure that results from different manufacturers are comparable.

**Relevance of PHM-based tool with respect to implementation of advanced materials (composites and HSS)**

The PHM-based tool developed in WS3 is relevant to the implementation of advanced materials, composites, HSS welds, and hybrid joints investigated in WS2 since it could be applied to better estimate the reliability of the different structural components over time. It is envisaged that the implementation of advanced materials (including specific joining techniques) in well-engineered solutions, along with efficient systems for condition and health monitoring would improve the reliability of specific structural components and sub-systems of the freight wagon. The condition monitoring systems may offer real-time, or close to real-time, data that could be elaborated by the PHM to generate the following data related to the use of advanced materials in freight wagons:

- the PHM could take advantage of the system models and structural monitoring methods developed in WS3 to precisely estimate the reliability of the structural components of the freight wagon, since they are able to better represent the health of the components;
- the real-time data could offer an always up-to-date reliability function of the components by integrating field data in the statistical model;
- the reliability function is also made more robust since there could be other variables to be integrated in the statistical model in addition to the one considered in D4.3.

The main relevance of generating this data about the freight wagon components using advanced materials is that monitoring their health and reliability and predicting their future condition reduces the risk of the implementation of novel advanced materials, increasing the acceptance of designs which use them.

In general, the balancing between corrective and preventive cost, made possible by the estimation of the reliability, offered by the PHM could significantly change the maintenance interval, and so the cost. This allows understanding the best maintenance policy to be adopted to maintain the freight wagon in service as long as possible and in a convenient economic way. In this sense, the exploitation of the PHM potentialities in correctly suggesting a certain maintenance policy, if corrective, preventive based on time, or condition monitoring, could be highly relevant to the implementation of advanced materials since it enables the optimum maintenance strategy for components made from these materials to be implemented. Finally, if the developed knowledge about the advanced materials allows the creation of mathematical models to forecast their behaviour, these models could be integrated into the PHM, which will also generate the future possible states of the system, enabling advice relating to whether immediate maintenance action is required or not.

## 3.2 Reliability and LCC modelling of lightweight freight wagons

Modelling of reliability, LCC and related issues requires knowledge of input parameters and models describing the behaviour of materials and components. For traditional materials (e.g. common structural steel), the parameters are known; statistical data from previous operation of traditional components and structures are available. For innovative solutions, it may be necessary to change the models, and it will certainly be necessary to use new parameters and values appropriate to those solutions. This can constitute a technical barrier in integration of novel design solutions with reliability & LCC models for freight wagons. Also, condition monitoring of new structures may be required as part of the risk mitigation associated with introducing new materials into freight wagon design.

The integration matrix elaborated by the INNOWAG team shows significant interrelation between the innovations in WS2 and WS3. WS2 has proposed different ways to reduce the wagon mass, using high strength steel (HSS) or composites. The use of these materials is totally new to freight wagons and hence requires that the behaviour in service of new components made of innovative materials is carefully considered for both reliability and total life cycle costs. WS3 proposed an approach for a reliability driven and cost-driven prioritisation of components in view of the potential application of condition monitoring / health monitoring concepts to different elements of the wagon's running gear. The same approach could be conveniently applied to monitor the reliability of the innovations introduced in WS2, such as the use of HSS in the bogie and/or in the carbody structure and the design of welded connections for structural parts made of HSS, and prioritise elements of the designs for the implementation of predictive maintenance. It is worth pointing out that standardisation and homologation issues are particularly relevant to the integration of new materials from WS2 and reliability / LCC analysis from WS3: the use of new materials will impact on existing standards and will require that modified or even totally new standards are issued e.g. covering design methods, testing for acceptance, fire resistance and toxicity, etc. The methods for reliability analysis can help with this process whilst the LCC calculation methods can be used to assess the economic viability of the proposed solutions.

## 3.3 Integration of on-board monitoring and communication solutions, for cargo and wagon condition monitoring

**Relevance of energy harvesting with respect to condition monitoring systems**

Energy harvesters can be used for powering sensors for the purpose of wagon condition monitoring. Energy harvesters are a key enabling technology for condition monitoring, delivering power to the sensor location when the wagon is moving without the operational difficulties of operating solely battery powered systems, or the expense of providing on-board power.  In an open market, such as freight wagon leasing, it may be necessary to define performance standards for sensor systems defining fixing methods as well as energy output.  Without such definitions to cost of maintaining monitoring systems in diverse maintenance depots across Europe may become prohibitive. The deliverable D1.1 and D2.2 reviewed different options of energy harvesting technologies and their applications for railway. The selection of energy harvesting solutions relies on the power demands and the installation position of the condition monitoring system.

**Relevance of communication solutions with respect to condition monitoring systems**

The wireless communication technologies investigated and developed for cargo condition monitoring can be used in wagon condition monitoring systems for transmitting sensor data to a gateway and forwarding to the cloud. Also, the same communication system could be used to collect and transmit data from both cargo and wagon monitoring systems, this dual purpose communication would benefit from having two types of function to justify the expenditure of implementing the system. Without adequate cross-platform communication standards (such as ITSS and ITSS2) there will be no interoperability between sensors mounted on bogies and communication gateways mounted on wagon bodies. This will hinder implementation by increasing the diversity of equipment required. Extensions to the communication standard may be required to include wagon condition in addition to cargo condition.

In a cargo condition monitoring system, the data is mostly sampled at very low frequency. For instance, the temperature, humidity and pressure can be measured every fifteen minutes. The generated data volume is small so that all raw data can be wireless transmitted to the cloud. In a wagon condition monitoring system, the measurement data could be in waveform, such as vibration data and acoustic emission, which requires a high-frequency sampling. The generated data volume is much larger than that in a cargo condition monitoring system. It is a challenge for the communication system. In the industrial area, the standard solution is to collect all raw data wirelessly through WLAN or 4G. However, it could be hardly achieved in railway freight operation. The track lines on which freight wagons are operated are usually not covered by 4G networks. As shown in the deliverable D1.1, the standard solution of Train-to-Ground communication for railway vehicles is 2G network. The capability of 2G network does not allow the transmission of all raw data obtained by a wagon condition monitoring system. The following questions should be considered when a wagon condition monitoring is designed: Is it worth collecting all the raw data? Can the raw data be first processed on-board and only the relevant extracted features sent to the cloud, at a much lower frequency, similar to the cargo condition data? What data should be wirelessly remotely transmitted? Are there any operational solutions for data communication? (For instance, raw data could be wireless collected through short range wireless technologies, when the vehicle stops at a station or depot.)

Nevertheless, a good design of the communication system can help collect as much as possible data obtained by a condition monitoring system. If more real-world data is collected, it makes it possible to continuously improve the condition monitoring system and the corresponding algorithms for diagnosis and prognosis.

**Relevance of condition monitoring models and algorithms with respect to communication and energy harvesting**

Wagon condition monitoring has different requirements related to data quality, data rates and data processing in comparison with cargo condition monitoring, which results in different requirements on power supply and data communication. This should be noted when energy harvesting and wireless communication systems intended for cargo condition monitoring are adapted for wagon condition monitoring. Different clients may require different diagnostic values. Data ownership, data processing costs, data communication standards must all be defined in the homologation and compliance process in order for the implementation of the innovation to be viable and successful.

For instance, as mentioned above, the current 2G network does not allow collecting raw data obtained by a vibration condition monitoring. In this case, a special algorithm could be developed for dimension reduction of the raw data in on-board pre-processing. On the one hand, the dimension of the reduced data should be small enough to be wirelessly remotely transmitted. On the other hand, the reduced data should be able to represent the raw data without significant loss of the required information. In terms of energy consumption, some algorithms cost more calculation power and thus more energy. Based on the fact that power provided by energy harvesters is limited, the design of algorithms should take the calculation expense into account. However, reducing communication is in general orders of magnitude better in terms of energy efficiency compared to computation power; therefore on-board implementation of such algorithms should always be considered if possible.

**Relevance of communication and energy harvesting with respect to LCC**

The use of energy harvesting and wireless communication technologies could tackle the issues of power supply and cabling on freight wagons, which could reduce the costs for the deployment of wagon condition monitoring systems. Homologation of open but secure communication standards is, however, a challenge which must be overcome in order to maintain an open market for maintenance and spares.

Condition monitoring of wagon components plays a fundamental role in the use of condition based and predictive maintenance for wagons and represents a major theme addressed in WS3. In the event that cargo monitoring is implemented on the wagons and, at the same time, a predictive maintenance scheme is envisaged for the wagon, there are clear advantages offered by the opportunity of achieving a synergy between cargo monitoring and wagon monitoring, given that many of the functions that have to be realised by the two systems can be performed by the same hardware. In particular, common hardware realising functions required both by the cargo monitoring and by the wagon monitoring systems could be the following:

- energy harvesting modules, assuming electric power supply is not available on the wagon;
- on-board communication devices;
- data processing and data storage units;
- units for data transmission to a central server, e.g. based on GSM-R or LTE;
- units for determining the position of the wagon, e.g. GNSS.

There are also less obvious but equally relevant interrelations between WS1 and WS3. For instance, innovations developed in WS1 for “data communication to central server and processing” would be extremely relevant to “models and algorithms for wagon health assessment” because improving the performance of data processing and / or data transmission units may enable the use of more powerful and accurate models for health monitoring and prognostics. Conversely, the requirements posed by condition monitoring methods in terms of CPU power available on-board the wagon, local data storage, frequency required for data transmission (e.g. once per hour / day / week or continuous) affect substantially the design (and the purchase cost) of the hardware developed in WS1. In WS1, these specifications were optimised for requirements of cargo condition monitoring, which might be inadequate for vehicle condition monitoring, it might be the case that vehicle condition monitoring systems, exploiting the innovations of cargo condition monitoring systems, have the added functionality of enabling cargo condition monitoring, rather than the other way round. However that distinction is merely related to perspective and it is clear that innovations related to cargo and wagon condition monitoring systems are potentially relevant to all forms of monitoring system on a wagon, and that the monitoring systems would be more efficient if integrated with each other rather than duplicated.

## 3.4 Impacts of certification and homologation requirements on potential integration of INNOWAG vehicle design solutions

The main impacts of certification and homologation requirements on potential integration of INNOWAG solutions are the requirements related to the strength and construction of the structure and the running performance of the vehicle. Two main items within the EC admission process to obtain an authorisation for a rolling stock are the type assessment (module SB) and a production quality audit (module SD). The type assessment is covered by different TSI-modules with reference to all relevant standards. The purpose of the production quality audit is to assure that the manufacturer is producing the rolling stock vehicles according to the relevant TSI-modules and to verify on a yearly base that:

- the quality management system of the manufacturer meets general standards and good working principles;
- the manufacturer works in accordance with its own quality management system;
- the quality management system of the manufacturer assures consistent quality;
- changes in design and production are well controlled and documented by the manufacturer.

Audit subjects to verify above items are:

- Quality organisation, management and documentation
- Design & change management
- Improvement processes
- Customer & supplier involvement
- Production process
- Supporting processes / departments

All the audit subjects will be equal for the manufacturing of composite components, except for the audit subject of the production process. According to the TSI, welding of rolling stock components needs to be in accordance with EN 15085. For other production methods like bonding (DIN 6701) and bolting (VDI 2230), standards are available to verify if the production processes are compliant. At this moment, no standard is available regarding the production of composite structures for the rail industry. When introducing composite materials within the rail industry, such a standard needs to be available. The aeronautics industry can be of great value with similar, relevant standards, so the railway industry doesn't have to re-invent the wheel.

**Certification of novel design**

Every novel design of the bogie frame which is a part of a freight wagon operated in the EU has to comply with TSI WAG (Commission Regulation (EU) No. 321/2013 of 13 March 2013 concerning the technical specification for interoperability relating to the subsystem 'rolling stock — freight wagons' of the rail system in the European Union and repealing Decision 2006/861/EC).

Innovative solutions, which do not fulfil the requirements specified in this TSI and/or which are not assessable as stated in this TSI, require new specifications and/or new assessment methods. In order to allow technological innovation, these specifications and assessment methods shall be developed by the process 'innovative solution'. If the subsystem 'Rolling stock — freight wagons' includes an innovative solution, the applicant shall state the deviations from the relevant clauses of the TSI, and submit them to the Commission for analysis. In case the analysis results in a favourable opinion, the appropriate functional and interface specifications as well as the assessment methods which are necessary to be included in the TSI in order to allow this solution will be developed. The appropriate functional and interface specifications and the assessment methods so produced shall then be incorporated in the TSI by the revision process. By the notification of a decision of the Commission, taken in accordance with Article 29 of Directive 2008/57/EC, the innovative solution may be permitted to be used.

**Testing of the freight wagon**

In general the new freight wagon has to undergo a set of certain tests before it is certified as the TSI WAG requires. The list of required tests is given below:

- Static strength test, impact test and lifting test (EN 12663-2)
- Dynamic strength test (EN 12663-2)

- Safety against derailment on twisted track (EN 14363); torsional stiffness test
- Testing of running safety under longitudinal compressive forces (EN 15839)
- Running safety and running behaviour (EN 14363)
- Gauging (EN 15273-2)
- The vertical loading characteristics
- Brake test
- Protective bonding test (EN 50153)
- Noise test (TSI NOI)

In case the new wagon is similar to an existing one not all of the above mentioned tests have to be performed if the wagon characteristics fulfil certain conditions given in standards.

Different lightweight wagon design concepts have been developed in the INNOWAG project. The lightweight concepts are based on the implementation of lightweight materials and novel lightweight systems onto optimised structural designs of the wagon and its main sub-system, the bogie. In the INNOWAG project an intermodal flat wagon and a cereal hopper wagon have been investigated as case studies. The effects of lightweight design are the same for both wagon types, i.e. reducing the weight and inertia, as well as lowering the centre of gravity of the entire wagon. Reducing the tare mass of the wagon might have negative effects on the dynamic performance of the wagon, such as the running stability, and also the decrease in vertical loading is unfavourable for safety against derailment.

From the above mentioned reasons the tests which the new lightweight wagons should undergo are:

- Bogie frame tests: in order to certify the bogie frame the integrity of its structure, all attached equipment and body to bogie connection shall be demonstrated based on methods as set out in point 6.2 of the European Norm EN 13749. The lightweight concepts developed in the INNOWAG included a lightweight bogie design with the frame made of high-strength steel (HSS). The bogie frame prototype was tested in the INNOWAG using the methodology of the European standard EN 13749. The equipment was the same as used routinely by the laboratory in homologation tests of bogie frames. However, since issues were identified with the INNOWAG prototype during testing, a revised design, or the same design with improved production methods, would have to undergo testing and pass those tests for the design to be accepted.
- Strength tests, impact test and lifting test;
    - structural strength and deformations of main carrying structures made of HSS, i.e. the hopper underframe and bottom discharging assembly should be investigated;
    - structural strength and maximum deformations of the composite panels on the hopper side walls should be verified; maximum deformation of a composite panel has been measured in a test rig in the INNOWAG project, which is sufficient for proof of concept; however, further testing of the final panel and joint design would be required;
    - hybrid joints between the composite and steel components should be tested; limited proof of concept testing has been carried out within INNOWAG, however, more detailed and specific testing of the selected final design would need to be undertaken.
- Safety against derailment on twisted track; as the decrease in vertical loading is unfavourable for safety against derailment.
- Testing of running safety under longitudinal compressive forces; as light wagons in tare condition can be more easily derailed when pushed through a reverse curve.
- Running safety and running behaviour; as the decrease in vertical loading is unfavourable for safety against derailment and reducing the tare mass of the wagon might have negative effects on running stability.
- Brake test; when reducing the tare mass of the wagon, its brake performance should be verified.

**The minimum wagon axle load**

Regarding the minimum wagon axle load it would have to be checked that the lightweight wagon design fulfils the following condition stated in the ERA document ERA/ERTMS/033281 version 3.0 from 04.12.2015, section 3.1.7.1. Vehicle axle load is:

1. at least 3.5 t for vehicles with more than 4 axles and wheel tread brakes,
2. at least 4 t for vehicles with 4 axles and wheel tread brakes,
3. at least 5 t for other vehicles (that is, vehicles that do not fall into categories 1 or 2).

For the lightest INNOWAG cereal hopper wagon (INNOWAG lightweight hopper concept 2 reported in Deliverable D3.1) the total tare weight is 16.523 t which results in a minimum axle load of the wagon which fulfils the above mentioned requirement.

However, for the INNOWAG lightweight intermodal 60’ flat wagon the total tare weight is 15.559t which results in a minimum axle load of the wagon which is less than required by above mentioned document. In this case, the existing regulation requires that some operational measures should be taken, or the design modified so that some of the weight saving measures are not applied and the tare weight is at least 16t.

# 4 CONCLUSIONS

Although development of the three Work Streams in the project have continued as largely separate endeavours, an investigation of the opportunities for integration and complementarity has shown that there are significant opportunities across the INNOWAG concept to deliver an integrated, cost effective and low risk lightweight smart freight wagon solution. For example, the new materials and manufacturing techniques envisaged in WS2 may be easier accepted for implementation if such solutions would be integrated with structural monitoring systems (exploiting innovations developed for cargo condition monitoring (WS1) that deliver information into the predictive maintenance module (WS3). In order to maintain an open and interoperable freight wagon leasing model in Europe, where maintenance can be undertaken in compliant facilities where and when it is convenient, the diverse products used to implement these wagons and monitoring systems must all comply with common standards. This presents the homologation challenges that may drive further development work.

The integration between cargo condition monitoring and wagon condition monitoring, at the level of on-board data aggregation, processing and wireless communication (both short range and long range), can be seen as a short-to-medium term recommendation. Also due to the challenges on the powering / energy harvesting side, it makes sense to combine the two data streams into one flow and not use two different systems. In this direction, a standardized interface and data encapsulation are important to be defined, in order to facilitate the adoption and implementation of this recommendation.

Regarding the integration of WS1 (Cargo Condition Monitoring) and WS2 (Wagon Design) solutions, on the one hand, the wireless communication, RFID and energy harvesting technologies may enable the continuous monitoring of lightweight wagons based on implementation of advanced materials such as HSS and composite materials. The high-TRL applications, such as solar and vibration energy harvesting, as well as Bluetooth wireless communication, can be directly deployed to obtain vibration data on different locations on the wagons during operation. This data could be used not only for adaptation of monitoring algorithms developed in WS3, but also to provide information on realistic dynamic load cases of freight wagons, which could be used for design and manufacturing processes. The low-TRL applications such as passive RFID sensors have been verified in laboratory and thus should be further tested in railway environment. On the other hand, new materials could affect the performance of RFID, wireless radio transmission and energy harvesting on freight wagons. This could be better investigated after relevant laboratory tests or long-term trials in operating conditions would be carried out. Based on the above considerations, the following further activities are recommended:

- in short-medium term:
    - specific laboratory tests could be designed and performed to assess the potential influences of new materials on wireless radio transmission, RFID and energy harvesting technologies; if necessary, adaptation or re-design of these technologies could be made;
    - a prototype of a lightweight wagon could be manufactured and instrumented with condition monitoring equipment, including wireless radio transmission, RFID and energy harvesting technologies for real-data collection;
- in long-term, the real-time data could be used for iterative improvement of condition monitoring equipment (including both software and hardware), as well as design and manufacturing solutions for lightweight wagons.

Concerning the integration of WS1 (Cargo Condition Monitoring) and WS3 (Predictive Maintenance) solutions, the main focus is on the onboard unit - it is envisaged to develop and implement a modular onboard unit to integrate cargo and wagon condition monitoring, in order to meet different customers' needs and reduce thus investment costs; this solution seems to be viable, considering the feasibility of already matured, as well as emerging technologies. Energy harvesting and wireless communication addressed in WS1 can certainly tackle the issues of power supply and cabling for condition monitoring applications on freight wagons. On the other hand, the adaptation of data processing algorithms developed in WS3 should be considered, when condition monitoring systems capable to collect significant amounts of relevant data would be implemented. Considering the potential of integrating these solutions, as well as the shortcomings that are still to be overcome, the following further activities are recommended:

- in short-medium term:
  - the architecture of a modular system, integrating cargo and wagon condition monitoring, should be designed, considering technical specifications and solutions for sensor systems, energy harvesting and wireless communication that have been investigated in INNOWAG;
  - design and testing of an integrated system for collection and processing of data that are related to both cargo and wagon condition monitoring; the main challenge is from the perspective of the software and algorithms;
  - the prototype of the integrated system described above should be tested on railway environment, in both controlled and operating conditions; a relevant potential demonstrator may be a wagon for dangerous goods transport;
- in long term:
  - the integrated condition monitoring system should be iteratively improved based on the results of long-term testing in operating conditions. Proper commercial use cases should be considered.
  - the monitoring results of the integrated onboard unit should be integrated into the current management system for cargo logistics and wagon maintenance.

Regarding the WS3 (Predictive Maintenance) solutions, their integration with innovations developed in the other Work Streams (mainly with those from WS2, Wagon Design), may enhance the potential use of the developed PHM-based tool. This would support the decision-making on the best maintenance procedures, to adopt more reliable maintenance policy. In particular:

- it would be extremely useful to implement methods for the structural health monitoring of welds on the structural parts of a bogie or carbody made of HSS;
- the integration of structural monitoring methods could improve the reliability estimation by increasing the number of monitoring variables.

Considering the above, different actions are envisaged for future developments in this direction:

- in short-medium term:
  - integration of the PHM-based tool with real-time data and structural monitoring method in order to better assess the reliability and support therefore the development of more robust maintenance policies;
  - take advantage of the real-time monitoring and integrate the PHM-based tool in the on-line monitoring portal, which would result in a continuous and real-time improvement of the reliability function that would react to an unexpected and unforeseeable event that could happen during normal operation of the wagon;
- in long-term, to further develop the PHM-based tool in order to make it prone to foresee the reliability behaviour in the future; in this case, the decision making within maintenance policies would not be based on historical data and real-time data only, but also on forecasted behaviour.

From a managerial viewpoint, the optimisation of maintenance procedures and policies could benefit significantly from a better estimation of the costs related to the freight wagons, which would be enabled by the implementation of WS3 solutions. Improving the estimation of purchasing cost, but especially of maintenance costs and hidden costs, along with the better estimation of the reliability function, could significantly provide advantages in the definition of new maintenance policy for the freight wagon.

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