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Integrated concept of lightweight wagon with cargo condition monitoring capabilities and predictive maintenance solutions

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Abstract

The article presents a novel wagon concept that integrates innovative solutions relating to the identified major challenges for the freight vehicles of the future, namely: *i. cargo condition monitoring; ii. Lightweight wagon design; and iii. Predictive maintenance.* These three essential areas are addressed by three subsequent work streams of the INNOWAG project, which is funded by the Shift2Rail Joint Undertaking under the EU's H2020 programme. INNOWAG aims to respond to major rail freight competitiveness challenges regarding the increase of transport capacity, logistic capacity and improved RAMS and lower LCC, by developing an autonomous self-powered sensor system for cargo tracing and monitoring, along with a predictive maintenance approach to enable efficient use of both condition monitoring and historical data for further implementation of predictive models and tools in freight vehicle maintenance, and to integrate the aforementioned innovations on a novel concept of modular and lightweight wagon, developed through an optimised structural design using lightweight materials.

Keywords: rail freight; wagon design; cargo condition monitoring; predictive maintenance.

Nomenclature

CBM	Condition Based Maintenance
CCMS	Cargo Condition Monitoring System
ECM	Entity in Charge of Maintenance
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
H2020	The EU Framework Programme for Research and Innovation Horizon 2020
LCC	Life Cycle Cost
LDHV	Low Density High Value
PM	Predictive Maintenance
PHM	Proportional Hazards Model
RAMS	Reliability, Availability, Maintainability, and Safety
RF	Radio Frequency
RFID	Radio Frequency Identification
T2G	Train-to-Ground
TRL	Technology Readiness Level

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V2L Vehicle-to-Locomotive
V2V Vehicle-to-Vehicle
WS Work Stream
WSN Wireless Sensor Network

1. Introduction

In comparison to passenger rolling stock, where significant innovations have been implemented in the last 20 years all over Europe, changes in rail freight have been mainly organisational, and technical innovations have not achieved a significant market uptake. However, the drivers of change in the freight market result in the new freight mobility needs. The rail freight system has to adapt to it to remain competitive through providing innovative services to satisfy the increased customer's needs, reducing the cost to satisfy the demand of competitiveness, imposing production systems capable of remaining sustainable over time in a greener perspective, etc. All the requirements need to be fulfilled by the hardware and software technologies applied to equipment and management of information.

In order to respond to these challenges, the Shift2Rail INNOWAG project determines how to effectively integrate innovative technologies for cargo condition monitoring into a novel high performance lightweight freight wagon, supported by effective health monitoring technologies, and predictive maintenance models for sustainable and attractive European rail freight, as shown in Fig. 1.

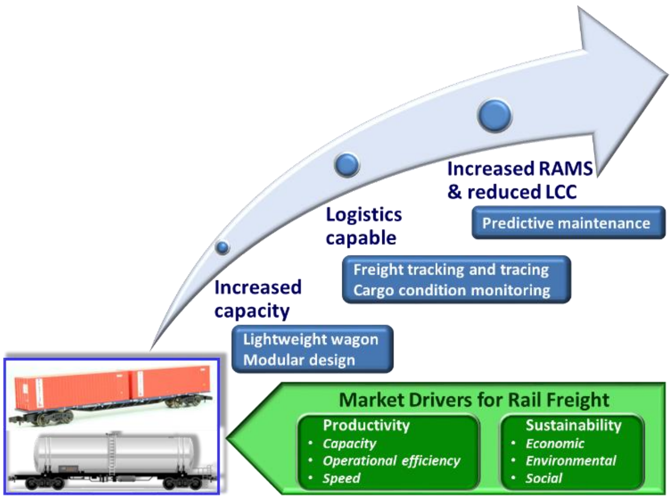

Fig. 1 INNOWAG challenges with respect to actual market drivers of rail freight

Therefore, the INNOWAG project aims at developing a rail freight service that fits the needs of modern manufacturing and supply chain through its following ***specific objectives:***

- Increase freight rail capacity by optimising the wagon design in order to considerably reduce its weight and increase thus the ration payload/wagon tare;
- Increase freight logistic capabilities by: i. offering real time data on freight location and condition through the use of smart self-powered sensors and communication technologies; ii. optimised wagon modular design capable to transport various types of goods; and iii. improved availability to freight customers, enabled by a safer and more reliable freight service, with better interoperability;
- Increase RAMS and reduce LCC by implementing modern and innovative predictive maintenance analytics, models, and procedures.

2. Innovative concepts for competitive rail freight

The development of novel technology concepts in the three essential areas, namely: *i. Cargo condition monitoring; ii. Lightweight wagon design; and iii. Predictive maintenance*, is separately addressed by three subsequent Work Streams (WS) of the project, which are presented in the following sections.

2.1. Lightweight wagon design

The reduction of the weight of freight wagons is a key element in improving the competitiveness of rail freight and, thereby, obtaining the societal and environmental benefits of increasing the modal share of rail freight. Lighter weight freight vehicles enable significant advantages such as:

- The improved ratio between the weight of the payload and the vehicles' tare in a train contributes to increasing the efficiency of the train and allow trains of the same total weight to carry more freight.
- They allow a greater payload to be carried by a vehicle within the same limits of the overall vehicle weight, as imposed by infrastructure managers, increasing thus the vehicle capacity and overall train productivity;
- The lower vehicle-track interaction forces reduce the impact on the infrastructure and on the vehicle itself, contributing to reducing maintenance costs and increasing the LCC.

2.1.1. Concept and objectives

The INNOWAG *wagon design* concept combines state-of-the-art knowledge on materials, design and manufacturing in order to develop a novel high performance, modular and lightweight wagon, with improved payload-dead weight ratio. The proposed lightweighting solutions include the use of smart selection of lightweight materials and the optimisation of the wagon structure design.

The aim of this Work Stream is to develop novel lightweight designs for structural components and subassemblies of freight vehicles, which would be validated and integrated into innovative lightweight wagon concepts. Specific objectives include:

- Development of a novel concept of modular and lightweight wagon through:
    - Smart selection of lightweight materials, and material specifications;
    - Optimised structural design;
    - Modular components and/or sub-assemblies to enhance the functionality and transport capacity;
- Structural strength and fatigue analysis of critical sub-assemblies under rail specific operational stresses;
- Validation of innovative lightweight design concepts through dedicated laboratory tests, including Quasi-static tests, Dynamic and fatigue tests, Non-destructive tests, and Material resistance tests.

2.1.2. Approach and methodology

Motivated by the necessity and opportunity for change in the freight rail transport, the INNOWAG approach proposes technical solutions for freight vehicles to improve the sustainability, competitiveness, increased capacity, and availability of freight rail. INNOWAG aims to develop a high performance lightweight design concept for freight vehicles facilitating cheaper, faster and an improved quality in freight services. Whilst the work focuses on lightweight vehicle design, other design innovations will be considered with respect to noise reduction, manufacturing cost, and interoperability issues. The critical aspects related to the novel conceptual design will be validated through modelling and simulation techniques, as well as through laboratory testing.

The methodology for developing the lightweight design concept comprises research activities that are organised within a specific Work Stream along the following lines of action (also shown in Fig. 2):

- Identification and review of technologies and solutions applicable to lightweight wagon designs, including lightweight materials, structural designs, construction techniques, and certification. The solutions were benchmarked and specifications and requirements were identified and defined.
- Assessment and selection of the identified candidate materials for the construction of lightweight vehicles using state-of-the-are assessment methodologies and tools; shortlists of candidate materials for different structural components were produced.
- Development of novel multi-functional modular concept designs for lightweight components, subassemblies and structural parts of freight vehicles using the selected candidate materials and approaches.
- Implementation of the novel lightweight solutions, including composite structures, into the design concept, so that the integrity of these solutions is analysed (with focus on the optimisation of the vehicle structure design within the constraints of the standards relating to structural and dynamic performance of vehicles).
- Modelling and analysis to both ensure the structural performance of the design and the dynamic behaviour of the new concept, under both loaded and unloaded conditions, to validate the performance of concept designs.
- Testing of critical components, sub-structures and sub-assemblies in loading conditions representative of a wagon in service, to validate the modelling and prove the design concepts. In addition to the loading tests, the

materials and constructions will be tested for their resilience to environmental conditions and the effects of the freight carried or spilt.

- Investigation of the potential integration of the outcomes related to cargo condition monitoring and predictive maintenance onto the novel lightweight design, to achieve a single intelligent wagon concept.

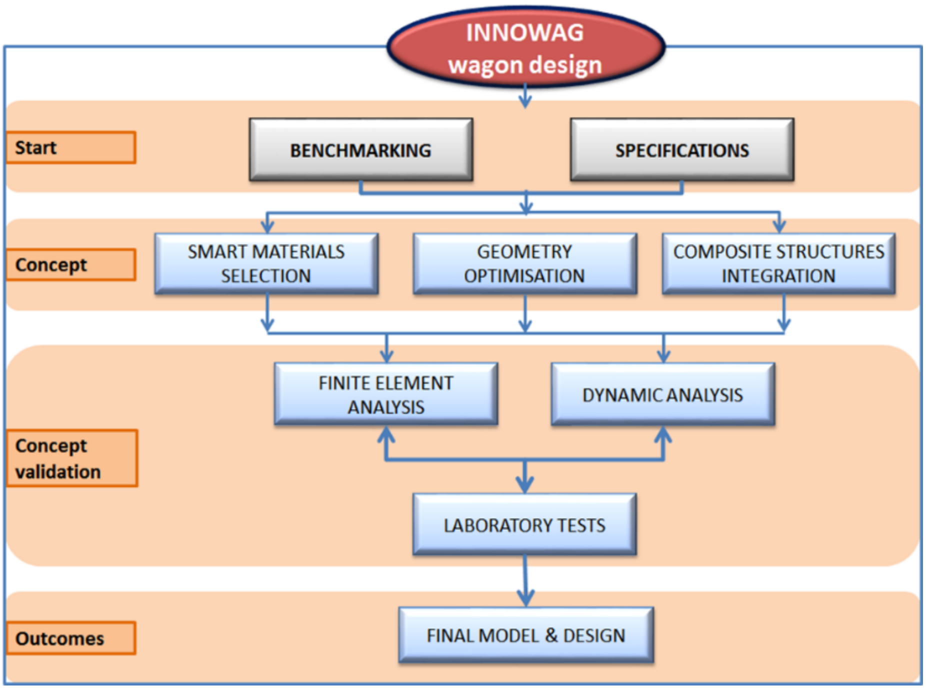

Fig. 2 INNOWAG Wagon Design WS – approach and methodology

2.2. Cargo condition monitoring

It is commonly accepted that the rail freight transport is more appropriate for bulk cargo and heavy goods like coal and ores. However, the type of transported goods has started to change over the past years. Low-density high-value goods (LDHV), which are mainly represented by consumer goods, food products, manufactured goods, etc., have been gaining share in contrast of bulk cargo with high density. When it comes to LDHV-goods, the requirements derived from customers' needs, logistic chains and service operation become particularly crucial for transport service providers (SPECTRUM, 2012). In this respect, monitoring and tracing of cargo can increase the attractiveness of rail freight transport by improving the reliability and visibility of railway freight service.

The transport of dangerous goods, such as flammable liquids and chemical products, is in the same situation, where safety and security are fundamental requirements. In this case, the continuously monitoring of the vital cargo parameters is a key feature to prevent potentially dangerous situations.

2.2.1. Concept and objectives

The concept behind *cargo condition monitoring* is to develop a system based on an autonomous self-powered wireless sensor network (WSN) for cargo tracing and monitoring the condition of key parameters for critical types of cargo. The proposed system will overcome the issues related to sensor wiring and power supply on freight trains by using a wireless communication network powered by energy harvesting solutions, contributing thus to the increase of the overall system reliability and availability and enabling an efficient planning for logistic freight transport towards the change to fully automated control of freight services. The development objectives of this WS are presented as follows:

- Formulation of the overall measurement concept in the case of LDHV-goods transported by container wagons and dangerous goods transported by tank wagons, especially considering the arrangement of data acquisition devices, i.e. sensor systems and tracing devices;

- Design of a power supply system providing an autonomous operation of cargo condition monitoring through utilisation of energy harvesting technologies, such as vibration harvesters, solar panels, radio frequency (RF) harvesters, etc.;
- Design of a WSN that ensures secure, regular and reliable data communication within the network, i.e. intra-train communication, as well as a communication system between the WSN and a central application server, i.e. Train-to-Ground (T2G) communication;
- Establishing an IT infrastructure for data processing, storage and representation;
- Validation of the developed technologies for cargo condition monitoring system (CCMS) in a relevant environment (at TRL 5).

2.2.2. Approach and methodology

The approach and methodology, comprising the specific research tasks for each step of this Work Stream, is illustrated in Fig. 2 below.

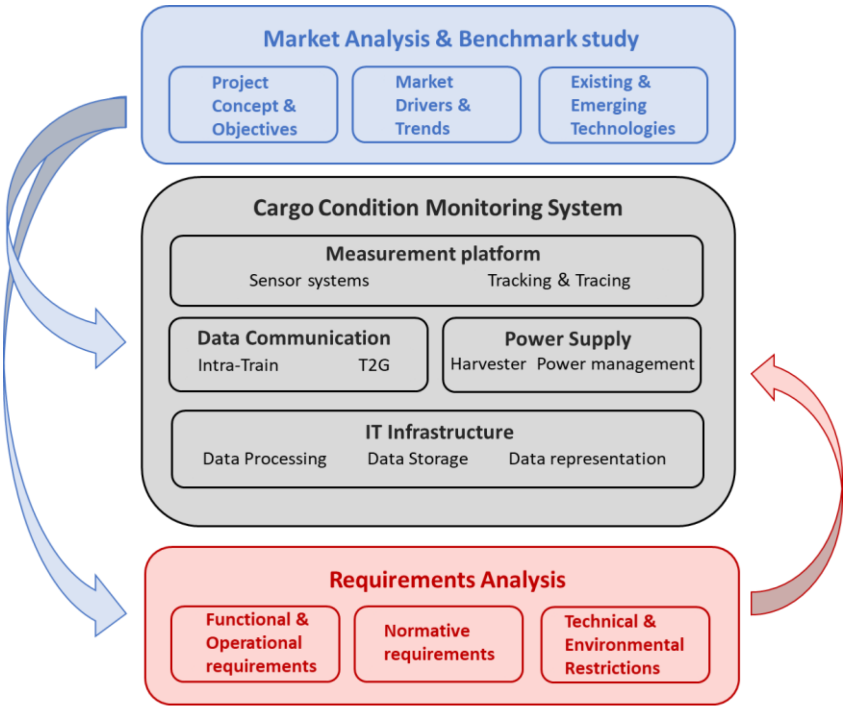

Fig. 2 INNOWAG Cargo Condition Monitoring WS – approach and methodology

The WS started with a market analysis and benchmark study in order to determine the freight market drivers as well as the existing and emerging technologies in the INNOWAG-related areas. In the second step, the analysis of specific requirements was carried out in the perspective of the monitoring system itself (in terms of system function and operation), and the boundary conditions (in terms of compliance to standards, operation environment and available technologies). Based on this analysis, two application cases, namely LDHV-goods transport and dangerous goods transport, were defined for further design of the CCMS.

The development of the CCMS aims at a modular design, and the implementation and integration of individual modules based on existing technologies. The first task was to setup a modular architecture of the envisaged CCMS, along with the formulation of the measurement concepts for both case studies. The available sensor equipment, the required features thereof, and installation specifications are identified accordingly.

The proposed concept of onboard autonomous powering system may comprise two levels of energy harvesters. The primary one could be based on harvesting of vibrations or solar energy, and its role is to power the "power-hungry" modules, while the secondary one is based on utilisation of electromagnetic waves, i.e. gathering energy from RF signals broadcasted from the side of the primary harvester, to power the distributed sensor nodes, on which the primary harvesters cannot be applied due to resource-constrained locations.

In terms of data communication, three feasible T2G communication solutions were selected as candidates for the INNOWAG CCMS:

- Communication via mobile network;
- Communication via satellite;
- Communication through interaction between onboard RF tags and trackside RF-readers.

The communication via mobile network (particularly GSM/GPRS) is considered to be the most common choice for the T2G communication solution on freight wagons due to its low costs and wide coverage of GSM base stations. RFID is traditionally used for vehicle identification; in the case of data communication, the RF tags should be able to transmit measured data to the readers installed alongside the track, when the train passes by the readers. The great advantage is that passive RF tags do not require additional power onboard.

Regarding the intra-train communication within WSN, vehicle-to-vehicle (V2V), vehicle-to-locomotive (V2L), and intra-vehicle communication are to be considered. It is more likely that each vehicle has a complete communication system, consisting of a local WSN and a T2G module, at least. Then, only intra-vehicle communication has to be considered. If V2L communication is necessary (e.g., for the purpose of sending alarm messages to the train driver), a relay node would be required for each wagon. Regarding the train length, relay nodes might not be able to send data directly to the locomotive. Instead, V2V communication will be involved for multi-hop communication to relay the messages to the locomotive. From the perspective of energy consumption, the best WSN architecture was not determined so far. The WSN must ensure the communication of sensor data with a good trade-off between power consumption and data delivery performance. Existing industrial standards are considered for the WSN design. The benchmark shows that IEEE 802.15.4 compatible transceivers were previously used for rail freight wagons. In addition to conventional WSNs, RFID technology provides good wireless communication between a reader and a tag, enabling the formation of a WSN. In RFID-based sensor networks, the sensor is connected to a control unit to gather the data and that data is transmitted by the tag to the reader wirelessly. In this case, the sensor and controller require power supply from the energy harvester and the tag can be either passive (does not require power supply, but has a shorter communication range) or active (require power supply, but has a longer communication range).

The IT infrastructure will depend on the selection of an appropriate existing platform, such as a cloud platform or a server centre, for data storage and offline processing. The data representation could be implemented in the form of a web application, which should be remotely accessible and in easily understandable manner.

Last but not least, the data acquisition modules, the powering concept with energy harvesting, and the functionality of data communication will be tested in a typical railway environment, e.g. a shunting yard, for different scenarios. The developed CCMS is thereby expected to reach TRL 5.

2.3. Predictive maintenance

Predictive maintenance (PM) approach and procedures should ensure a high degree both of functionality and requirements to guarantee its application in an extensive way. Generally speaking, one of the most important requirements “Predictive maintenance” should have is a high degree of reliability, which means that availability of critical information to infrastructure managers and operators should be guaranteed in a continuous and certain way. The expected advantages of adopting predictive/preventive maintenance procedures are a reduction in maintenance costs due to only carrying out maintenance and component replacement when necessary, but before a failure, whilst maintaining operational availability.

2.3.1. Concept and objectives

Within INNOWAG, the *predictive maintenance* concept is to develop predictive models and maintenance procedures for selected components of rail freight vehicles, along with tools to assess the effect of applying predictive maintenance practices on the life cycle cost of rail vehicles.

The *predictive maintenance* WS aims to define and validate a PM strategy for freight wagons in order to reduce the maintenance costs and improve the availability of vehicles. The specific objectives of this WS are:

- Development of an integrated PM approach to enable efficient use of both remote condition monitoring and historical data and further support the implementation of predictive models and tools in rolling stock maintenance programmes;
- Development of guidelines for maintenance procedures to implement PM practices for the cases studied;
- Assessment of the benefits provided by the developed PM strategies;
- Definition of an integrated strategy for implementing PM on freight rolling stock.

2.3.2. Approach and methodology

Implementing a predictive maintenance regime requires a greater understanding of the failure mechanisms and life cycle of the system and its components than other maintenance systems, where data handling and maintenance management are the core themes. The activities within the Predictive Maintenance WS are organised in tasks as shown by Fig. 4.

The first task addressed the selection and analysis of available data in order to prioritise the freight vehicle components and sub-systems in terms of their relevance for PM. The prioritisation considered both historical data and data stream from condition monitoring systems. Collecting and storage of historical rail vehicles and components maintenance and failure data is already a mainstream commercial practice, which is required in most of the cases by current national and European regulations. The starting point is the typical maintenance programme applied in Europe on freight wagons (VPI rules). The relevant information on preventive maintenance operations, failures' records, and economic aspects are accessible from freight operators and ECMs. The collection of condition monitoring measurements is available from research, or commercial systems installed on relevant components of operational rail vehicles, such as brakes, wheels and bearings.

The data were firstly selected on the basis of a top-down approach (cost-driven analysis), then analysed in order to extract useful information concerning the reliability and failure modes of the wagon. The cost-driven analysis takes into account for each type of inspection and preventive maintenance operation, the related costs, periodicity (km or years) and the duration of the activity. In addition, records of failures of various wagon components including accidents resulting from the failure and their associated cost, as well as potential financial penalties for operational delays due to failures or accidents were considered. This basic task enables to determine the life cycle cost of the wagon, and further the identification of the critical components, which have the greatest impact on operating costs. Furthermore, the cost information will be fed into the guideline tool that will be developed for helping make decisions on maintenance activities. The cost analysis also provides a baseline for further assessment of the benefits provided by the developed PM strategies.

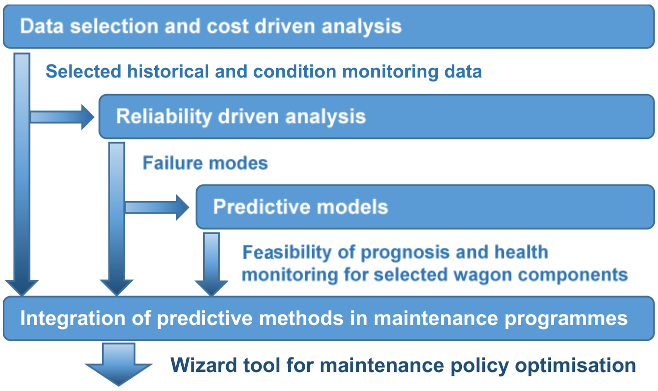

Fig. 4 INNOWAG Predictive Maintenance WS – approach and methodology

The reliability-driven analysis was performed on the prioritised components and subassemblies in a bottom-up approach, based on the RAMS standard EN 50126. Different analysis techniques, including FMEA-FMECA, modelling of different damage mechanisms (e.g., fatigue, wear) and root cause analysis, will be used to extract useful information related to failure mechanisms.

In a second step, strategies for data integration and models for the health monitoring and prognostics of the relevant components will be developed. Two possible approaches to developing predictive models are machine learning, applying artificial intelligence and neural network to develop predictive models from large amounts of data, and applying human expertise to develop models based on physical processes and the observed data, or to build up rules and improve the algorithms. Since failures are rare, the failure signal from which to develop the model is week, therefore it is difficult to use with machine learning. Another issue is that the predictive model is a sealed input/output box which does not give in-depth knowledge of the causes or mechanisms, therefore, if conditions are changed, the model has to be retrained. When using predictive models developed with human expertise, the initial estimation of the effect of changes to the system can be predicted by altering parameters in the model and refined based on experience; in-depth knowledge can be also applied to analysing the system, and, potentially, identifying improvements.

The identified key failures and defects will be addressed during the development of predictive models. Two main challenges are related to data processing: on one hand, there is the need to consider large data sets, continuously updated by real-time data made available by condition monitoring systems; on the other hand, there is the need to integrate information coming from historical data (being continuously updated) with data from condition monitoring systems. These challenges will be addressed in the last task, which aims at the development of a Wizard tool for maintenance policy optimisation. A Wizard is a tool that guides the user through an activity or through a decision-making process. The dedicated tool developed in INNOWAG will integrate a Proportional Hazards Model (PHM), which is able to estimate the failure rate as a function of the age of the entity, through reliability analysis using historical failure event data along with predictive models using condition monitoring. This tool will also integrate the cost information needed in order to effectively define the effect on LCC of the vehicle, so that the optimal maintenance procedures can be selected. The overall development of the Wizard tool will consider the existing standards for Condition Based Maintenance (CBM), e.g., the MIMOSA standard (ISO-13374), in order to perfectly fit a standardised vision of CBM/PM, and not just a specific system.

Finally, an integrated PM system including the PHM model, a LCC model, and information on maintenance rules, limits, procedures, etc. will be implemented to different cases studies to estimate if and how much the periodicity of maintenance actions can be enlarged, or if unexpected damages or accidents can be prevented. These results will enable an overall assessment of the PM procedures, identifying the most promising solutions.

3. Discussion of preliminary results

3.1. Lightweight Wagon Design

The wagon lightweighting will be addressed through:
- Materials (selection, new manufacturing techniques, new joining processes, etc.)
- ‘Smart’ optimised design (using novel profiles, optimised shapes, etc.).

The analysis and assessment of different candidate materials was carried out through a two-level methodology. The main candidate materials that were identified belong to two families:
- Steels (especially high strengths steels, austenitic steels, martensitic steels, etc.); and
- Fibre reinforced polymer composites.

In addition to the above, other lightweight materials such as Aluminium and steel foams could be further considered, however, just for some specific applications.

The potential mass reduction is foreseen in key parts of a freight vehicle, i.e.:
- *Running gear* (the mass reduction is still limited due to stability and running behaviour issues);
- *Structural frames* (good potential for reduction, up to 25-30%; ~20% was achieved for a flat wagon in SUSTRAIL);
- *Wagon body* (very good potential, foreseen up to 40-50%).

The potential to reduce the mass of auxiliary equipment and components (e.g., draw gear, braking system, coupling system, etc.) is still limited by both technical and regulatory barriers. Therefore, INNOWAG will not aim to reduce the mass of components in these categories. In order to address the relevant wagon parts, and considering the market drivers and trends as well, three different types of wagons have been selected for further work:
- Flat wagon enabling container transport – classes R and/or S (or a combination of these types allowing the modification of a platform wagon into a covered one);

- Open self-discharge wagon class F for bulk materials (open ‘hopper’ type, e.g., Faccs type);
- Cereals ‘hopper’ wagon class U or T (e.g., type Uagps, Uagpps, Tdgs, etc.)

Current work focuses on developing novel design concepts for lightweight components, subassemblies and structural parts of the selected types of freight vehicles, by using the suitable options from the range of selected candidate materials. In addition to the use of selected lightweight materials, the lightweight design concepts will also consider two other approaches:

- the optimisation of shapes and dimensions, and
- modular design of overall wagon structure by using interchangeable re-designed components, for increasing the vehicle capacity and availability.

3.2. Cargo Condition Monitoring

Several options of the CCMS architecture have been designed, incorporating different solutions and technologies for each module. Since the identified technologies and solutions have different TRL levels, the proposed system architectures were grouped into low-TRL designs and high-TRL designs. In this way, the CCMS with higher TRL can be identified and further validated through testing in real environment within the project duration. On the other hand, innovative technologies with lower TRL could be investigated and tested as well.

The following system functionalities were defined in the case of LDHV goods transported by container wagons:

- Tracking and tracing the containers;
- Measuring environmental conditions inside containers (such as temperature and humidity);
- Measuring shocks and vibrations that containers are exposed to;
- Detecting intrusion.

The system functionalities in the case of dangerous goods transported by tank wagons include:

- Tracking and tracing the tank wagons;
- Measuring condition of key parameters inside tanks (such as temperature, pressure and filling level);
- Detecting gas leak.

Further work will focus on the development of the communication system and the powering system. The developed CCMS should allow the adaptation to the wagon condition monitoring system, which could be used for acquiring condition monitoring data, which would feed into the integrated PM system.

3.3. Predictive Maintenance

Based on historical data, cost and reliability driven analysis have been performed. Wheelsets (including bearings) and braking systems are identified as the most critical subassemblies. The study further identified the following issues commonly experienced in freight wagon, which could be tackled through PM approaches:

- wear and rolling contact fatigue, representing two possible modes of degradation of the rolling surface establishing the interaction of the vehicle to the track;
- metallic and fretting fatigue that may take place in the body of the wheels and of the axle connecting the wheels; typically, these fatigue phenomena occur at the positions in the body of the wheels and axles at which maximum alternate stresses are occurring and / or where friction effects related with the press-fit mount of the wheels on the axle occur;
- damage of the roller bearings in the axle boxes related to both the interface between the rotating part (wheelset) and the non-rotating part (bogie frame) of the running gear;
- failures and alteration of elasticity or damping properties in the suspensions; for freight wagons, most suspension components use dry friction damping, which means the actual performance of the suspension is highly affected by its condition.

Considering that existing data could not be sufficient for the implementation of the integrated PM approach, the hardware for condition monitoring of specific components could also be considered within the project scope. This can be integrated with the platform developed for cargo condition monitoring.

4. Conclusions

Lightweight wagon design

- The potential to reduce the mass of large and heavy wagon parts and subassemblies is realistic and significant; materials already existing on the market, along with specific manufacturing techniques enable the development of a new generation of light freight vehicles;
- The INNOWAG wagon design concept will comply with the existing standards and regulation (EN, ISO, UIC leaflets, TSI, etc.); however, it is anticipated that there might be situations where the existing regulation is not appropriate (e.g., the integration of composite components on metallic structures);
- Lightweight wagon concepts should also consider outcomes of ongoing work in other Shift2Rail projects that could be considered for inclusion and integration into the INNOWAG concept design; these might include novel designs of suspension system, disk brakes, automatic coupler, and other equipment and components.

Cargo Condition Monitoring System

- The CCMS consists of the onboard units and IT infrastructure. The envisaged innovative technologies belong to the onboard units, whilst IT infrastructure is to be established based on the existing cloud platform and/or software;
- The development of the onboard units is based on different approaches that are distinguished by TRL;
- Due to the nature of the energy harvesting powered system, the implementation of technologies could be restricted by the limited power supply.

Predictive Maintenance

- PM strategy relies significantly on data, namely data acquisition, data processing, as well as data management and maintenance management;
- PM can only be applied on certain components and subassemblies of railway vehicles. Therefore, the optimisation of maintenance strategy and procedures on freight wagons by introducing PM must envisage an integrated solution, where all of intelligent prognostic models for the specific components / subassemblies, LCC analysis of vehicles and present maintenance policy play significant roles.

In addition to the work carried out within its three work streams, INNOWAG will also investigate the potential to integrate the outcomes in a single intelligent wagon concept. Considering the nature and specifications of the innovative concepts and solutions developed by INNOWAG work streams, the first step will be to identify the critical aspects related to their further integration – both the technical challenges and the boundaries and restrictions related to standards and regulatory framework.

INNOWAG will further propose a set of recommendations for further integration and implementation of the innovative solutions in the three area, including:

- Recommendations and proposed solutions for technical issues;
- Recommendations related to regulatory aspects, in relation with the certification of the novel solutions, interoperability, etc.

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