INNOWAG

Innovative monitoring and predictive maintenance solutions on lightweight wagon

Shift Freight to Rail:

Midterm Event for S2R Projects from Call 2015-2016

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INNOWAG consortium

University of Newcastle upon Tyne, UK *Project Coordinator*	[UNEW]
Inertia Technology B.V., NL	[INE]
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Lucchini RS SpA, IT	[LRS]
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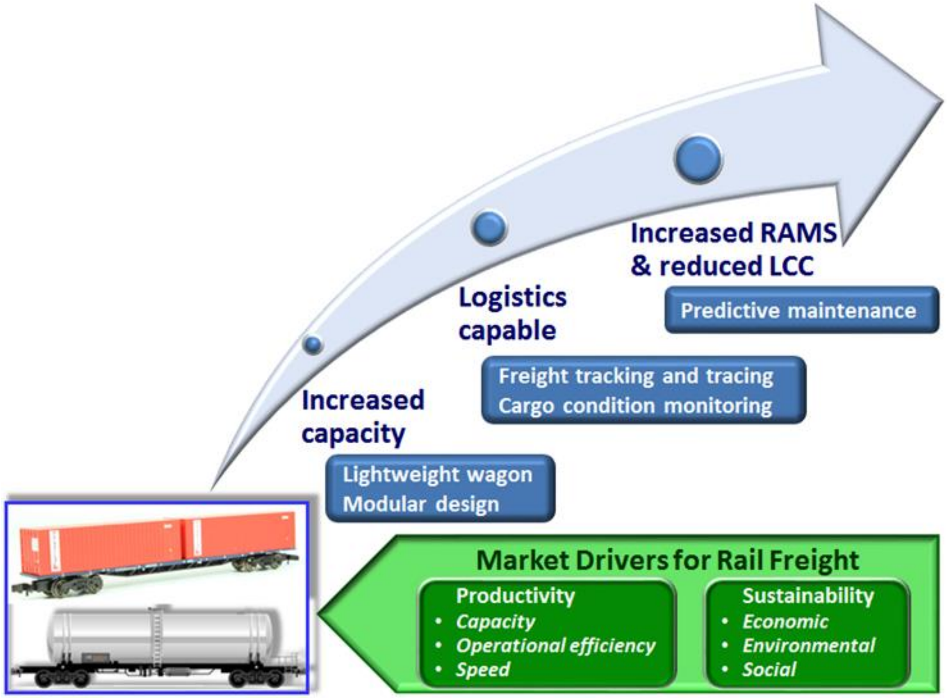
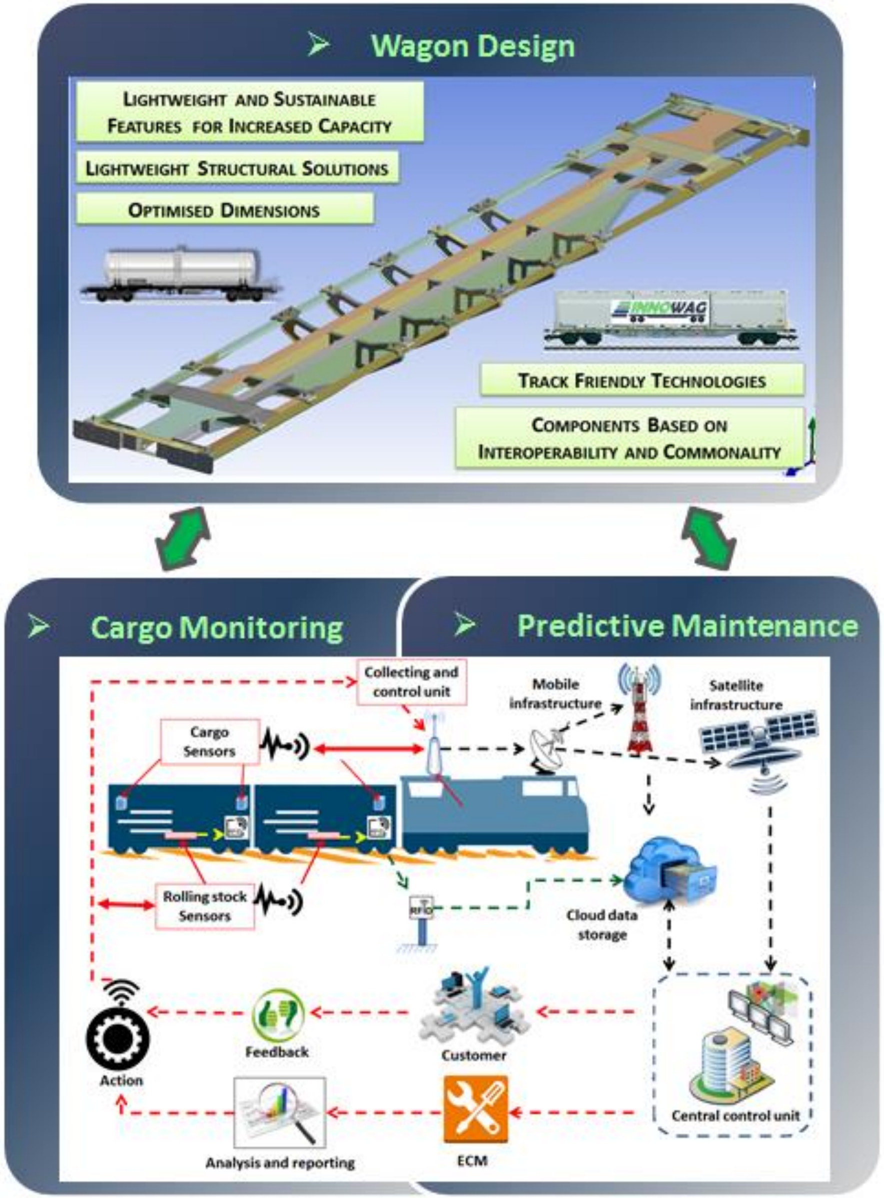
INNOWAG aim and objectives

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 and lightweighting the wagon design for increasing the ratio payload/wagon tare;
- ***Increase freight logistic capabilities*** by:
  i. *offering real time data on freight location and condition through a smart self-powered sensor system 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 and interoperable freight service;*
- ***Increase RAMS and reduce LCC*** by implementing modern and innovative predictive maintenance analytics, models, and procedures.

INNOWAG concept and approach



INNOWAG tackles the internal drivers of change, with the overall goal to increase the rail market share in accessible segments. INNOWAG develops innovations in **three macro-areas** (wagon design, cargo condition monitoring, and predictive maintenance), from concept to laboratory and real environment testing, for further integration and implementation.

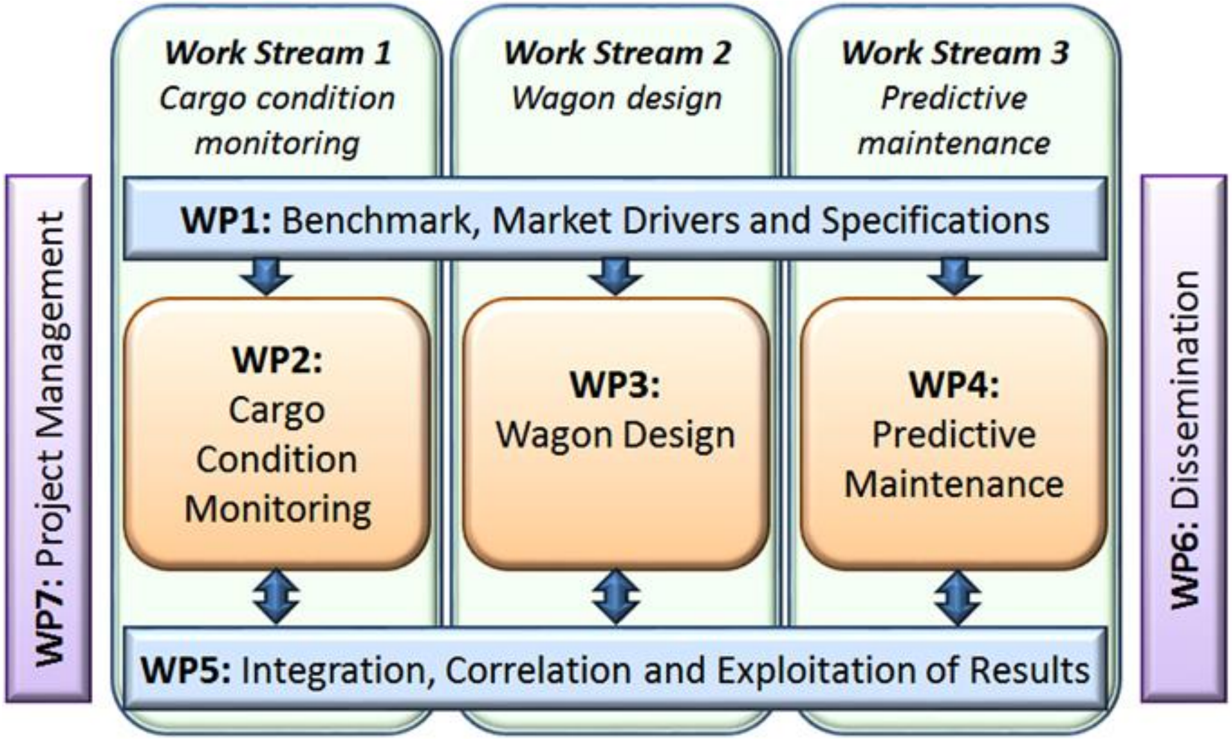
1. ***Wagon design:*** *novel concept of modular and lightweight wagon;*
2. ***Cargo condition monitoring:*** *autonomous self-powered sensor system for cargo tracing and condition monitoring;*
3. ***Predictive maintenance****: integrated approach (use of both remote condition monitoring and historical data) to support the implementation of predictive models and tools in rolling stock maintenance programmes.*

INNOWAG structure and work plan

The methodological approach implements the INNOWAG concept over three phases:

- **Phase 1** – Market drivers, benchmark and definition of specification and requirements;
- **Phase 2** – Development of innovative solutions and technologies, and validation of concepts;
- **Phase 3** – Integration of innovations and correlation with S2R IP5 actions.

INNOWAG structure and main interactions between work streams and work packages



Selected design case studies

- Flat wagon enabling container transport (classes R and/or S, or a combination of these types);
- Open self-discharge wagon class F for bulk materials (e.g., Faccs type);
- Cereals 'hopper' wagon class U or T (e.g., type Uagps, Uagpps, etc.)

Flat wagon enabling container transport (e.g., UIC classes R or S)	
Max. axle load:	(17 - 22.5) t
Length over buffers:	(18.4 – 19.9) m
Distance between bogie pivots:	(14.2 -16) m
Tare weight:	Lower than the reference vehicle (22 -24.5) t
Load weight:	Higher than the reference vehicle (39.5 - 56t)
Loading capacity	51 m²
Max. speed (unloaded):	120 km/h
Max. speed (loaded):	100 km/h
Min. curve radius (on track):	150 m
Min. curve radius (single wagon):	75 m
Bogie type:	Y25 series

Figure 1 Example reference flat wagon type Rgns

Source: http://www.sektorel.com/Images/39361-4B4CBC69B767D7302D9893FEB3C5F3CD.jpg (accessed: 18.05.2017)

Cereals 'hopper' wagon (e.g., UIC class U or T)	
Max. axle load:	(21 - 22.5) t
Length over buffers:	(14.2 – 17) m
Distance between bogie pivots:	(9.4 – 12.1) m
Tare weight:	Lower than the reference vehicle (21.5 - 25.5) t
Load weight:	Higher than the reference vehicle (55 - 66.5t)
Loading capacity	(60 – 80) m³
Max. speed (unloaded):	120 km/h
Max. speed (loaded):	100 km/h
Min. curve radius (on track):	150 m
Min. curve radius (single wagon):	75 m
Bogie type:	Y25 series

Figure 1 Example reference cereals 'hopper' wagon type Uagps

Source: http://www.ansett-logistics.ro/services/wagon-fleet/ (accessed: 17.05.2017)

Open self-discharge wagon class F for bulk materials (e.g., Faccs type)	
Max. axle load:	22.5 t
Length over buffers:	(12.2 – 14.8) m
Distance between bogie pivots:	(7.2 – 9.8) m
Tare weight:	Lower than the reference vehicle (20 -21.5) t
Load weight:	Higher than the reference vehicle (~68.5t)
Loading capacity	(34 – 48) m³
Max. speed (unloaded):	120 km/h
Max. speed (loaded):	100 km/h
Min. curve radius (on track):	150 m
Min. curve radius (single wagon):	50 m
Bogie type:	Y25 series

Figure 1 Example reference open self-discharge wagon type Faccs

Source: http://www.hvle.de/en/rail_vehicles/FACCNS.html (accessed: 02.05.2017)

Wagon design | Selection of materials

- Selection methodology based on:
  - The importance/effect on the behaviour and overall properties of the rail vehicle
  - The practicality in using them in the selection methodology.
- Level 1 criteria:
  - Specific elasticity modulus: stiffness divided by density;
  - Specific tensile strength: strength divided by density;
  - Fatigue behaviour/strength;
  - Material cost (Euro/kilogram);
  - Applicability to different components of the wagon:
    - Manufacturing processes;
    - Joining;
    - Specific stresses on different vehicle components and/or sub-assemblies (flexural, tensile, compressive, etc.)

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- Level 2 criteria:
  - Life-cycle-cost (LCC)
  - Environmental impact:
    - Recyclability;
    - CO2 footprint;
    - Noise reduction;
    - Energy save/use;
    - Etc.
  - Resistance to degrading factors:
    - Impact resistance;
    - Fire-smoke-toxicity resistance;
    - Resistance against chemicals, humidity, temperature, etc.;
    - Abrasion resistance;
    - Etc.

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Level 1 assessment and pre-selection of candidate materials

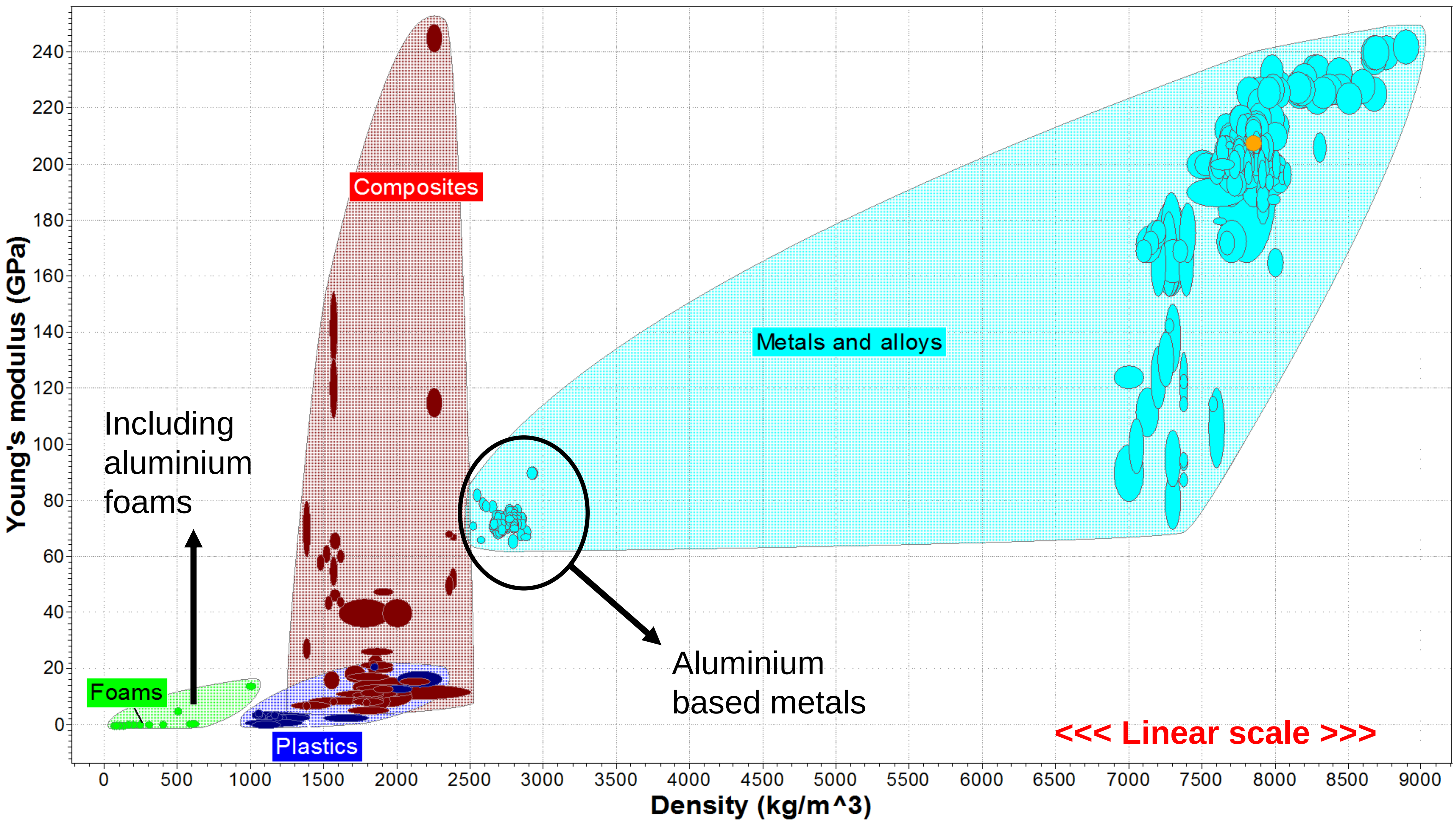
Identification and assessment tool: Granta CES EduPack 2017 software

Selection of example candidate materials for rail vehicle applications.		
Material Family	**Material type**	**Examples**
Steels	Conventional	S275, S355
	High strength steel	S890, S960, TWIP steels, TRIP steels
Composites	Monolithic	Carbon and Glass fibre reinforced laminated polymers
	Sandwich	Fibre reinforced laminates with foam or honeycomb core
Aluminium		Al6160-T6, Al6082,-T6, Al7020-T6

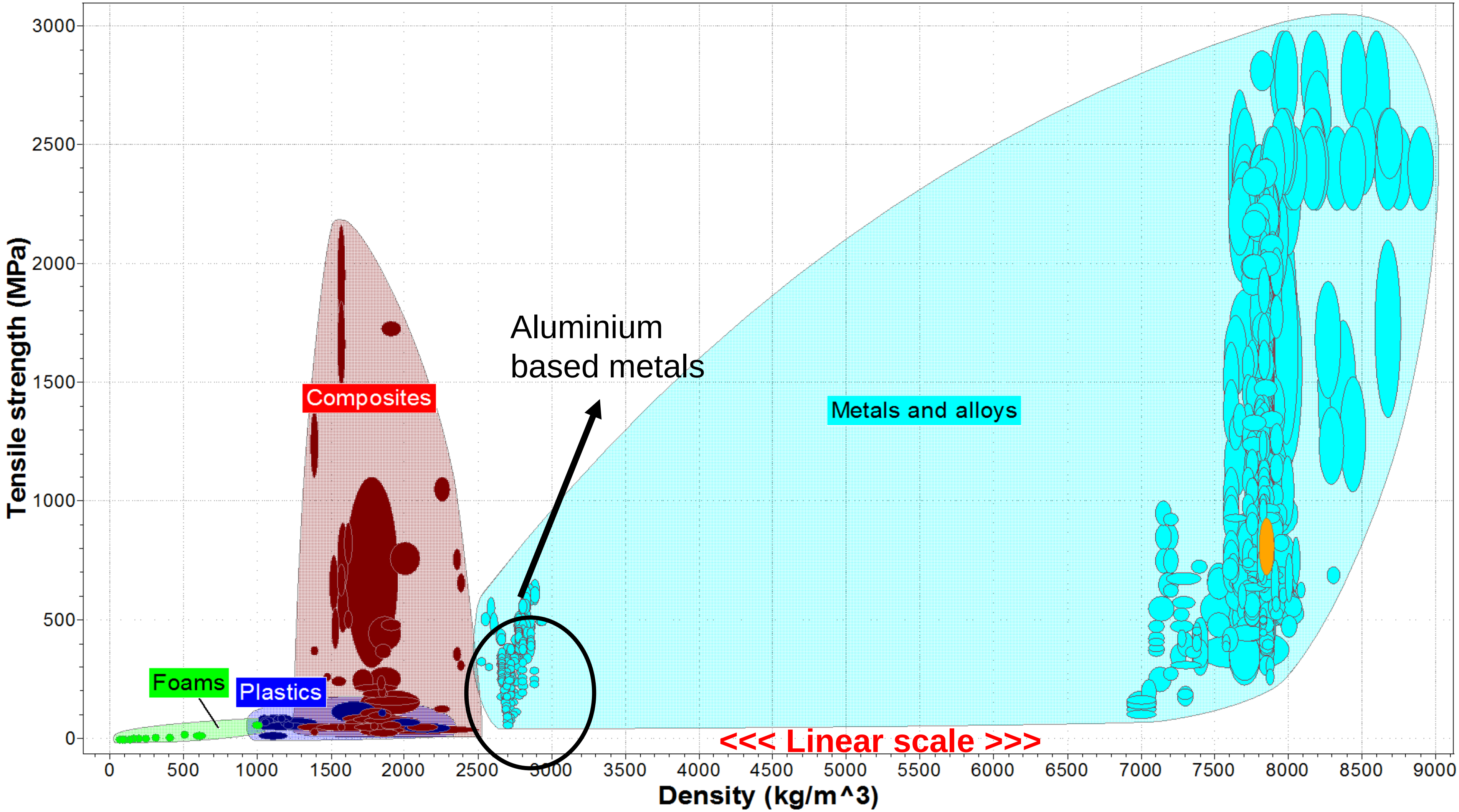
The ***important specifications*** for rail vehicle parts include:

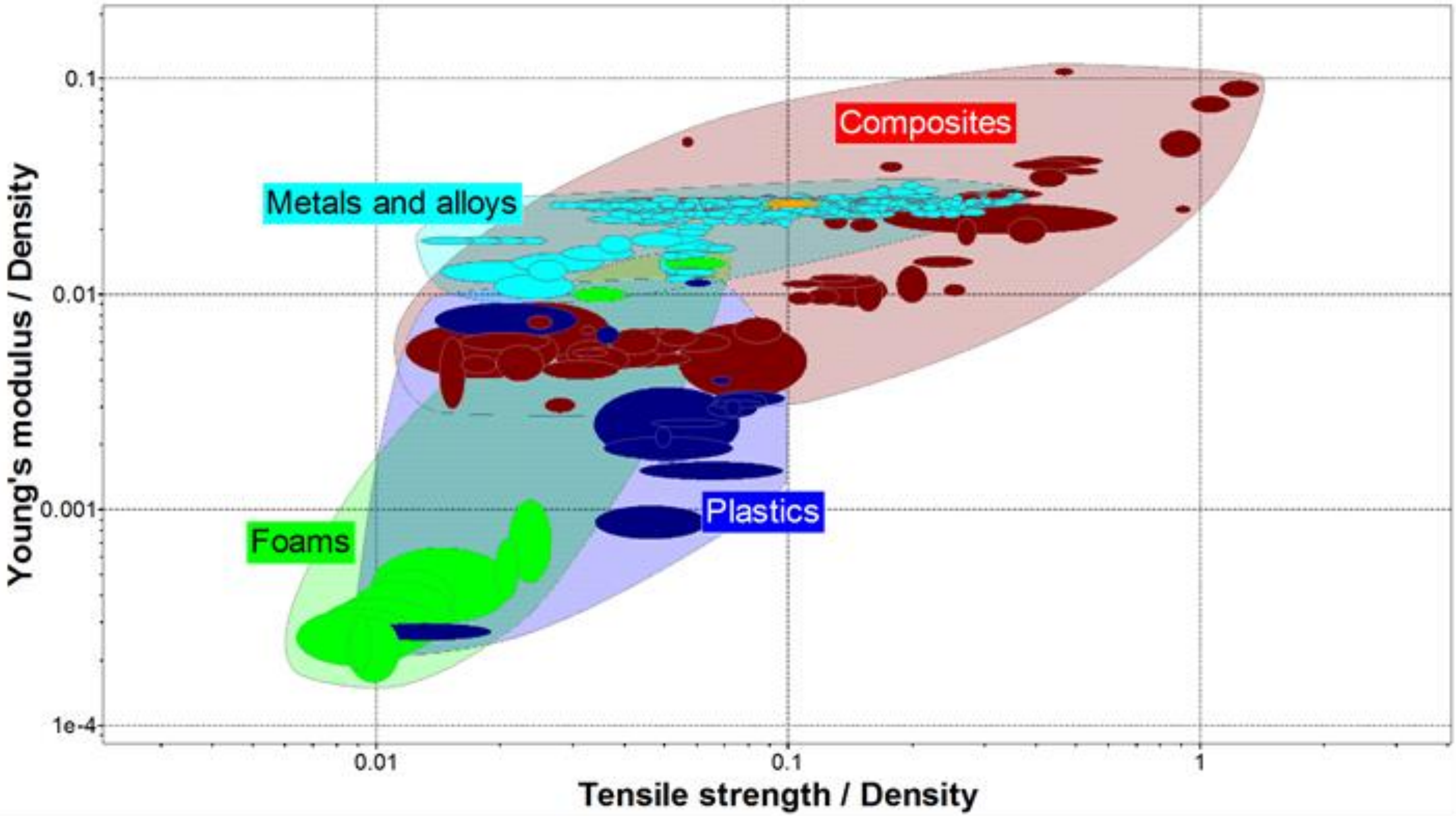
- *Tensile strength (and yield strength for metallic materials);*
- *Elongation at failure;*
- *Density;*
- *Young's modulus, and*
- *Price.*

The ***relevant material families*** are conventional metallic materials, lightweight composite materials, plastics, and foams (which have important applications in sandwich composite configurations).

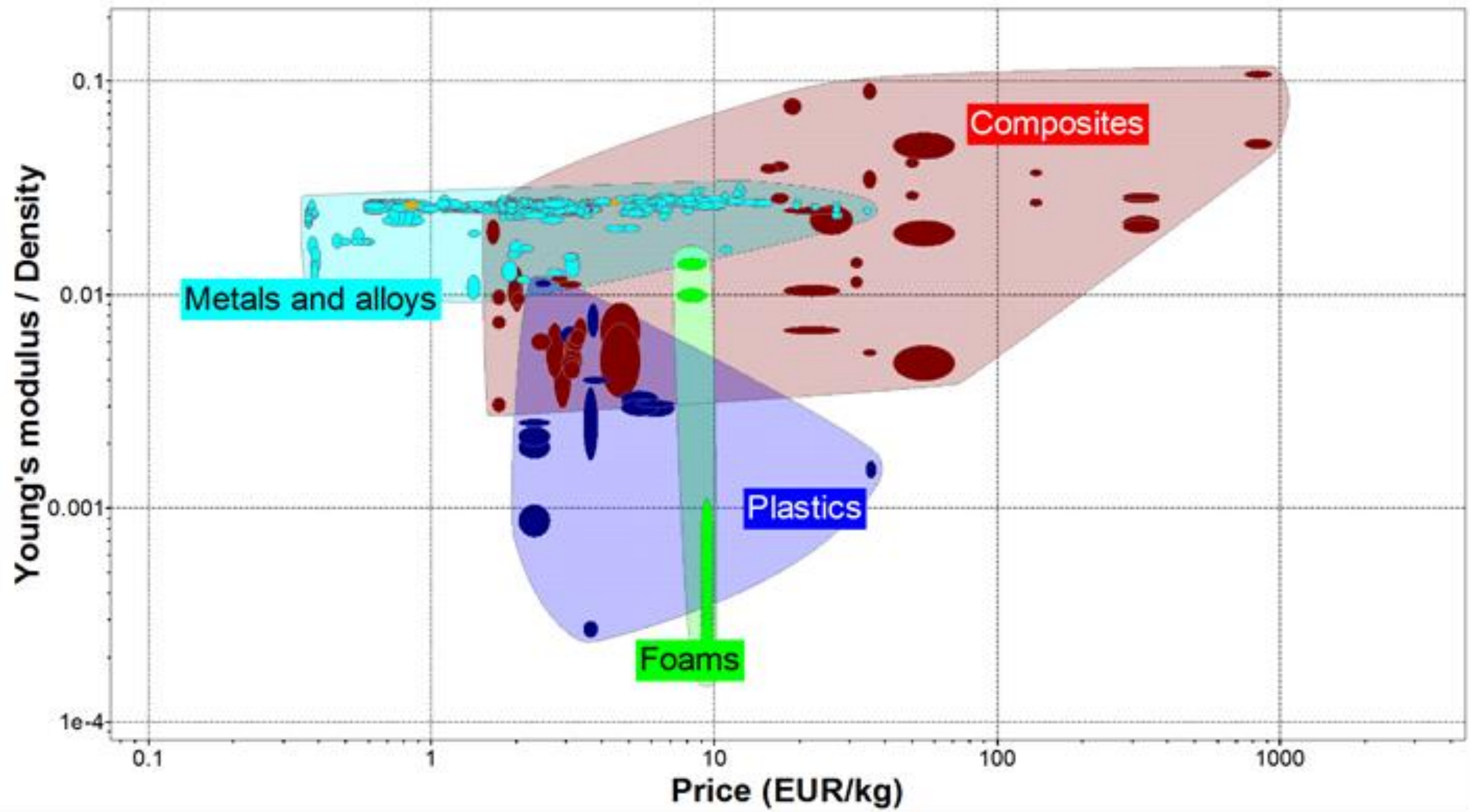

Young's modulus (GPa)
240
220
200
180
160
140
120
100
80
60
40
20
0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
7000
7500
8000
8500
9000
Density (kg/m^3)
Composites
Metals and alloys
Foams
Plastics
Including aluminium foams
Aluminium based metals
<<< Linear scale >>>

❖ Example analysis of considered material families

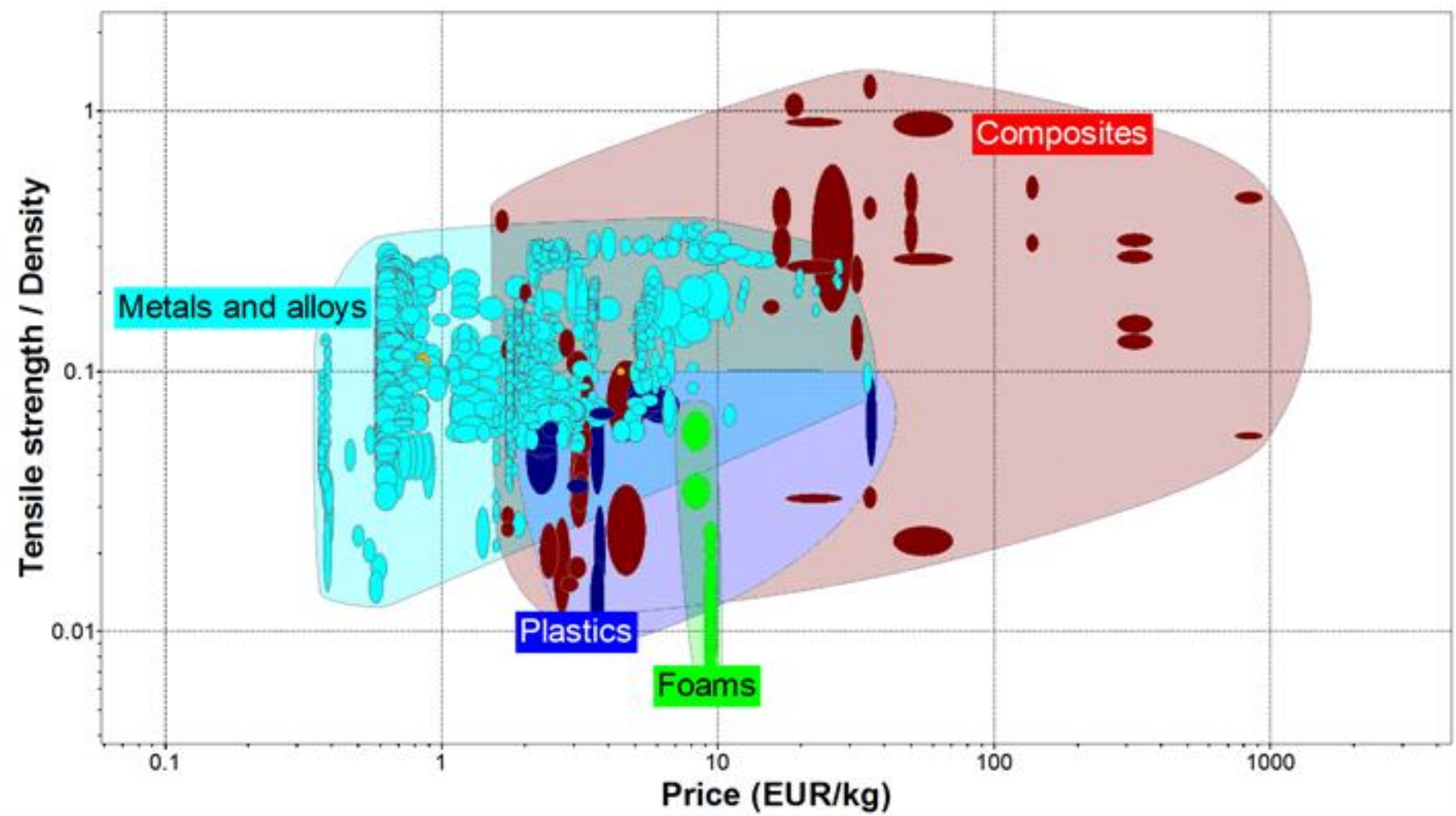




General comparison between the potential material families
(Specific modulus vs specific tensile strength for candidate material families)



Specific modulus vs price for candidate material families.



Specific tensile strength vs price for candidate material families.

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Level 1 assessment and pre-selection of candidate materials

Shortlist of example selected materials.

Fam	Material type	Yield S (MPa)	Tensile S (MPa)	Elonga-tion (%)	Price (EUR/kg)
Metallic Materials	TRIP (Transformation induced plasticity) steel	47.88%	52.72%	20.45%	-131.11%
	TWIP (Twinning induced plasticity) steel	40.84%	78.18%	150.00%	-170.00%
	Structural steel, S960QL	170.42%	93.63%	-54.54%	n/a
	Structural steel, S275N	-32.39%	-21.81%	6.81%	-19.22%
	Aluminium - Al6106-T6	-43.66%	-54.54%	-63.63%	-840%
	Aluminium - Al6005-T6	-30.98%	-46.72%	-55.90%	-750%
	Aluminium - Al6082-T6	-26.76%	-41.81%	-55.90%	-895%
	Structural steel, S355JR	355	470 - 630	22	0.4 - 0.5
Composites	Polyester/E-glass fibre, woven fabric, QI lay-up	-74.70%	-74.70%	-32.50%	-23.89%
	Epoxy/E-glass fibre, woven prepreg, biaxial lay-up	-41.30%	-41.30%	-11%	-1817%
	Epoxy/E-glass fibre, UD prepreg, UD lay-up	-7.77%	-7.77%	25%	-1487%
	Polyester/E-glass fibre, pultruded rod	690 - 828	690 - 828	2	1.6 - 1.8

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Level 2 assessment and final selection of candidate materials

Assessment using qualitative indicators.

Example comparison of selected materials with respect to some relevant Level 2 criteria.

Property (Resistance to)	Candidate Material		
	TWIP steel	TRIP steel	Polyester/E-glass fibre, pultruded rod
Water	Acceptable	Acceptable	Excellent
Weak acids	Limited use	Limited use	Acceptable
Strong acids	Unacceptable	Unacceptable	Acceptable
Weak alkalis	Acceptable	Acceptable	Unacceptable
Strong alkalis	Limited use	Limited use	Unacceptable
Organic solvents	Excellent	Excellent	Unacceptable
UV radiation (sunlight)	Excellent	Excellent	Good
Flammability	Non-flammable	Non-flammable	Highly flammable
Galling resistance (adhesive wear)	Acceptable	Acceptable	-

- ***High strength steels in railway vehicle applications***
  - ✓ Potential applications: structural parts (bogie and vehicle frames, vehicle body, etc.);
  - ✓ Potential mass reduction: 30-35%;
  - ✓ Recyclability: 100%;
  - ✓ Price: above traditional structural steels, however, convenient.
  - ✓ Drawback: gaps in manufacturing, lack of standard acceptance norms.
  - ✓ frames,

- ***Polymer composites in railway vehicles applications***
  - ✓ Focus and successful applications so far - in passenger vehicles;
  - ✓ Potential applications: bodyshells, tanks, support elements, etc.;
  - ✓ Potential mass reduction: 50-75%;
  - ✓ Flexibility in manufacturing of 3D complex shaped parts - significant advantage leading to reduction of no. of parts, labour time, etc.;
  - ✓ Major barriers: the lack of relevant standards to take into account composite intrinsic properties; different inner structures and failure mechanisms compared to metallic materials (e.g., FRPs are sensitive to impact loads).

- ***Aluminium in railway vehicle applications***
  - ✓ Potential mass reduction: 50% (e.g., carbodies);
  - ✓ Potential power savings: 14%;
  - ✓ Relative higher cost (however, could be compensated from the lower consumption within 2-3 years);
  - ✓ Time for individual maintenance of aluminium alloy body is typically shorter than that of the steel by 15%-45%;
  - ✓ Recyclability: up to 80% (when the vehicle comes to the end of life cycle).

- ***Other potential materials in railway vehicle applications***
  - ✓ Steel foams:
    - *new forms of steel that can be produced through different manufacturing processes such as powder metallurgy, polymer/oxide ceramic foam precursor, lotus-type, etc. (non-standard so far);*
    - *potential applications: bulky cast or forged parts in the running gear like housings/covers, supports, etc., which do not require to withstand intense loads/stresses, however, can achieve significant mass savings.*
  - ✓ Natural or recyclable fibre reinforced composites (e.g., for interface or support elements).

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Lightweight Design Solutions *(ongoing work)*

Objective: Develop **novel design concepts** for ***lightweight components***, ***subassemblies*** and ***structural parts*** of freight vehicles.

Target: a mass reduction of ***up to 50% for the relevant items***. Novel design concepts will address the wagon and bogie frames, as well as the wagon body parts.

Approaches:

- Use of selected options from the range of analysed candidate materials, e.g.:
  - HSS (TRIP/TWIN) for wagon and bogie frames and structural elements;
  - FRP (Polyester/E-glass, pultruded) for wagon body (e.g., hopper).
- Optimisation of shapes and dimensions;
- Modular design of overall wagon structure by using interchangeable re-designed components, for increasing the vehicle capacity and availability.

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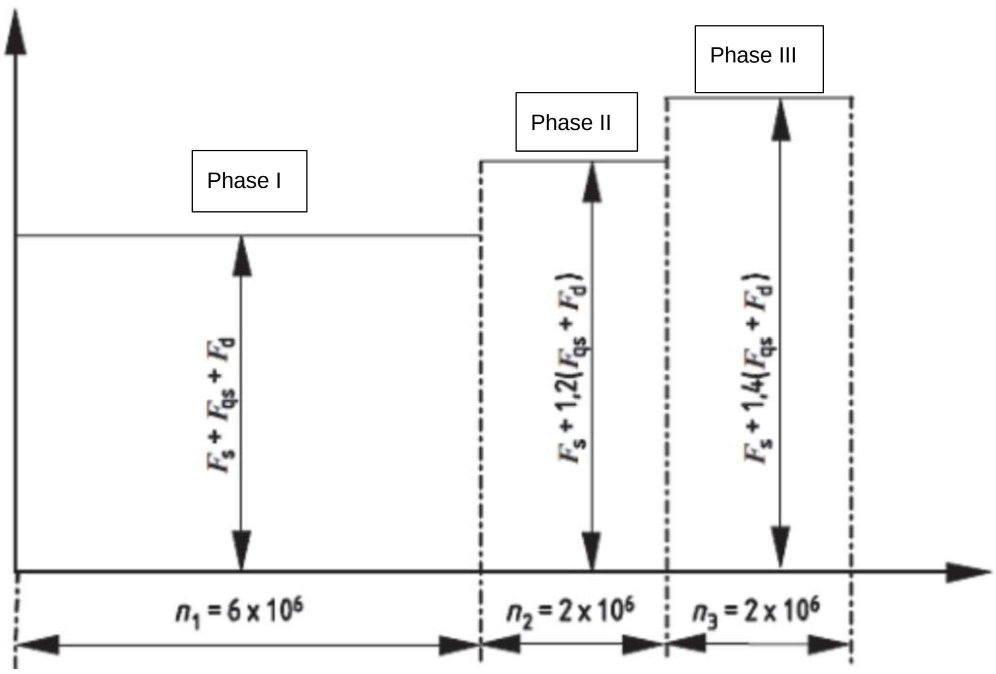
Lightweight Design Solutions *(ongoing work)*

Identified challenges (for analysis and testing):

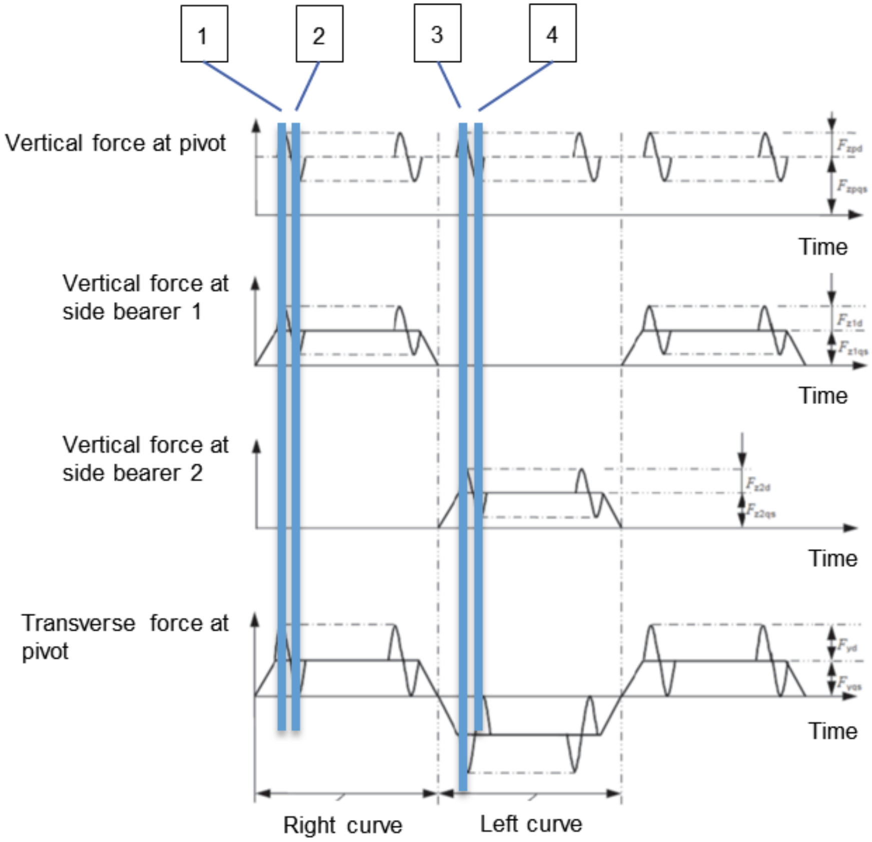
- Fatigue behaviour of structural frames made of HSS (particularly in welds);
- Structural design of large bodies (e.g., hopper) made of FRP (static and dynamic loads);
- Specific issues related to FRP solutions, e.g.:
  - *Dissimilar joints*
  - *Resistance to impacts;*
  - *Resistance to abrasion;*
  - *Adhesion to coating and painting (e.g., hoppers for cereals).*

Fatigue test according to EN 13749:2011

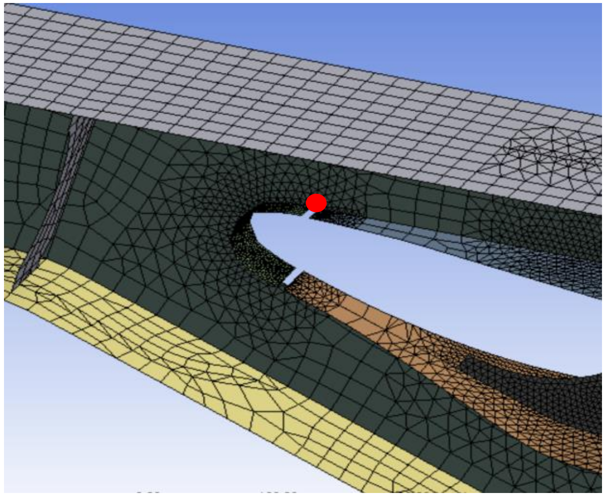
Load phases of fatigue test

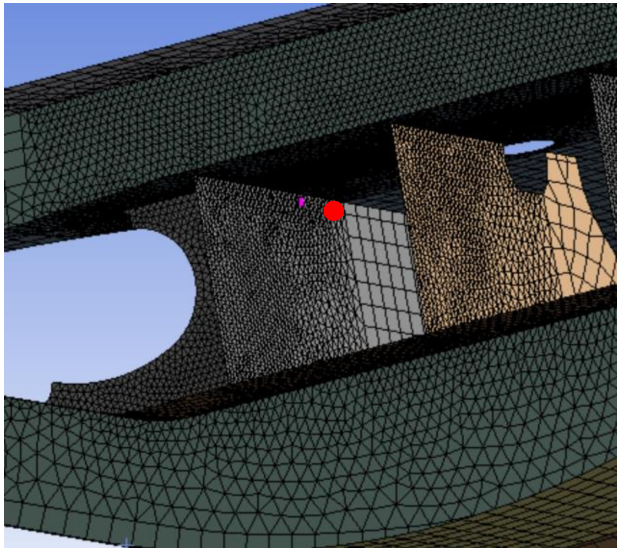


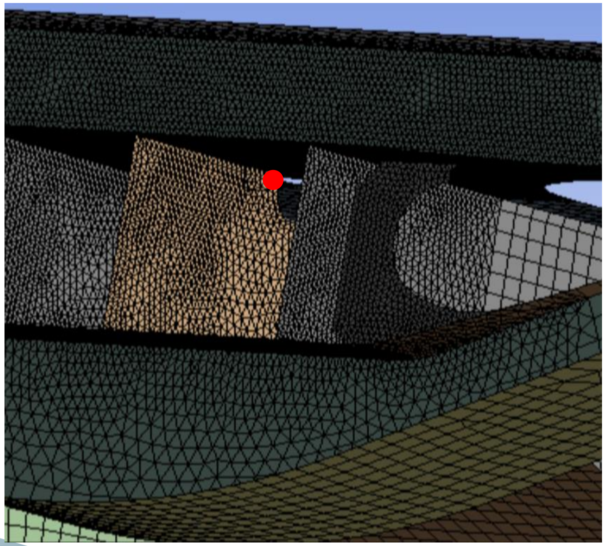
Simulation loadsteps for each phase

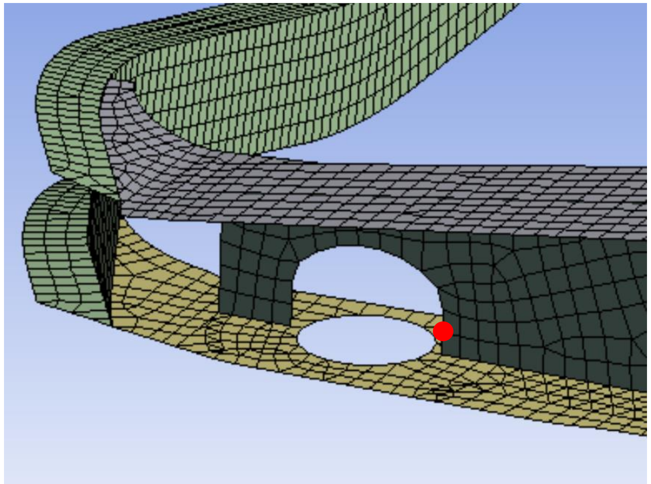


Locations for stress life evaluation



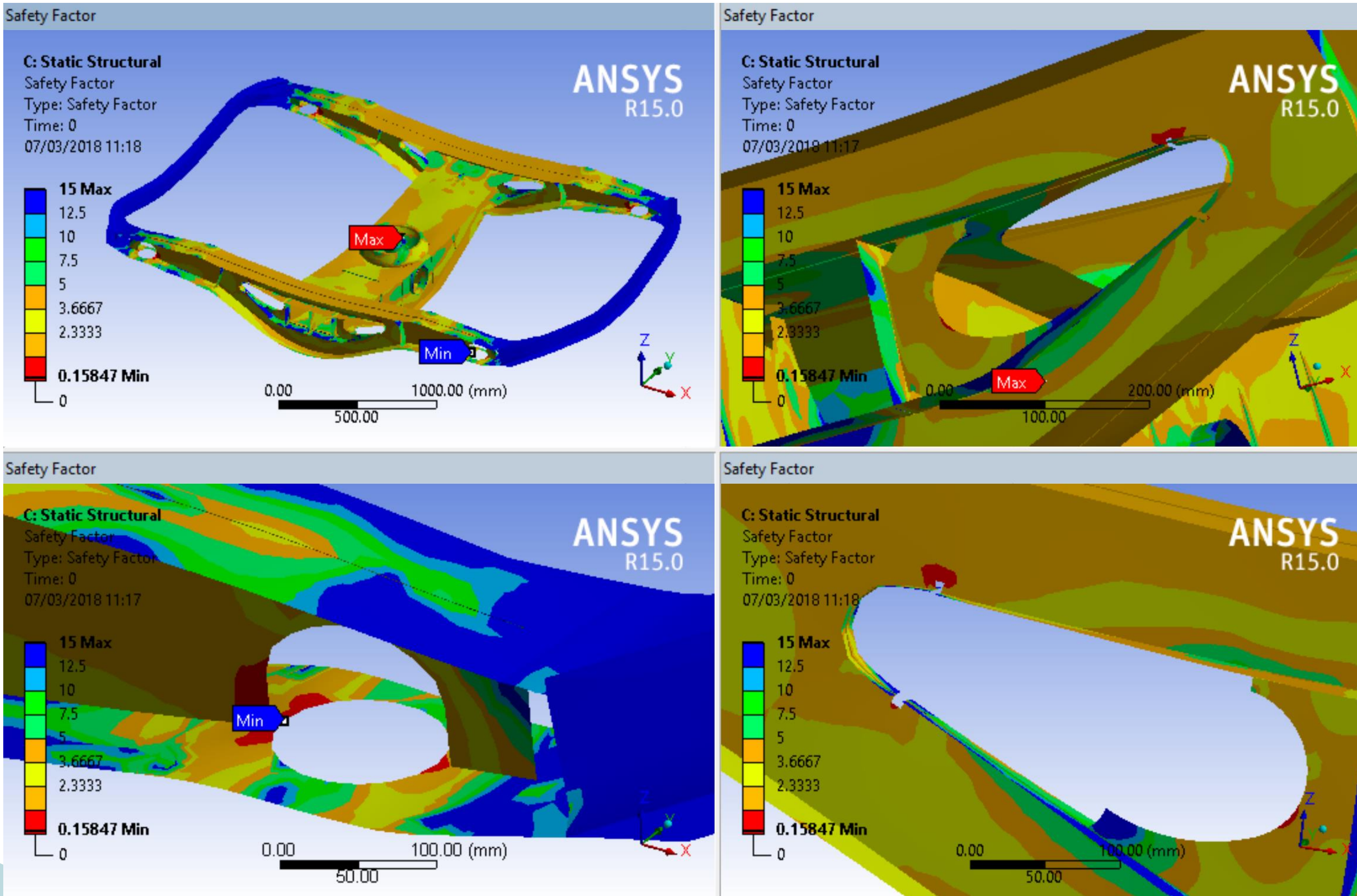




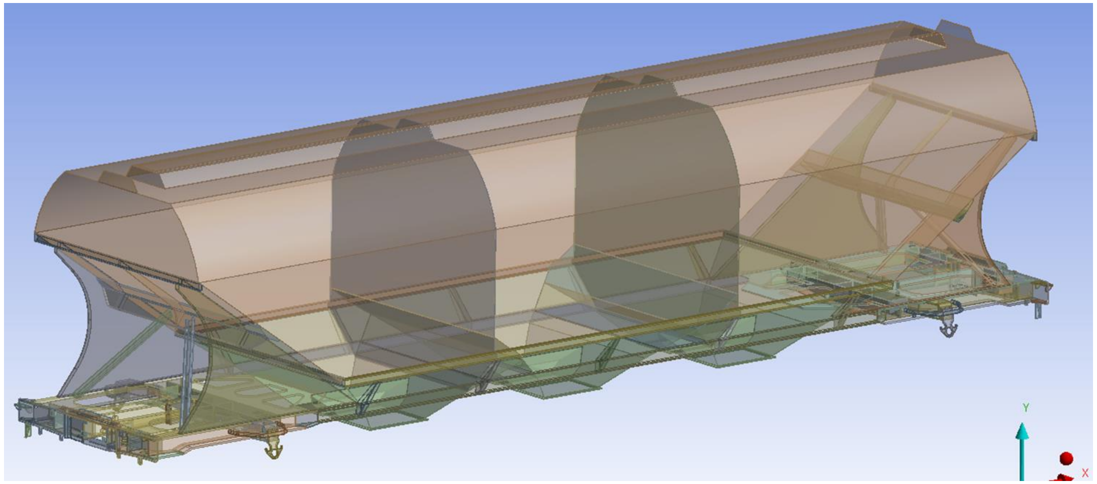


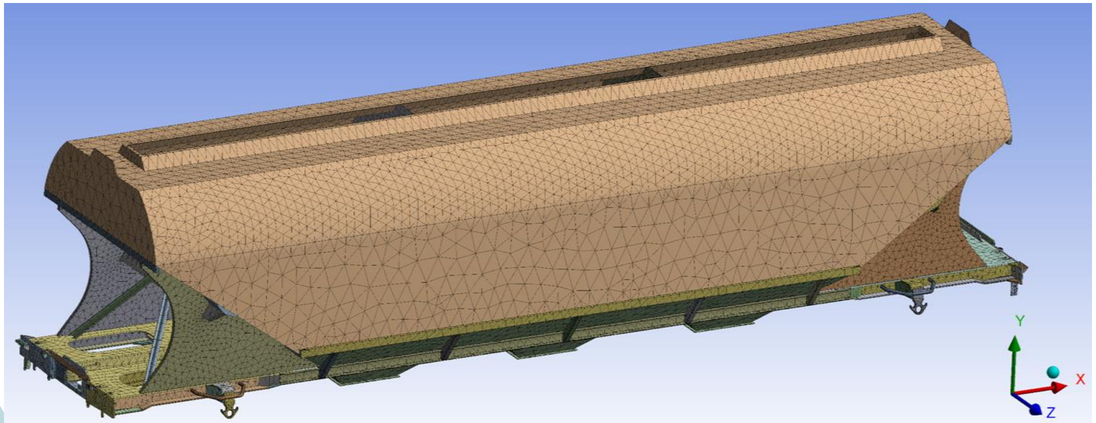
Example preliminary results: fatigue analysis

Safety factor results:

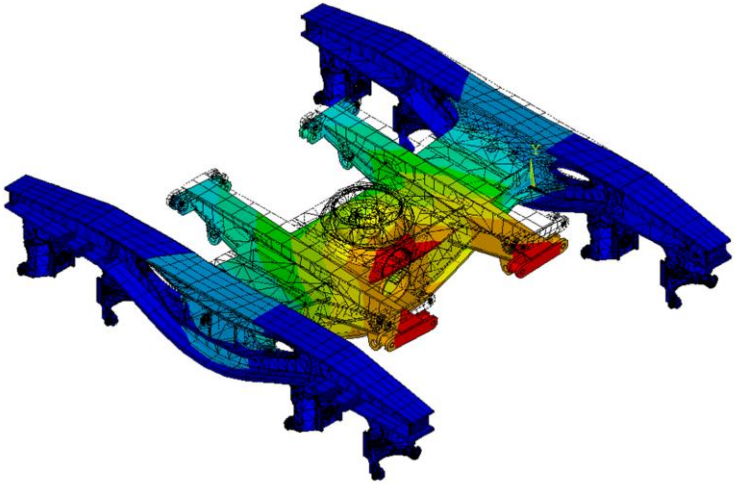


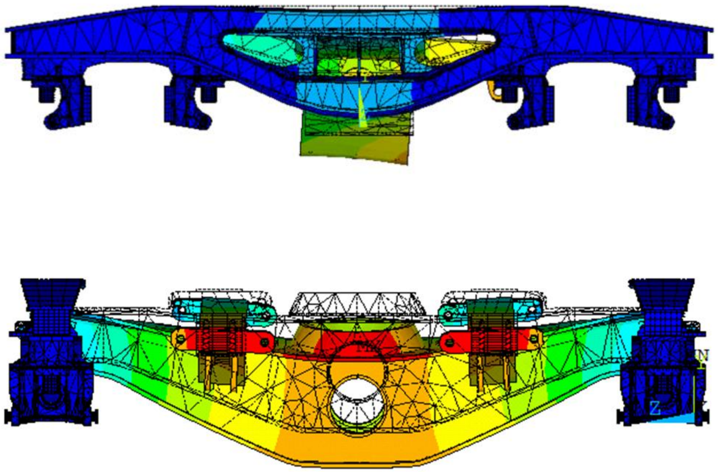
FEM/FEA of modified designs:





FRP Cereals hopper





Modified Y25

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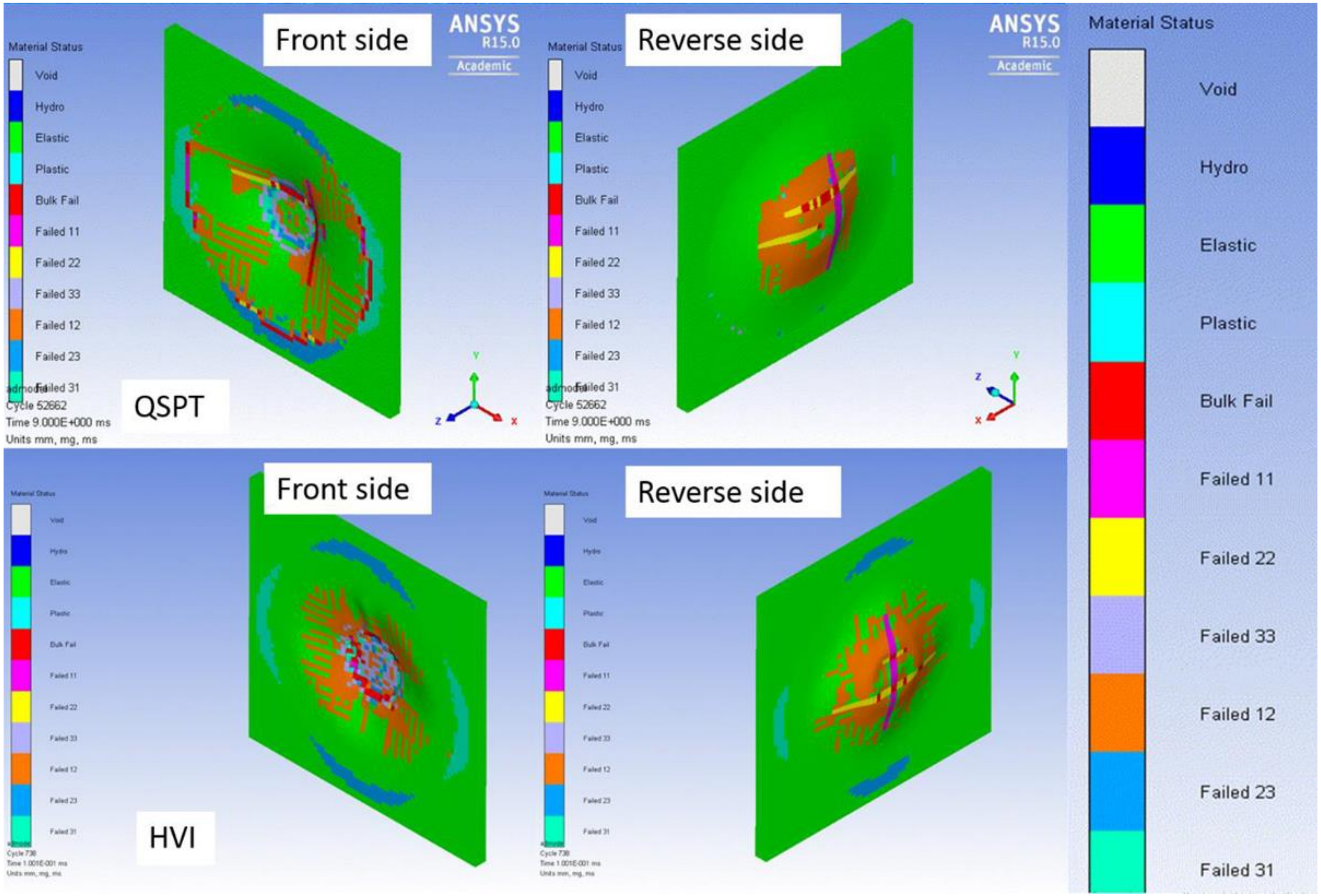

Numerical model prediction of penetration resistance of GFRP laminates (top) showing the variation. (Bottom) Front and reverse side figures of the laminates under QSPT and high-velocity impact (HVI) showing the failure modes were similar (Onder et al.)

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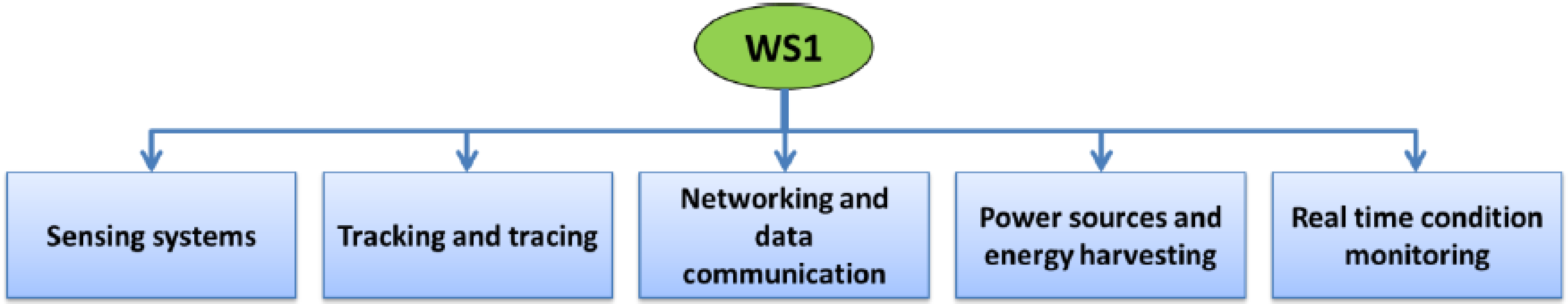
Specific technical objectives

Development of an autonomous self-powered sensor system for tracing and condition monitoring of key parameters of for critical types of cargo

- Formulation of the **overall measurement concept** and the sensor arrangement;
- Design of a **power supply system** through use of energy harvesting technologies;
- Design of a **communication system**, including Wireless Sensor Network (WSN) for intra-train communication and Train-to-Ground (T2G) communication between the WSN and a central application server;
- Establishing **IT infrastructure** for data processing, storage and representation



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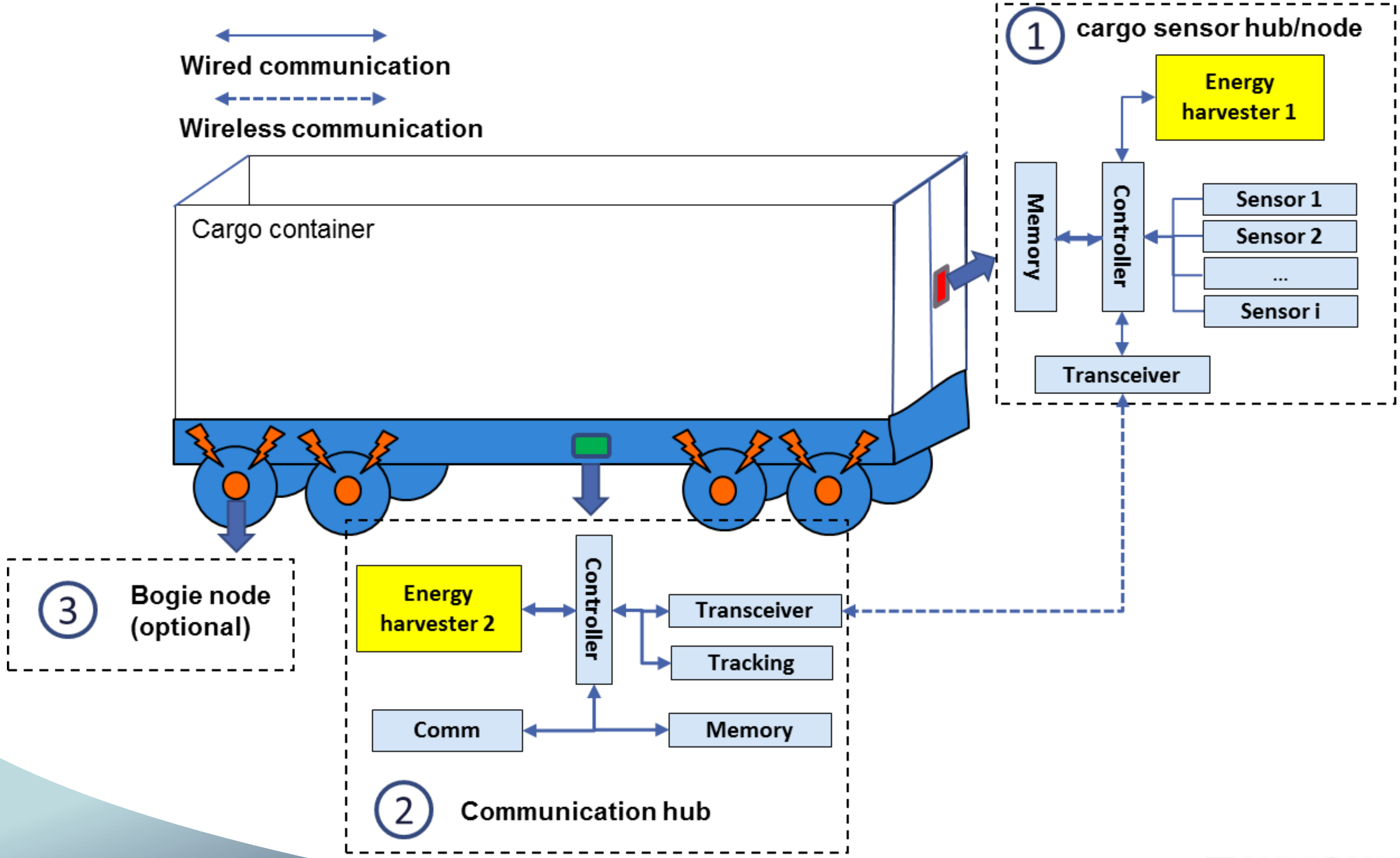
Achievements in Task 2.1

- Definition of user cases:
  - ***Container wagons*** *transporting high-value sensitive goods;*
  - ***Tank wagons*** *transporting dangerous goods;*
- Design concept
  - *Vehicle-side **hub** for the basic functions, i.e. tracking and T2G communication;*
  - ***Distributed sensor*** *nodes for cargo parameter sensing, ensuring the scalability for wagon condition monitoring;*
  - *Permanent power supply or long battery life by using different **energy harvesters**;*
  - *Development and testing of the **RFID-based solutions** at a lower TRL;*
- Possible sensor montage solutions
  - *Container: **door mounting***
  - *Tank: using the **existing fittings** such as the dip tube and the dome*
- Sensor features: measurement range, sample rates, accuracy, etc.
- Potential system architecture with different technical risks

Achievements in Task 2.1 Monitoring Sensor System

- Example - System architecture 1



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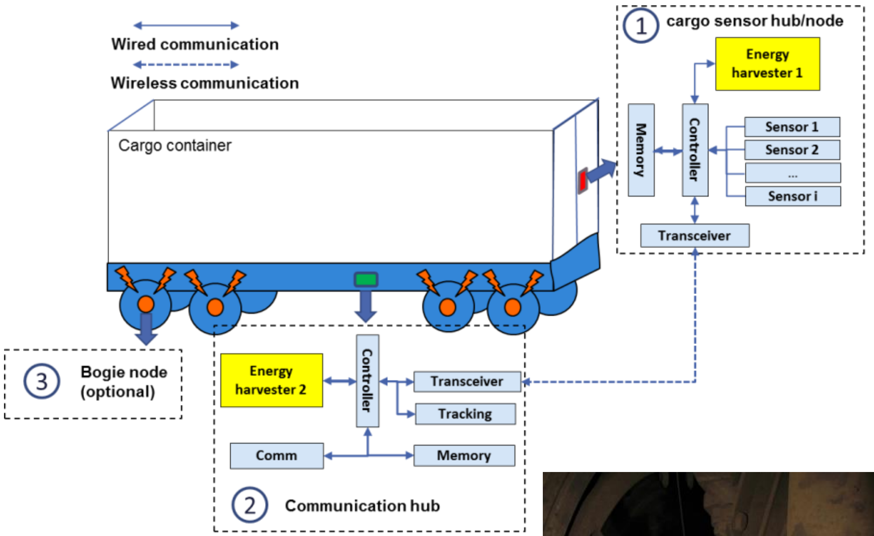
Achievements in Task 2.1 Monitoring Sensor System

- Communication hub
  - *Power supply: solar*
  - *Tracking: GPS*
  - *T2C*
  - *Receiver for WSN*
- Bogie nodes
  - *Power supply: vibration harvester*
  - *Sensor: temperature and acceleration*
  - *Sender for WSN*
- Cargo sensor node
  - *Power supply: Radio Frequency (RF) harvester*
  - *Sensor: temperature, humudity, light, etc.*
  - *Sender for WSN*



Prototype of RF powered temperature sensor

Bogie node from Perpetuum

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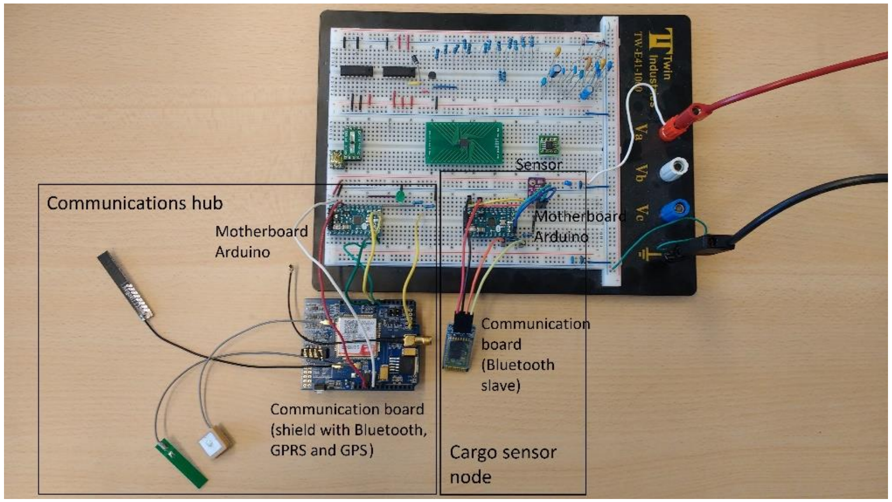
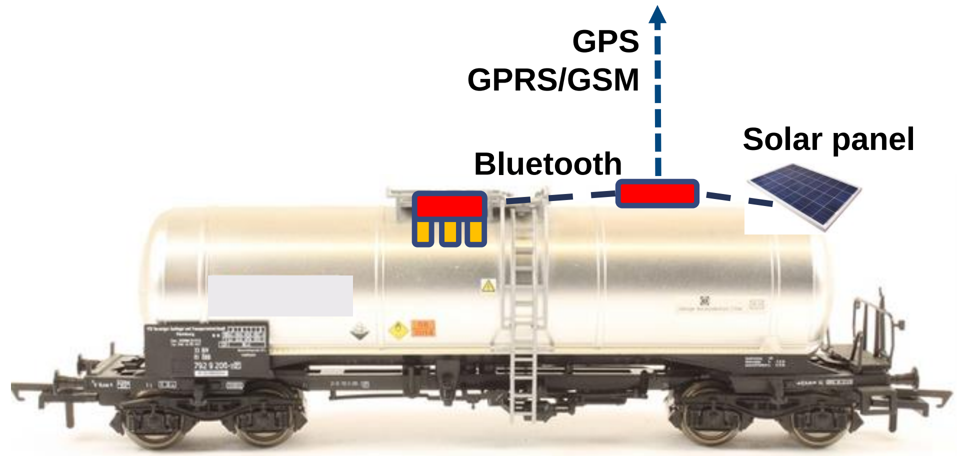
Activities in Task 2.2 Energy Harvesting Powering Systems

- Trade-off analysis of energy requirements, with respect to
  - ❑ *System architecture options*
  - ❑ *Operation requirements*
  - ❑ *Installation*

  Through
  - ❑ *Theoretical calculation based on the assumed scenarios*
  - ❑ *Laboratory measurements for different operational modes*
- Assessment of potential energy harvesting solutions
  - ❑ *Vibration energy harvesting*
  - ❑ *RF energy harvesting*
  - ❑ *Solar energy harvesting*

Activities in Task 2.3 Wireless Sensor Networks and Communication



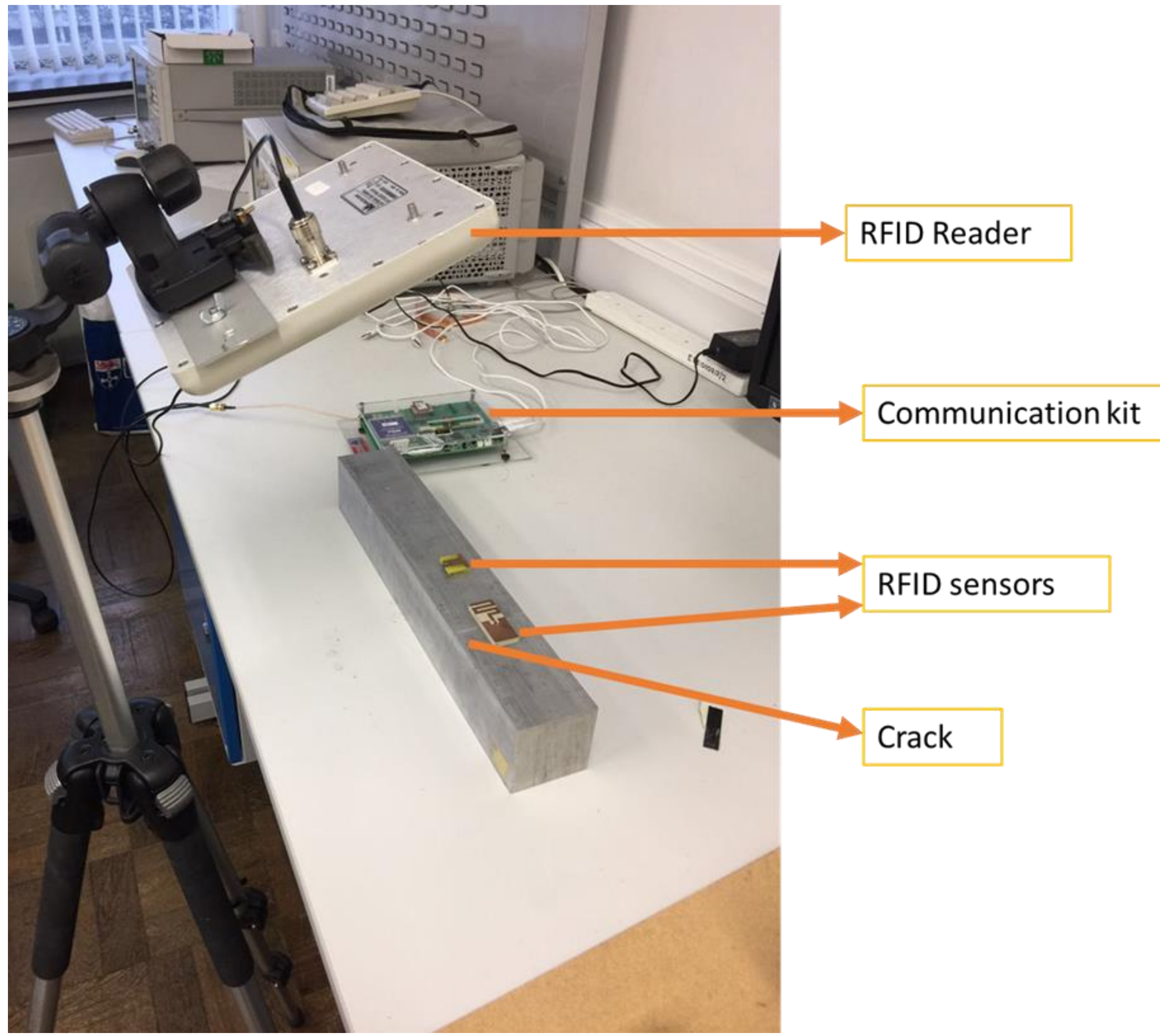


Name	Freq. band	Topology	Range	Data rate	Packet size	TX power consumption
802.15.4	2.4 GHz	Mesh	50 m	250 kbit/s	100 bytes	0.69 µJ/bit
Bluetooth LE	2.4 GHz	Star	10 m	1 Mbit/s	100 bytes	0.26 µJ/bit
Proprietary (Perpetuum)	*433 MHz*	*Star*	*> 70 m*	9600 bps	*160 bytes*	*10 µJ/bit*
LoRa-based radio (Perpetuum)	*920 MHz*	*Star*	*100 m*			*10 µJ/bit*

Activities in Task 2.3 - RFID technology

Battery Free Humidity and Temperature System (with Hygro-Fenix-HT221-DKSWB reader)

MS5803-14BA pressure and temperature sensor (FARSENS)



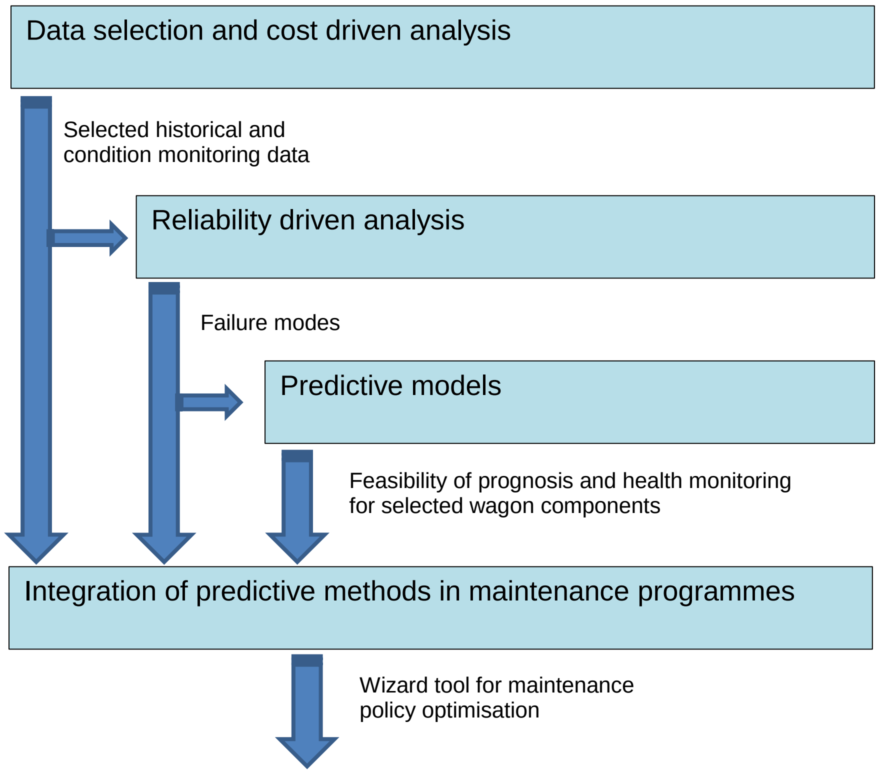
Predictive maintenance (PM) | Objectives

High-level objective: to define and validate a predictive maintenance strategy for the intelligent freight wagon

Specific objectives:

- Development of an integrated predictive maintenance approach using both condition monitoring and historical data, and further support the implementation of predictive models and tools in rolling stock maintenance programmes:
  - *Identify methods for the predictive maintenance of freight wagons in order to increase substantially the performance and cost effectiveness of rail freight transport;*
  - *Define a prioritisation of freight vehicle components and sub-systems in terms of their relevance for predictive maintenance;*
  - *Investigate failure mechanisms and fault detection methods for the selected vehicle components and sub-systems highly significant to the whole vehicle's LCC and reliability;*
  - *Select the available condition monitoring and failure history data for selected critical wagon components and sub-systems, and develop predictive models and detect trends in the monitored condition towards a failure state with a time-to-failure prediction;*
- Develop guidelines for maintenance procedures to implement predictive maintenance practices for the cases studied
- Perform an assessment of the benefits provided by the developed predictive maintenance strategies.

- The WS3 will develop specific **failure mechanisms** and **fault detection methods** for selected components based on a prioritisation of their relevance for PM;
- These will be integrated with improved maintenance rules, limits and procedures, resulting in an **integrated predictive maintenance procedure**.
- The final outcome of the WS3 will be a **wizard tool for maintenance policy optimisation**, able to use health monitoring information to define an optimal maintenance policy



PM | Participants and roles

Horizon 2020
European Union Funding
for Research & Innovation

- LRS, reliability-driven analysis of existing data, structural health monitoring of railway wheelsets
- POLIM, cost-driven and reliability-driven analysis of existing data, SHM of wheelsets and suspension components, integration of monitoring and models in predictive maintenance
- TUB, reliability-driven analysis of existing data, models for wheel wear, support to the implementation of PM policies
- UNEW, cost-driven and reliability-driven analysis of existing data SHM for wheels, model of roller bearing damage, support to the implementation of PM policies
- PER, reliability-driven analysis of condition monitoring data, SHM of roller bearings
- HVLE, provision of historical data and data for LCC evaluation
- UVA, provision of historical data and data for LCC evaluation
- VUZ, compliance of PM policies with the existing regulation

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Shift2Rail

Approach to the LCC evaluation

CAPEX	PURCHASING COST	€
OPEX	MAINTENANCE COST	
	CORRECTIVE MAINTENANCE COST	€/year
	PREVENTIVE MAINTENANCE COST	
	HIDDEN COST	
	OPPORTUNITY COST	€/year
	SERVICE DISRUPTION COST	
	DISPOSAL COST	€

Prioritisation of subsystems in the bogie based on their Net Present Value (NPV)

	WHEELSET	BRAKING SYSTEM	SUSPENSION SYSTEM
NPV	23.228,77 €	9.770,56 €	6.872,42 €
Critical components	1	2	3

Prioritisation of wheelset failure modes based on the reliability-driven analysis

Failure	GCU code	Nc (failure per 100 sub-assemblies)	Failure rate	Frequency rank	GCU class	GCU control criteria	Severity		Detectability		Frequency		Risk Priority Number (RPN)
axle crack	1.6.1.1	2	1.31E-06	4	5	VC	unsafe without warning	10	moderate	5	low: relatively few failures	3	200
wheel out of round	1.3.3; 1.7.2; 1.7.2.1	23	6.04E-06	6	4	M; VC/VC	very high	8	very low	7	moderate: often there are failures	6	336
wheel crack	1.3.5; 1.3.6; 1.5	4	3.50E-07	3	4	M; VC/VC	very high	8	very low	7	low: relative few failures	3	168
Wheel: build-up of material	1.3.4;	3	1.97E-06	4	4	M	very high	8	very low	7	moderate: seldom there are failures	4	224
wheel thermomechanical crack	1.3.5; 1.3.6; 1.5	4	3.50E-07	3	4	M; VC	very high	8	very low	7	low: relatively few failures	3	168
wheel flat	1.3.3; 1.7.2; 1.7.2.1	23	6.04E-06	6	4	M	very high	8	very low	7	moderate: often there are failures	6	336
wrong tread profile	1.2.3	1	1.31E-06	4	4	M	very high	8	very low	7	moderate: seldom there are failures	4	224

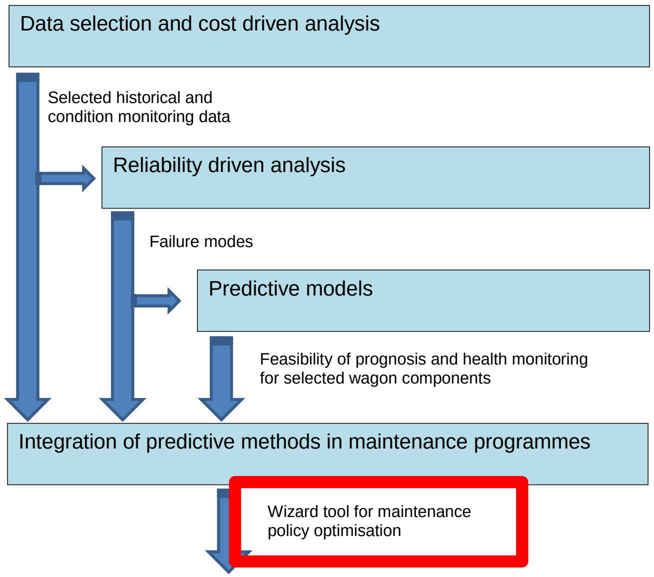
Main conclusions from component prioritisation

- Based on the results of cost-driven and reliability driven analyses, the **most critical failure modes are**:
  - Wheel flat and wheel out-of-roundness;
  - Axle crack;
  - Broken helical coil springs;
  - Worn shock absorbers;
  - Bearings

- The economic savings enabled by PM are mainly in terms of **reducing the downtime of the wagon** and the related opportunity costs

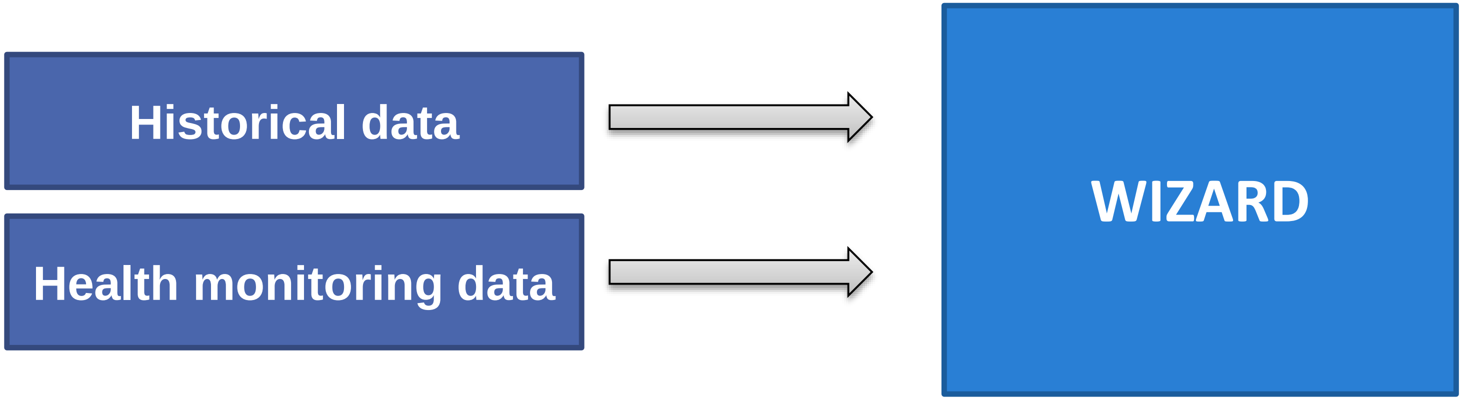
- Based on the results of the reliability-driven analysis, important benefits can be expected by the implementation of monitoring and PM in terms of **increased reliability and safety**.

The PM Wizard as the final outcome of WS3



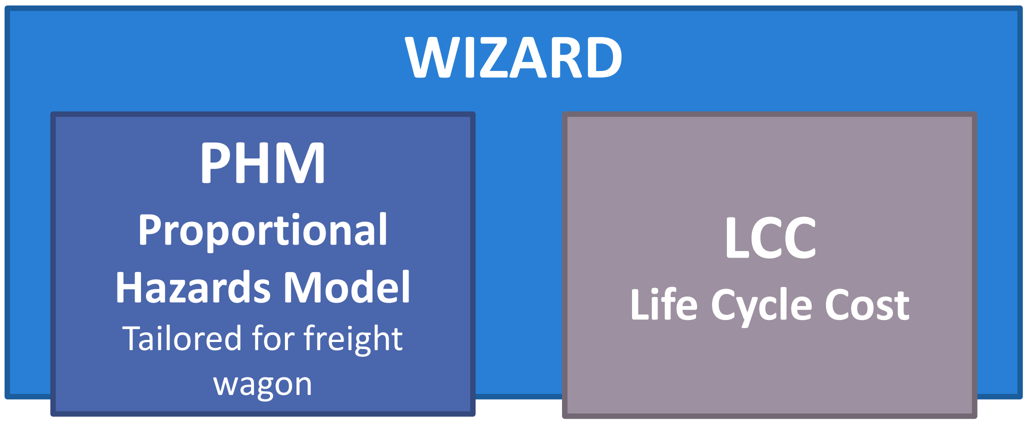
WS3 ends with the development of a wizard tool able to assess the effectiveness of the predictive model considering the MIMOSA standard (ISO 13374) to allow fitting with a standard vision of predictive maintenance.

The inputs of the wizard are both historical and health monitoring data.



The PM Wizard as the final outcome of WS3

The effectiveness of the predictive maintenance policy will be assessed on a life cycle cost (LCC) basis. This will allow the selection of the most suitable maintenance strategy that will optimize the overall cost of component during its whole life.



The wizard, based on Proportional Hazards Model (PHM), covers the role of a Decision Support System (DSS) that enables maintenance operators to take decisions about the most adequate maintenance policy considering historical data and real-time (or close-to-real) health data of the component.

Thank you for your kind attention!