LCA Neoballast
(Life Cycle Assessment Neoballast)

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Barcelona, 19/06/2014

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ACKNOWLEDGMENTS

First of all, I am grateful to the Spanish company COMSAEMTE for its collaboration, contribution and support in this project development.

I wish to express my sincere thanks to Carlos Saborido and Nahuel Manzo, for providing me with all the necessary facilities.

I place on record, my sincere gratitude to Andrés López Pita, for his constant collaboration and guidance in this project.

I also place on record, my sense of gratitude to one and all who, directly or indirectly, have lent their helping hand in this venture.
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Abbreviations

ALAF  Asociación Lationamericana de Ferrocarriles
AP    Acidification Potential
CH₄   Methane
CLA   Coefficient of Los Angeles
CML   Centrum coor Milieukunde Leiden
CO₂   Carbon dioxide
DCB   Dichlorobenzene
ELT   End of Life Tires
EP    Eutrophication Potential
EU    European Union
GHG   Green House Gases
GWP   Global warming potential
HTP   Human Toxicity Potential
ISO   International Organization for Standardization
LCA   Life Cycle Assessment
LCC   Life Cycle Cost
LCI   Life Cycle Inventory
LCIA  Life Cycle Impact Assessment
PO₄³⁻ Phosphate
SO₂   Sulfur dioxide
UNE   Una Norma Española
1. Executive summary

1.1 Introduction

Among the tools available to evaluate environmental performance, life cycle assessment (LCA) provides a holistic approach to evaluate environmental performance by considering the potential impacts from all stages of manufacture, product use and end-of-life stages. This is referred to as the cradle-to-grave approach.

LCA is a tool for quantifying the environmental performance of products taking into account the complete life cycle, starting from the production of raw materials to the final disposal of the products, including the material recycling if needed. The most important applications for a LCA are:

- Identification and improvement opportunities through identifying environmental hot spots in the life cycle of a product.
- Analysis of the contribution of the life cycle stages to the overall environmental load, usually with the objective of prioritizing improvements on products or processes.
- Comparison between products for internal or external communication, and as a basis for environmental product declarations.
- The basis of standard metrics and the identification of Key Performance Indicators used in companies for life cycle management and decision support.

In recent years, life cycle thinking has taken a more prominent role in environmental policy making. Renowned institutions, have adopted life cycle thinking and an increasing number of different stakeholders are feeling the pressure to reduce the environmental impact associated with global consumptions. In parallel to these activities the European Commission is working on a standard for environmental footprint.

LCA generally comprises four major components (Figure 1):

- Goal and scope definition.
- Life cycle inventory (LCI) – data collection and calculation of an inventory of materials, energy and emissions related to the system being studied.
- Life cycle impact assessment (LCIA) – analysis of data to evaluate contributions to various environmental impact categories.
- Interpretation – where data are analysed in the context of the methodology, scope and study goals and where the quality of any study conclusions is assessed.
The environmental management standards relating to life cycle assessment used in this project are as follows:


1.2 Goals

The primary goal of this study is the comparison in environmental aspects between Neoballast and the conventional ballast, in accordance with ISO 14040:2006 and ISO 14044:2006 standards.

The secondary goal is to provide reliable and up to date data to meet requests from customers and external studies.

It is also of interest for future product developments, the analysis of the different environmental impacts caused by each stage of the product life and the more detrimental ones.
1.3 Scope

This document is realized in a way to analyse the environmental impact of a product, for such a purpose this document compiles a Life Cycle Assessment (LCA) of the product in case. This technique shows the environmental impacts in all the stages of a product. The major stages in a LCA study are raw material acquisition, materials manufacture, production, use/reuse/maintenance, and waste management. The system boundaries, assumptions, and conventions to be addressed in each stage are presented.

LCA is a versatile tool for quantifying the overall (cradle-to-grave with end of life recycling) environmental impacts from a product, process or service.

The product to be analysed is the ballast used as track bed on the railroad system.

The scope details of the study is outlined in the following sections covering the product systems and system boundaries, the functional unit, the allocation procedures, the types of impacts considered in the LCIA methodology, some data requirements and assumptions, as well as the limitations of the study.

As the goal of the study is the comparison in environmental aspects between the new performed ballast (Neoballast) and the conventional ballast, a big part of the information utilised deserves both.

1.3.1 Common information for Neoballast and ballast

For the product systems and system boundaries, the life cycle inventory and assessment tools for ballast developed comprise the hard rock primary aggregates system. That means three life cycle phases: Extraction, Processing and Waste Management/Restoration.

The Extraction phase includes three sub-phases, namely overburden removal, primary fragmentation, loading and hauling. These operations are considered to include all the necessary elements representative of the primary aggregates extraction processes (Smith, 2001).

The Processing life cycle phase is composed of 5 sub-phases for the ballast: primary crushing, scalping screening, secondary crushing, tertiary crushing and final screening. The specific processing operations vary greatly as they are influenced by a large number of parameters, such as the aggregate properties, potential waste products, operating criteria, methods of stockpiling, storage and transport, space availability and safety (Barksdale, 1996). In any case, we consider ballast as being the only product considered is this LCA analysis and then those parameters can be reduced and monitored.
The **Restoration** in most sand and gravel operations is progressive. On the other hand, restoration of crushed rock quarries is often carried out after a major production phase is completed. The soil/overburden is usually replaced in the disturbed areas of the operation surrounding the quarry to help restoring vegetation, making these areas ready for a previously agreed purpose. This may be for land filling, agriculture, wildlife or as a new public amenity.

The **Distribution system to the work site** also serves both the conventional ballast and the Neoballast. In this study, two types of transport are considered: road transport by heavy goods vehicles and rail freight. It may be the case that the two types of transport are combined for the distribution in a particular case. Normally for the ballast utilized in track renewal only rail transport is utilized, while road vehicles are used mostly in the construction of the new lines. Then, the option of combining different transportation scenarios is provided in the life cycle assessment tool for aggregates distribution.

### 1.3.2 Neoballast particular information

The Neoballast manufacturing phase is composed of two different sub-phases: obtaining of components from other industries (rubber powder and binder) and the production of the Neoballast from the components obtained before and ballast.

### 1.3.3 Differences between Neoballast and ballast

First difference appreciated is clearly the different processes for obtaining the Neoballast in comparison to the conventional ballast. On one hand once the aggregate is in accordance to appropriate characteristics required for conventional ballast, it is directly transported to the railway for its use. On the other hand, for Neoballast, the aggregate passes by the intermediate process of Neoballast manufacture.

As a consequence of that process, Neoballast has better properties and different behaviour than the conventional ballast. In particular the rubber powder and binder binding and protection improve its resistance to abrasion and to fracture. This results in a different lifetime for each product, clearly higher for Neoballast, as detailed in future chapters of this LCA.

Once the ballast is on the work site, it has to be put in place under the track and then tamped and cleaned in the railroad maintenance process during all its life. Railway maintenance is used to prolong the life of the rail infrastructure. With each passing movement of trains along a ballasted railway track, the track bed is exposed to live loads that deteriorate the condition of the infrastructure.
Track bed operations do not contribute to excessive emissions in overall railway emissions (Farnham, 2007 and Von Rozycki, 2003) but for the scope of this LCA study it is key to know how the different types of ballast affects the maintenance processes and then changes the emissions from the resurfacing fleet currently used (tampers, profilers, ballast cleaners and stabilizers).

Furthermore, the bed cleaning process is realized equally for both ballasts, excepting the fact that non reused materials take different paths depending on ballast type. For conventional ballast after bed cleaning machine reused the material available, the rejected material can be also used in other works with other material requirements. On the other hand, Neoballast shows its effectiveness allowing the rejected material (only ones which lost coverage, rejected majority) to return to the Neoballast performing process and so on recovering the lost layer.

1.4 Methodology

In a LCA the results quality and the extent to which they can be applied depends critically on the methodology used. It is an important fact to use a clear and transparent methodology which is also in accordance with previous goal and scope definitions. International Organization for Standardization (ISO) standards have been deployed to provide guidance on methodological choices and to set rules for reporting.


There are many universities researching and developing LCA particular methodologies and data. In accordance to our purpose and taking into account GaBi manual explanations the methodology adopted is the so-called CML 2001 method. This is the methodology of the Centre for Environmental Studies (CML) of the University of Leiden, in Netherlands, and focuses on a series of environmental impact categories expressed in terms of emissions to environment. The main reason to adopt this methodology is that it uses European data to derive the impact factors. This geographical particularization is highly important for this LCA, as it is also relevant its extended utilisation in Europe and the compatibility with GaBi 6. Furthermore the CML method includes classification, characterization, and normalization. The impact categories for the global warming potential and ozone layer depletion are based on the IPCC factors. Further information is available at the Centre for Environmental Studies (CML), University of Leiden.
2. Project context

2.1 Ballast and its influence in track stability

The railway system represents a huge investment and is build for very long periods. It is then very important to study how this initially invested amount can be minimised, an even more important, how to reduce the maintenance cost over the years and/or extending its lifecycle.

In the particular case of the railway track, over its different components, the ballast is the one with less innovations and improvement since its origin. But, at the same time, represents one of the more important sources of maintenance costs as it transfers the efforts to the platform and guarantees the track stability. Ballast good performance is necessary for trains to run at the expected speed under safety conditions.

2.1.1 Importance and requirements for the ballast bed to be used in railway track

The ballasted track has been and still is predominant in the railway lines built around the world. Despite the recent implementation of the concrete slab tracks the predominance of ballasted tracks is justified due to the lower investment cost, much easier construction and less technical difficulties.

Among the most important functions provided by the ballast bed to the entire infrastructure, we can highlight:

- The uniform transmission to the platform of the received stress from the sleepers and produced by trains circulation;
- The provision of certain elasticity to the whole track;
- The stabilization of the sleepers, against the longitudinal and transversal charges coming from trains passing over the track;
- The vibration damping and sound absorption, providing greater quality and comfort for trains;
- The semi-rigid structure allows the correction of most of the distortions on track profile, using tamping and stabilizing machines;
- The effective drainage of the track structure, thus eliminating the problems of freezing and thawing.

To fulfill the above detailed functions, it is necessary to have a certain thickness of ballast. This magnitude is between 25 and 35 cm, as with lower values the objective would not be achieved, but with higher ones the track would have unacceptable vertical deformation and the geometric defects would also increase.
To meet abrasion conditions, the ballast requires Deval coefficient generally greater than 15.

Ballast is obtained by crushing rock mass and must meet certain specifications in terms of quality of the parent material and grain size. It is transported by truck to where is needed or it can be loaded into special wagons that allow trains to discharge it on track.

In the Spanish case, as established by the UNE EN 13450, ballast must come from:

- The extraction of quarried stone, followed by crushing, screening and classification, with or without subsequent industrial process involving thermal or other modification.

- Reuse of existing ballast coming from railway tracks after renewal.

The rocks chosen for ballast must be siliceous and preferably of igneous or metamorphic origin. Therefore, not limestone or dolomitic nature can be accepted.

In addition ballast can not contain any fragment of wood, organic matter, metals, plastics, alterable stones or thixotropic, expansive, soluble materials, combustible or pollutants (industrial waste).

Ballast consisting of river boulders and coming from rocks of different geological nature is not accepted.

The higher are the requirements, the greater the difficulty in finding natural aggregates to meet them and, simultaneously, the greater is the transport cost as it has to be found in remote locations far away from the work sites. That is why the Railway Infrastructure Managers select and homologate only the quarries able to provide material meeting the requirements.

2.1.2 Ballast laying, tamping and other maintenance conditions required

One of the methods to put ballast in place is initially installing the track components (sleepers, attachments –clips- and rails) and then to run trains over this provisional track hauling the hopper wagons that discharge ballast on infrastructure. To provide the required support to the sleepers it is necessary to compact the ballast forming the track layer: this process of compression is undergone by performing an operation called track tamping.

In this operation, vibrating metal “tamping tools” are inserted below the lower face of the sleepers (Figure 2) holding ballast compaction. To do so, the railroads have the so called tamping machines, an example of which is shown in Figure 3. For tamping being possible and effective, ballast particles need to be above a certain
size, with a particular granulometry and to have certain hardness in order to avoid excessive deterioration when vibrated.

![Figure 2: Tamping tools movement](image2.png)

From the practical point of view, the experience has highlighted the suitability of available ballast sizes between 20 and 60 mm. In Figure 4 suitable ballast granulometric profile is shown for the Spanish network in operating conditions according to the FOM 1269:2006 order.

![Figure 3: Tamping machine](image3.png)

![Figure 4: Sieve for all types of ballast](image4.png)
Into the granulometric profiles within permitted by law, there are different categories of ballast according to the particle size distribution. In Table 1, taken from the UNE EN 13450 standard, ballast types labeled A to F are distinguished. An A type ballast is the most utilized and has the best quality.

<table>
<thead>
<tr>
<th>sieve size (mm)</th>
<th>ballast size from 31.5 mm to 60 mm</th>
<th>ballast size from 31.5 to 83 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>weight percentage which passes through %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>granulometric category</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td>80</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>63</td>
<td>100</td>
<td>97 a 100</td>
</tr>
<tr>
<td>50</td>
<td>70 a 99</td>
<td>70 a 99</td>
</tr>
<tr>
<td>40</td>
<td>30 a 65</td>
<td>30 a 70</td>
</tr>
<tr>
<td>31.5</td>
<td>1 a 25</td>
<td>1 a 25</td>
</tr>
<tr>
<td>22.4</td>
<td>0 a 3</td>
<td>0 a 3</td>
</tr>
<tr>
<td>31.5 a 50</td>
<td>≥ 50</td>
<td>≥ 50</td>
</tr>
<tr>
<td>31.5 a 63</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Table 1: Ballast classification
Source: UNE EN 13450

Together with the general classification, it should be noted that the quantities of fine material from the different categories of ballast has to be under a maximum established. This constraint is intended to prevent the loss of ballast bed porosity and the reduction of the elastic characteristics. In the following two tables is shown the standard according to UNE EN 13450.

<table>
<thead>
<tr>
<th>sieve size (mm)</th>
<th>maximum weight percentage which passes through small particles category</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
</tr>
<tr>
<td>0.5</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Table 2: Maximum content of small particles on the ballast
Source: UNE EN 13450

<table>
<thead>
<tr>
<th>sieve size (mm)</th>
<th>maximum weight percentage which passes through category</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
</tr>
<tr>
<td>0.063</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 3: Ballast categories depending on the fines content
Source: UNE EN 13450

There is the obligation to minimize the presence of flat particles, thus because the difficulty that they introduce in the tamping process and for its tendency to slip. The regulations state that the particles of the ballast need to have polyhedral shapes fractured faces defined by sharp edges, with not more than 3 times the smallest dimension (thickness) the greater size. The minimum thickness of the
granular elements is 25 mm and the percentage of stones with a maximum length greater than 100 mm shall be ≤ 4%.

2.1.3 Physical and mechanical ballast properties

When a vehicle axle travels all along the track on the rails, two simultaneous phenomena are produced: first, a vertical bending, depending on the vertical resistant capacity, that affects a length in between 3 to 4 m; second, the lifting of portion of the track in front of the axle in the direction of its advancing movement.

The vertical deflection has a maximum value just under the point of load application (axle of the vehicle) and it is usually between 1,5 and 2 mm under the action of a wheel load of 10 tones. The magnitude of the waveform of the lift is typically around 1/10 of the vertical deflection, then 0,15 to 0,20 mm. Although the small elevation of the track and its subsequent annulations due to the continuous movement of the vehicles axles may appear to have no practical influence, the reality is huge different.

Indeed, the subsequent batting of the sleepers over the ballast, as a consequence of the successive axes passing through (a freight train can represent the effect of more than 160 axes) and the increasing use of concrete sleepers (300-380 kg) versus primitive wooden sleepers (80 kg), can cause a rapid deterioration of the ballast particles.

To meet the condition of hardness, it is required that the rock mass for the ballast has a simple compression resistance of at least 120 MPa. The rock mass that most often fulfills these conditions are those of igneous and metamorphic origin.

With respect to ballast fragmentation criteria it is required for this material to have a coefficient of Los Angeles (CLA) below a certain value. The references are the following quantities: CLA ≤ 15 for railway lines ready for trains running above 200 km/h, and CLA ≤ 18 for conventional lines with less maximum speeds allowed.

Depending on the type of ballast, the UNE EN 13450 standard defines the values of CLA required. For type 1 ballast CLA must be equal to or less than 14% for type 2 less than or equal to 16% and finally the ballast Class 3 must have a CLA ≤ 20%.

During the construction of high-speed lines in Europe, the French railways established for the ballast, the so-called global hardness ratio, which includes both Deval coefficient and coefficient of Los Angeles (Figure 5). For main lines with speeds up to 200 km/h and heavy traffic, the overall coefficient of desirable hardness is around 17. For high-speed lines the required value is 20.
Figure 5: Coefficient determination abacus overall hardness (DR)

Note in Figure 5 as above for the first group of lines (V≤200 km/h) a global hardness ratio of 17 corresponds to a coefficient of Los Angeles equal to 20 and Deval coefficient greater than 15. For high-speed lines in where the global hardness ratio is equal to 20, the coefficients of resistance to fragmentation (Los Angeles) and abrasion resistance (Deval) are around 17 and 20 respectively.

By way of synthesis, in Figure 6 a scheme of reference set out to reduce the functions required to be used for ballast materials determination, also including variables endurance, size or shape that allows more or less verify the performance of such functions.
2.1.4 The ballast role in Track Life Cycle

The ballast has sometimes been defined as the "weakest element in the conventional track" (Lozano, 2007), because of its key role in the stability of the geometrical conditions of the railway track. Cyclic loads to which it is subjected, and the cyclical nature of the contacts between its discrete component parts, causes its crushing over the time and is gradually polluted with small particles, requiring it to be washed or replaced.

The process of deterioration and contamination depends on the load cycles, but also on the characteristics of the ballast itself (such as hardness) or the design of the superstructure (sub base, pollution control layers, geotextiles layers, etc...).
Puebla (2000) quantify the lifetime of siliceous ballast above 300 million gross tons, equivalent to a period of 25-30 years and obviously depending on the railway traffic. French infrastructure manager, RFF, quantifies the lifetime of the ballast in 20 years for high-speed lines and 30 years for more conventional heavy used lines.

In any case, it is interesting to note that the ballast bed under the sleepers is characterized by a marked heterogeneity resistance as revealed by Cabos in 1977 (Figure 7).

![Figure 7: Distribution of the compaction degree of the ballast under the sleepers](image)

Source: Cabos, 1977

The available results demonstrate that in certain railway lines a sudden modification of the track vertical deformation is produced above certain traffic, while in other cases that vertical deformation development presented a much more linear approach.

In relation to the this fact, it is clear that over a certain number of cycles, the vertical deformation of the ballast bed grows significantly for high values of the ballast stress (4 kg/cm²), and then its vertical deformation is multiplied by almost three (Figure 8).
2.1.5 Influence of the different track components (infrastructure and superstructure) in the ballast behaviour

The work of the committee D-117 ORE has made possible to quantify the influence of the components of the track itself (rail and sleepers) and the thickness of ballast in track deterioration. As for the rail, the tests carried out in France and Germany reflected the limited impact of the different rail weights when between 50 and 60 kg/ml. With respect to the sleepers, the experience of conventional French railway lines showed that the ballast bed vertical deformation depends on the square of the sleeper area in contact with it.

In recent years it has been analyzed the effect that the placement of so called elastic pads (the under sleepers) have on reducing the deterioration of rail track. The purpose of those elastic pads is:

- To remove the hardness of the contact between the concrete sleeper base and the ballast.
- To increase the effective bearing surface of the sleeper over the ballast bed.
- To reduce the level of pressure on the surface of the ballast.
- To increase the vertical elasticity of the track.

During the period 1997-2000 the behaviour of different track sections equipped with various solutions in the high-speed line Hannover-Göttingen gave a good opportunity to observe it in detail. Four sections were placed without elastic pads and two more were equipped with elastic pads: then, six sections with the same type of sleeper (B-70-DB) were considered.
The Figure 9 shows the evolution of maximum longitudinal level defects in the period of time mentioned. Discontinuous points correspond to dedicated maintenance operations to reduce the magnitude of track defects.

![Figure 9: Effect of resilient pads in the railway track deterioration](image)

As shown, areas with elastic pads (equipped sleepers) have had a defect rate of increase that is lower than in the other ones. Specifically, in the sections with elastic base sleepers average annual growth rate of maximum longitudinal level defects ranged from 0.7 to 1 mm/year, while the sections with sleepers without elastic base rate variation was 2.4 to 4 mm/year. Since the speed of the defects in the first case were between 25 and 30% lower, it would be reasonable to expect that the maintenance intervals in railway lines fitted with such sleepers could be 3 to 4 times lower. Of course it is necessary to consider the total cost and the economic benefit of using them and also in which type of lines their use would be more suitable.

The final decision to use or not sleepers with elastic pads has to be based on economic considerations, analyzing whether the higher initial economic cost of the sleeper is offset by lower maintenance requirements throughout the full life cycle of the track. The cost of the rubber sole can become significant compared to the cost of the sleeper (40%).

Regarding the thickness of the ballast bed in relation to the vertical deterioration of the track, the Figure 10 confirms the negative effect of increasing it on both the track vertical deformation and the defects themselves.
Another way to quantify the effect of the different parameters defining a track is to consider its vertical rigidity. According to studies conducted in the field of Eurobalt II (2000), it was possible to roughly establish the relationship between the track bed and the magnitude of the stiffness. Mathematically:

\[ S = \frac{1800}{K^2} \]

Being,

- \( S \): Vertical track deformation (mm/Mtones)
- \( K \): Vertical track stiffness (KN/mm)

Analogously the standard deviation of longitudinal level defects (\( \sigma \)), can be obtained on the following expression:

\[ \sigma = \frac{100}{K} \]

Combining the two equations above:

\[ \sigma = 2.35 \sqrt{S} \]

Thus it becomes clear that when the track vertical deformation increases, also the magnitude of the defects.
2.1.6 Track traffic and maintenance influence in ballast

With respect to the parameters that characterize the traffic line (top running speed, axle load and tonnage supported) several investigations have been done by various authors. Some of them refer to freight traffic, some others to passenger and then the remaining to mixed traffic. Since half of the twentieth century many investigations have been carried out, which have proposed different formula for estimating ballast vertical deformations depending on the supported traffic.

Within the assembly of a railway track and its maintenance two facts have to be taken under consideration: one is what might be called historical memory of the track; the second, the effects of the tamping machines.

In relation to the first one, Robson (1980) shows the evolution of leveling longitudinal defects on a track before the usage of tamping machines, immediately after, and after a certain time. Note how the existing geometrical defects in a particular area of the track practically disappear with the tamping process, but under the action of traffic goes back to a position close to the initial dimension. It can be said that the sections of the track that present some constructive weakness maintain their limitation throughout its lifetime.

Related to the second fact, Janin (1982) graphically shows the effects of track tamping in reducing the magnitude of the standard deviation of the defects. Mathematically $\sigma_d \sim 0.5 \sigma_a$, $\sigma_d$ and $\sigma_a$ being the standard deviation of the defects after and before tamping the track. This relation can be seen in Figure 11.

![Figure 11: Tamping effect in reducing the standard deviation of the defects in a railway line](image)

Source: B. Lichtberger, 2005
2.1.7 Track deterioration due of the vibrations generated in the ballast bed

Concerns about the vibrational behaviour of the ballast under train circulations at high speed began over the 60s of XX century during the studies carried to allow trains running over 200 km/h.

In fact, in 1967, Birman said the ballast bed was submitted to an alternative load, transmitted through the sleepers, due to the passage of trains at high speeds. For a speed of 300 km/h, with axes distance equal to 3 m, the excitation frequency was around 28 Hz.

Precisely, the first steps made in the new Tokaido line showed that vibration levels in the roadbed ranged between 0.3 and 0.6 g for maximum of up to 210 km/h. However, on the figures above is showed that values of 1 and 1.5 g can be reached in the case of track sections on rigid platform, as with measurements in the Rokko tunnel.

With respect to the French experience it is convenient to remember the measurement made on main line sections with conventional materials of different characteristics and different train speeds. According to Prud'homme (1976), the values shown below were obtained.

<table>
<thead>
<tr>
<th>Locomotives or Type of Train</th>
<th>Maximum Speed</th>
<th>Acceleration in the ballast bed</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNCF locomotive CC 6500</td>
<td>140 km/h</td>
<td>0.8 g</td>
</tr>
<tr>
<td>TGV 001</td>
<td>140 km/h</td>
<td>0.88 g</td>
</tr>
<tr>
<td></td>
<td>245 km/h</td>
<td>1.4 g</td>
</tr>
<tr>
<td></td>
<td>300 km/h</td>
<td>1.4 g</td>
</tr>
</tbody>
</table>

Table 4: Vibration levels on the track bed according to Prud'homme

The acceleration was measured in the ballast between two sleepers and approximately 15 cm below the bottom face thereof. The French author noted that the elevation of acceleration could cause an additional compression compared with what happens on conventional lines with no high speed trains running, increasing the costs of conservation.

More recently, Le and Ripke (2000) published the results for the root mean square acceleration measured at different depths below the surface of the rail, with ICE trains running at speeds between 250 and 300 km/h. Figure 12a shows the points where the accelerometers were placed and Figures 12b and 12c display the results. It can be observed that the maximum acceleration values were at an interval of 1.4 to 2 m/s², 80 cm below the surface of the rail. It is good to remember that the UIC 60 rail has a height of 17.2 cm; the sleeper is 18 to 20 cm height, and the ballast bed is up to 35 cm. Then the maximum acceleration value corresponds to the
subballast layer or the surface of the platform. It is interesting to see how as more traffic passes on the track, accelerations measured decrease significantly (Figure 12c).

2.1.8 Effects of vibrations caused by railway traffic

The traditional way to characterize the potential for damages due to vibration was the maximum vibration speed of ballast particles. Therefore, from the commissioning of the first high-speed lines in Germany: Hannover-Wülzburg and Manheim-Stuttgart in 1991, it was tried to measure the vibration speed of the ballast particles for different train speeds.

Nowadays the vibration speed at a particular point can be easily measured in the direction of the three axes X, Y and Z. From the above three speed components, the full vibration speed is obtained.

Furthermore, the influences of the train axle loads for a given train speed in the ballast particles resulting vibration speed can be seen in Figure 13A).
Synthetically it can be seen, according to those sources, that:

- For train running speeds around 160 km/h, vibration speed approximates 20 mm/sec. When the train speed reaches 250 km/h, the vibration speed is in the range of 24 to 28 mm/sec.
- For train running speeds in the vicinity of 100 km/h and axle loads of the order of 19 to 20t the vibration speed is below 10 mm/sec.

At this point the question is to know at what effective vibration speed the ballast structure becomes unstable. According to the information available in other engineering disciplines it can be said that the permissible limit speeds of vibration is in the vicinity of 10 to 15 mm/sec. This fact is confirmed in practice by observing the variation of the vertical deformation of the ballast bed with the vibration speed of the ballast particles, for a constant pressure average under the sleepers (Figure 14).
From the structural point of view the track can be designed to reduce the vibration on the ballast bed. To do this it is necessary to:

- Reduce the level of pressure on the surface of the ballast bed.
- Reduce the vertical stiffness of the base plate.

The test section in Stendal, in the Hanover-Berlin railway line, made possible to compare the behaviour of three types of superstructure:

- UIC 60 rail sleepers B70 (bearing area per rail of 2.850 cm$^2$) and base plate with stiffness 500 kN/mm.
- UIC 60 rail sleepers B70 and base plate with stiffness 60 kN/mm.
- UIC 60 rail sleepers B75 (bearing area per rail of 3.780 cm$^2$) and base plate with stiffness of 27 kN/mm.

In the Figure 15, the spectrum of the vibration speed of ballast particles can be seen for each of the three mentioned types of superstructure. In particular, the positive effects in reducing the vibration particle speed once the bearing area of the sleepers and the increased flexibility of the base plates are increased. On the other hand, a similar effect is obtained using sleepers with elastic pads or base plates (Figure 16).

Figure 15: Influence of the type of superstructure on the vibration speed of the ballast
Source: Leykauf G. et al, 2001
Figure 16: Vibration speed on track with ballast and sleepers with and without elastic pads

\[ v = 160 \text{ Km/h} \]

Source: Stahl, 2005

It shall be noted, finally, that the effective vibration speed under the sleeper (\( V_{\text{res. effect}} \)) varies with the speed of a train vehicle passing over the track (\( V_{\text{tren}} \)) according to the expression:

\[ V_{\text{res. effect}} = K_1 e^{k_2 V_{\text{tren}}} \]

Being \( k_1 \) and \( k_2 \) two constants which are taken according to the following values (Gotschol, 2002).

<table>
<thead>
<tr>
<th>Geometrical track quality</th>
<th>( k_1 )</th>
<th>( k_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goog</td>
<td>0.9</td>
<td>0.0075</td>
</tr>
<tr>
<td>Bad</td>
<td>0.9</td>
<td>0.009</td>
</tr>
</tbody>
</table>

Table 5: \( k_1 \) and \( k_2 \) coefficient depending on track quality
2.1.9 Up to date track maintenance and ballast treatment

Nowadays the traditional “cyclical maintenance over the different track components” has been replaced by the "maintenance based on materials condition”, preventive maintenance. That means that maintenance work is performed on the elements where the parameters show that some kind of defect is in the process of being developed. Clearly, this system requires for its implementation a comprehensive and continuous check of the real situation of the railway line. To perform this check three types of vehicles are used: track geometric quality control (inspection vehicles), rail defects control (inspection ultrasonic vehicles) and control of rail corrugation.

Apart from the use of such vehicles and the results derived from the observations, the decisions of track maintenance also come from what is indicated by the work brigades doing the general inspection but also from the dynamic track inspection. In this case, dynamic inspection is an indirect measure of the quality of the track geometry as recording the accelerations in a train vehicle, and then it is possible to have a certain reference to the track quality.

With all the information obtained, the maintenance teams belonging to the Infrastructure Managers decide the operations to be carried out and plan the human, technical and financial resources to perform them.

The main activity of maintenance operations is focused on tamping, aligning, leveling, etc., with the aim to keep track geometric quality within the tolerance criteria established for this purpose. In general, the ultrasonic and the corrugation control provide very relevant information about rail grinding.

Then, the interest in the utilization of good quality track elements is obvious in order to have a of good track quality and maintain good geometry for as long as possible, in order to reduce maintenance interventions and then to have lower costs.

The frequency of maintenance should always keep in mind its dependence on the degree of deterioration of the track condition, and therefore the parameters governing such impairment: traffic intensity, type of operation, trains speed, axle loads and track characteristics (particularly the vertical rigidity).

2.1.9.1 Inspection

Inspection is the first task required to ensure optimum operating conditions. Inspection frequencies are in principle fixed by the rules of each Infrastructure Manager and therefore are not subject to changes depending on the track condition.
As Ubalde (2004) noted on the analysis of the frequencies of maintenance in the French network, the frequency of the inspection is superior to high-speed lines (Table 6), and in particular in the case of the dynamic inspection.

<table>
<thead>
<tr>
<th></th>
<th>Conventional Railway Lines</th>
<th>High Speed Railway Lines</th>
</tr>
</thead>
</table>
| Walking inspections provided by workteams | Every 2 weeks              | Main line: every 10 weeks  
Switches: every 5 weeks
Infrastructure: every 5 weeks |
| Main inspections made by the District Chief | Walking: every 2 months
On the train: every 2 weeks | Walking: every month
On the train: every 2 weeks |
| Special Inspection           | ---                        | Daily, before the first commercial train passing, from a train not running over 160 km/h |
| Geometrical Inspection       | Every 6 months             | Every 3 weeks             |
| Dynamic Inspection           | Every 6 months (portable device) | Every 3 weeks using a specific for purpose vehicle |
| Rails ultrasonic test        | Once a year                | Once half a year          |

Table 6: Periods between control on conventional railway lines and high-speed railway lines in France

Source: Ubalde, 2004

In Spain, the frequencies of inspection in high-speed lines are once a year for the geometric and rail inspection and once every three weeks for dynamic inspection.

Similarly, the dynamic inspection of the high speed line Rome - Florence in Italy is carried out every three weeks and rail ultrasonic control every year. In the Belgian high-speed line between Brussels and the French border geometric inspection is carried out once a month and dynamic inspection once every two weeks. In high-speed lines German inspection frequencies listed in Table 7 are applied.
### Geometrical Inspection
- 160<V≤230 km/h: 3 months
- V>230 km/h: 2 months

### Dynamic Inspection
- 160<V≤230 km/h: 6 months
- V>230 km/h: 6 months (except Köln-Frankfurt: 4 months)

### From Train Inspection
- 160<V≤230 km/h: 3 months
- V>230 km/h: 3 months

### Walking Inspection
- 160<V≤230 km/h: 3 months
- V>230 km/h: 2 months

### Switches Inspection
- 160<V≤230 km/h: 3 months
- V>230 km/h: 3 months

### Ultrasonic Inspection
- 160<V≤230 km/h: 4 months
- V>230 km/h: 4 months

### Head or Rail Geometrical Inspection
- 160<V≤230 km/h: 18 months
- V>230 km/h: 12 months

**Table 7: Periods between inspections on conventional lines and high speed lines in Germany**
*Source: Ubalde, 2004*

#### 2.1.9.2 Tamping

In the high-speed lines, European Infrastructure Managers carry out the activities of tamping and dynamic track stabilization based on the result of inspection.

In the case of the high speed line Madrid-Sevilla, in the period between 1992 and 2003, interventions related with ballast maintenance were around 0.043 km/month per km, which is an equivalent performance average of an intervention every 23 months, although there are differences between the different sections of the railway line (Ubalde, 2004).

In the Belgian line between Brussels and the French border, the frequency with tamping operations are performed are estimated at once every 3 or 4 years.

In France, in between Paris and Sud-Est, the annual rate in 2003 was equal to 0.63, equivalent to an intervention every 19 months.

The ALAF (Latin American Railroad Association) has published an article which mentions the effectiveness of tamping over the life of the rail track. In Figure 17 can be seen how after the first tamping, the geometric quality of the track is maintained for a longer time, while the accumulation of tamping cycles reduces its effectiveness. This is because, both the circulation of train and the tamping operations, generate fines than reduces the ballast quality.
2.1.9.3 Rail grinding

The rail grinding activities are generally conducted at a lower frequency than tamping operations.

In the German high-speed lines, rail grinding is performed preemptively every 20 or 30 million tons passing over the rail. According to Marks (1991), the expected frequency for grinding rails in the high speed line Hannover-Würzburg was once every four years.

In the French high-speed line Paris-Sud-Est, grinding is necessary generally every five years (Figure 18).
2.1.10 UIC comparative study about the Track Life Cycle Costs

The life cycle costs (LCC) is crucial for the economic success of any railway investment. A UIC study on comparative assessment of rail infrastructure costs compared 4 railways in Asian countries, 5 in of North America and 12 railways (state own) in Europe. The objective was to compare the investment and maintenance costs and to identify which factors contribute to increase those costs and to find right ways to reduce them.

The companies were:

<table>
<thead>
<tr>
<th>ASIA</th>
<th>NORTHAMERICA</th>
<th>EUROPA</th>
</tr>
</thead>
<tbody>
<tr>
<td>JR East, JR</td>
<td>BNSF, CSXT, UP, NS</td>
<td>RENFE, SNCF, SBB, SNCB, NS, DB</td>
</tr>
<tr>
<td>Central, JR West</td>
<td>y KCRC</td>
<td>AG, RT, BS, JBV, BV, FS, ÖBB</td>
</tr>
<tr>
<td>y CR</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The costs of the entire rail network (main and secondary railway lines) were analyzed. Benchmarking intended to compare life cycle costs, then it was calculated and evaluated the influence of the density of switches and crossings, the length of bridges and tunnels, the length of sections with several tracks, the percentage of curves, the degree of electrification, the level of network usage, the number of trains circulating, the average gross tonnage, etc. It is important to highlight the difference in between the services operating in U.S. and Southeast Asia; railways in US are focused on freight transport while South Asian are mainly devoted to passenger trains.
As for comparison element, the study choose the life cycle cost expressed in € per km of main railway line (not per km of track).

The results of the investigation revealed the lowest cost was for double track lines, with percentages of 40% savings. Table 9 shows the life cycle costs by continent and separate the maintenance costs of the track renewal costs:

<table>
<thead>
<tr>
<th>Continent</th>
<th>LCC (€)</th>
<th>Maintenance Costs (€)</th>
<th>Full Renewal Costs (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>European Railways</td>
<td>57.000</td>
<td>33.000</td>
<td>24.000</td>
</tr>
<tr>
<td>Asia Railways</td>
<td>163.000</td>
<td>78.000</td>
<td>85.000</td>
</tr>
<tr>
<td>Northamerican Railways</td>
<td>19.900</td>
<td>7.900</td>
<td>12.000</td>
</tr>
</tbody>
</table>

Table 9: Lifecycle costs of main road
Source: Track Compendium

The results in Table 9 highlights the importance of maintenance costs in the European railways, since they mean 58% of the total cost, while for Asian railways account only for 47 % and the U.S. 40 %.

In Figure 19 the number of trains per kilometer of track is detailed in terms of LCC per kilometer of track. This relationship allows calculating the increasing maintenance costs for traffic increases. It can also be seen how big is the ratio of trains per kilometer of railway track in the Asian railways, which explains the higher LCC per kilometer.

![Figure 19: Train*Kilometer per Kilometer of railway track compared with CCV per Kilometer of track](image)

Source: Compendium Track

~ 36 ~
It has also to be taken in consideration that the performance of the railways network in East Asia is very high as a possible lack of a train can cripple entire cities. So the costs of keeping the infrastructure in good condition are always lower than the cost of stopping trains running due to a technical failure.

With respect to U.S. transport, mainly focused in freight, the required geometry is not as demanding as the train speeds are not very high, which results in less expense for maintaining the track in good condition. Added to this factor should be considered strong competition among U.S. railroads, which keeps the costs of conservation and renovation at a rather low level. Costs represent only a third of European, but its performance is four times higher.

As regards the European situation, the railroad is in the middle between freight and passenger. This condition imposes the track maintenance in good condition, since the lines have heterogeneous traffic, rolling stock and axle loads (low speed freight trains and high speed light trains using the same track in many cases). The necessity to maintain a good geometrical quality, to ensure the smooth flow of passenger trains, results in a greater number of maintenance tasks due to the deterioration that occurs at high loads per axle.

### 2.1.11 Innovative ballast enhancing better track behaviour

In recent decades, the growing environmental awareness of society has led to a shift towards rail transport. This is demonstrated by the new European guidelines on transport, rail transport being perceived as one of the most sustainable transport systems and therefore most promising.

This growing interest around the railway sector has required advances in the field to meet and exceed the expectations created around it. This has pushed plenty of investigations and research processes regarding both the rolling stock and the railway track.

Just being focus in track research some cases need to be highlighted: the improvement made to pass from the wooden sleepers to the concrete sleepers, the transition from rigid to elastic fasteners, the use of pads below the sleepers to improve them (Figure 20) and the welding of the rails to avoid discontinuity of the surface, among others.
Despite all the improvements, there is still an element of track on which has not been innovated and clearly needs real solutions to improve it in the short term: the ballast. The need to extend the life of the ballast bed, together with the environmental demand to reduce the use of raw materials, require to immediate solve the problems related to the deterioration of the ballast bed below the sleepers.

Once the problems around the accelerated degradation of the ballast bed have been introduced and their backwardness compared to the other elements of the railway (in general) and track (in particular), the race has begun to raise, from different angles, the possibility of incorporating new technologies to give an effective solution to the existing problems and contribute towards improving rail infrastructure.

There are different lines of research. On the one hand there are studies that focus on replacing the stone by precast concrete, while on the other side are the technologies that focus on improving the stones quality that make up the ballast.

2.1.11.1 Artificial ballast

Regarding the replacement of ballast by reinforced concrete elements, the project is called "Artificial ballast". It proposes the development of elements made of high strength mortars with certain geometries, as an alternative to the natural rocks used in the conventional ballast. That would allow having better control of what is going on under the sleepers. The results obtained are very encouraging in regard to the strength and surface hardness of the artificial ballast particles, and the research is now going towards finding improved alternatives. To determine the resistance of
the artificial ballast particles a new test called "vertex strength test" has been introduced (Figure 21). The problem that this project face is in the current high cost in comparison with the conventional ballast, that makes it not a available solution in the very short term.

![Figure 21: Vertex strength test](image)

Source: Artificial Ballast Project

2.11.2 XiTRACK®

In regard to the addition of polyurethane (as a binder) on ballast, two types of solutions shall be considered: the first irrigates the existing ballast bed with polyurethane forming a kind of network, while the second coats the ballast particles with polyurethane and later on puts them on track.

The study of the irrigation with polyurethane on the railway infrastructure has been carried out since 2004 in the UK by Professor Peter Woosward, at the Heriot-Watt University (Scotland). The commercial name of this product is "XiTRACK®" and has been tested on several occasions. The product places a mixture of liquid polyurethane through an applicator onto the surface of the ballast layer (Figures 22 and 23), which leaks away trough the ballast particles and begins curing in about 10 seconds.
After an hour of the last application, the mixture acquires 90% of optimum strength. Once curing is complete the mixture keeps ballast particles in perfect condition and improves its resistance, delaying erosion. As shown in Figure 24, the application fails to meet all the volume of all existing voids in the ballast.

This type of solution has been used in the UK mainly at critical points where needed frequent maintenance tasks were either due to the poor quality of the platform or the difference in stiffness bridges. The results have been very good, but like the "Ballast Artificial" the cost of implementation is high, which makes the product attractive only in specific cases.
The other alternative for applying the polyurethane on ballast has been developed by BASF through a product called “Elastotrack®”. As mentioned above, the idea of this product is based on coating all the ballast particles with polyurethane (Figure 25) and then to form the ballast bed with the already coated ballast. This product has been recently used in the passenger railway line between Wu and Guang (China) in order to reduce flight ballast, noise and to increase its life and also in some specific places in the U.S. but still in both cases without visible results.

The researcher Marcus S. Dersch of the University of Illinois has tested shear strength of this product in order to determine the benefits obtained from the use of the same versus untreated ballast.
After 14 days of curing achieved, polyurethane ballast bed shear resistance becomes about 1.5 times higher than for the conventional ballast, due to better internal friction angles and cohesion. For faster curing, catalysts are used to achieve optimal resistance results in 6 hours after usage. One of the weaknesses of this product is that during the first hours of curing the strength of the ballast decreases, since the coating acts as a lubricant and reduces friction between ballast particles.

2.1.11.4 Analysis of the existing innovations

After the ongoing innovations introduced we can draw some interesting conclusions.

First, the fact that there are simultaneously three studies that focus on improving the characteristics of the current ballast indicates the necessity and importance of this on the times to come.

Second, we should note on the three experiences mentioned, the good results obtained in the wear and resistance of the ballast. Increased resistance is obtained in the implementations of XiTRACK® and Elastotrack® which encourages further research lines to improve the conventional ballast compared to the option to change it. Likewise, the use of polyurethane as grain protection gives them durability.

However, there are a number of factors that make these products unattractive for implementation in railway lines.

With respect to XiTRACK®, the mesh structure created by the polyurethane with stones, make not feasible tamping the track. This results in the inability to repair misalignments once irrigation applied and consequently, the need to completely revamp the section that is affected by some important defects. Since railway lines do not have homogeneous platforms, it is inevitable that as traffic increases, defects in the track begin to appear. Having to completely renovate the damaged section makes this type of technology very expensive. Furthermore, the irrigation decreases the porosity and therefore the permeability of the ballast bed, which for sure result in problems in track leveling.

Regarding the application of Elastotrack®, it is in its initial stage of implantation and it has a very few visible results. From the information known, it can be seen the lack of tests required by standard regulation, since it has only been tested on track but no any other tests necessary to meet existing requirements in railway infrastructure have been fulfilled.

Another disadvantage of this product is the long curing time required to acquire acceptable resistances, which results in the need to increase the cost of the product using catalysts which still involve setting 6 hour minimum.
Being aware of the strengths and weaknesses that these innovations bring to the railway world, the present research has chosen to continue the studies on the aggregation of materials to the existing ballast, with the idea of bringing new ideas that make possible the implementation of such advances in the railway lines in the future.

2.1.12 Neoballast

In the previous pages the problems involving the accelerated degradation of the ballast bed were referred, and the alternatives that have been proposed have been presented. The purpose of this study is to present a new alternative product with high expectations of solving current problems, respectfully with the environment and society concerns.

This product consists in the addition of three components to achieve the stated objectives. Those are rubber powder, binder and the ballast stones. The combination of these materials intends to surround the ballast stones by a binder to ensure that the rubber powder adheres to the surface of the stone generating new ballast that resists abrasion and increases the life of the ballast bed (Figure 26).

2.1.12.1 Neoballast components

2.1.12.1.1. Rubber powder from ELT

In Spain 300,000 tonnes per year of End of Life Tires (ELT) are generated. This enormous volume of waste, together with the regulations promulgated by the EU, has led the Ministry of Environment to develop the National Plan for ELT. The Plan cites public works as a priority way of recycling, provided that the use of recycled materials ELT would be technically and economically feasible.
In 2004, the total ELT produced in Spain were managed as follows: 12.2% were for retread (retread or covering the existing fissures in the usable tires); 13.9% for recycling; 17.2% to energy valorization and the most percentage (50.3%) were deposited in landfills, abandoned or spilled. Taking into account the comparison shown in the following table in comparison with the European Union, the margin in recycling can be appreciably increased.

<table>
<thead>
<tr>
<th>Year 2004</th>
<th>EU</th>
<th>Spain</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ELT (tonnes)</td>
<td>%</td>
</tr>
<tr>
<td>Generation</td>
<td>2.796.000</td>
<td>100</td>
</tr>
<tr>
<td>Retread</td>
<td>325.000</td>
<td>12</td>
</tr>
<tr>
<td>Recycled</td>
<td>852.000</td>
<td>30</td>
</tr>
<tr>
<td>Energy valorisation</td>
<td>901.000</td>
<td>32</td>
</tr>
<tr>
<td>Spill</td>
<td>414.000</td>
<td>15</td>
</tr>
<tr>
<td>Reusage and export</td>
<td>304.000</td>
<td>11</td>
</tr>
</tbody>
</table>

Table 10: ELT management in EU and Spain
Source: AER and BLIC

Covering the aggregates of the ballast with rubber powder (coming from ELT), increases the contact area between particles, moreover decreasing the triturating and weathering of the arid. This is traduced in an increased durability and reduction of the maintenance due to the reduction in ballast layer problems.

The combination of the railway, being one of the most respectful transports with the environment, combined with the usage of recycled rubber powder covering the aggregates of the ballast, justify the shown interest in the development of this product.

2.1.12.1.2 Ballast

As mentioned throughout this document, ballasted tracks are used in the huge majority of the existing railroads over the world, so any improvement in this area can reach a significant impact, however small it may be, because the huge amount of tonnes of stone that are used for the construction of railway lines.

Intends to prolong the life of this material on the track came from the need to reduce the extraction of new rock at quarry and thus minimize the problem of shortage of materials suitable for use as ballast in railway infrastructure characteristics.
2.1.12.1.3 Binder

Binders are used on rocks in coastal protection with very good results, so use within the railway industry is an alternative of no less interest.

The needs to have an element which ensures the binding of rubber powder and stone and prolonged effectively its life make the use of binder very convenient. This type of binding allows not only to link the stone with the rubber powder, but to eliminate the rubber flammability problem and to contribute to strength the friction between stones, giving the ballast bed more durability.

Originally only one layer of binder was used for the purpose explained before, but later on, a second binder layer was applied after the rubber powder. Due to the fact that it was seen that thanks to friction there was being lost in time part of the rubber powder recovering. So on, a second binder recovering was used to disable rubber powder loses.

2.1.12.2 Validation of the project

2.1.12.2.1 Laboratory tests

With respect to the tests to be performed by ballast particles in laboratory, most of the Infrastructure Managers agree on them. The more relevant are:

- **Test of Los Angeles**

  This test determines the resistance to breakage of natural rock. A sample of approximately 10 kg is introduced in a cylinder together with a number of steel balls. The cylinder rotates about its axis 1000 times at a speed of 33 rpm. After the test sample is sifted in a sieve of 1.6 mm mesh. The value of Los Angeles is determined:

  \[
  CLA = \frac{m}{M} . 100
  \]

  where,
  
  m = mass of the sieved fraction
  
  M = mass of the sample

  The higher the CLA, the lower the breakage resistance of the material.

- **Deval test**

  The test determines Deval wear resistance of rock material. To determine the abrasion resistance, French Railways (SNCF) and many other Infrastructure Managers introduces the ballast together with steel balls and water (wet Deval test)
in an inclined cylinder of 200 mm diameter. After 10,000 revolutions cylinder content is screened and analyzed. The analyzed sample with a grain size of 25/50 mm, should weigh 7 kg after washing and drying. After the test, the sample is sieved with a sieve of 1,6 mm. The Deval value is calculated by:

\[ DH = \frac{2800}{m} \]

\( m = \text{mass of the sieved fraction (g)} \)

- **Petrographic analysis**

Petrographic analysis involves polishing the sample to determine its mineralogical composition (type, volume percent and particle size). In basalt samples cooking assay is performed to test the resistance of burns. This analysis of the crystal structure, the pores and cracks if any, is added.

- **Impact resistance**

The impact strength is to measure the fragmentation of a sample under impact loads. The test sample dry and have a standard granulation (35,5 to 45 mm). The sample is introduced into a cylindrical container and the impacts with a standard mass of 50 kg, twenty times from a height of 380 mm on the sample. Then sieved and the percentage of the total grinding is determined.

- **Shape analysis**

The shape of the particles is determined by a special gauge to not exceed a ratio of length to width of 1:3. This analysis aims to avoid flat particles within the ballast bed.

- **Erosion**

The erosion resistance of the ballast is determined by a test firing crystallization in saline. Equally important is the water absorption test. Through these two trials ballast resistance to environmental, climatic or chemical attack is checked.

Table 11 provides a brief comparison of the standards applied in Spain in ancient times and today as a reference for this project.
<table>
<thead>
<tr>
<th>TEST</th>
<th>ASSOCIATED NORM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FORMER</strong>&lt;br&gt;N.R.V. 3-4-0.0: 1987&lt;br&gt;N.R.V. 3-4-0.2: 1996&lt;br&gt;P.R.V. 3-4-0.0: 1996</td>
<td><strong>PRESENT</strong>&lt;br&gt;UNE-EN 13450: 2003&lt;br&gt;ORDEN FOM 1269: 2006</td>
</tr>
<tr>
<td><strong>Sampling</strong>&lt;br&gt;N.R.V. 3-4-0.2: 1996</td>
<td>UNE-EN 932-1&lt;br&gt;UNE-EN 13450 Annex A &amp; B</td>
</tr>
<tr>
<td><strong>Granulometry</strong>&lt;br&gt;N.R.V. 3-4-0.2: 1996 Circular aperture sieves. Serie: 80, 71, 63, 45, 31,5, 25 &amp; 20 mm.</td>
<td>UNE-EN 13450&lt;br&gt;ORDEN FOM 1269&lt;br&gt;UNE-EN 933-1 Square aperture sieves. Series: 80, 63, 50, 40, 31,5 &amp; 22,4 mm.</td>
</tr>
<tr>
<td><strong>Cleaning. Fine particles</strong>&lt;br&gt;N.R.V. 3-4-0.2: 1996 Sieve UNE of 0,63 mm.</td>
<td>UNE-EN 933-1 Sieve UNE 0,5 mm. ORDEN FOM 1269</td>
</tr>
<tr>
<td><strong>Cleaning. Powder</strong>&lt;br&gt;N.R.V. 3-4-0.2: 1996 Sieve UNE 0,063 mm.</td>
<td>UNE-EN 933-1 Sieve UNE 0,063 mm. UNE-EN 13450 ORDEN FOM 1269</td>
</tr>
<tr>
<td><strong>Particles form. Slabs Index</strong>&lt;br&gt;Not considered</td>
<td>UNE-EN 933-3</td>
</tr>
<tr>
<td><strong>Particle shape. Index form</strong>&lt;br&gt;N.R.V. 3-4-0.2:1996. Acicular elements and slabs. Mobile comb.</td>
<td>UNE-EN 933-4 Caliber Vernier ORDEN FOM 1269</td>
</tr>
<tr>
<td><strong>Particle shape. Minimum thickness</strong>&lt;br&gt;N.R.V. 3-4-0.2:1996</td>
<td>UNE-146147, Annex b</td>
</tr>
<tr>
<td><strong>Particle shape. Maximum length</strong>&lt;br&gt;Similar to N.R.V. 3-4-0.2:1996 Maximum length (80mm).</td>
<td>UNE-EN 13450 ORDEN FOM 1269</td>
</tr>
<tr>
<td><strong>Composition. Homogeneity</strong>&lt;br&gt;N.R.V. 3-4-0.2:1996 Not homogeneous when CLA &gt; 20%.</td>
<td>ORDEN FOM 1269 Not homogenous when its CLA &gt; category limit</td>
</tr>
<tr>
<td><strong>Petrographic composition</strong>&lt;br&gt;Not considered</td>
<td>UNE- 932-3</td>
</tr>
<tr>
<td><strong>Composition. Petrographic diffraction</strong>&lt;br&gt;Not considered</td>
<td>Not considered</td>
</tr>
<tr>
<td><strong>Composition. Harmful components</strong>&lt;br&gt;Not considered</td>
<td>UNE-EN 13450 ORDEN FOM 1269</td>
</tr>
<tr>
<td><strong>Fragmentation resistance. Method of Los Angeles</strong>&lt;br&gt;UNE 83-116-90/NLT 149. Granulometry F (Tamices UNE 25-50mm.)</td>
<td>UNE-EN 1097-2 UNE-EN 13450 ANEO C</td>
</tr>
<tr>
<td><strong>Fragmentation</strong>&lt;br&gt;Not considered</td>
<td>UNE-EN 1097-2</td>
</tr>
</tbody>
</table>
| Wear resistance. | Not considered | UNE-EN 1097-1  
| Coefficient Micro-Deval | | UNE-EN 13450 ANEJO E |
| Resistance to weathering. | UNE 83134 | UNE-EN 1097-6 |
| Density - Water Absorption | | |
| Resistance to weathering. | Not considered | UNE-EN 1367-1  
| Ice Melting Test | | UNE-EN 13450 ANEJO F |
| Resistance to weathering. | UNE 7136 according with | UNE-EN 1367-2  
| Magnesium Sulfate Test | P.R.V. 3-4-0.0 | UNE-EN 13450 ANEJO G |
| Resistance to weathering. | Not considered | UNE-EN 1367-3 |
| Sonnenbrand | | |
| Resistance to weathering. | Not considered | UNE-EN 932-3 |
| Petrographical study | | |
| Simple Compressive Strength | UNE 22950-1:1990 | Not considered |
| ( source’s rock ) | | |
| Point load strength | UNE 22950-5:1996 | Not considered |
| ( source’s rock ) | | |

**Table 11: Current and former Spanish legislation concerning ballast tests**

Source: compiled from Llop Martinez Gutierrez

### 2.1.12.2.2 In situ test

The present research includes a pilot project test in a work site during 7 months in order to observe the behaviour of Neoballast under charge. For this period of application the following objectives are set:

- Commissioning of the material in a section of track.
- Observing the Neoballast behaviour before and after the passage of traffic trains and loads.
- Establish plan of long-term observation.
• **Work commissioning in the test section**

The selection of the test track section will be decided taken into account an ADIF maintenance base being nearby.

It should be noted if there are variations in the laying process of this material over traditional ballast. The handling of this material should reduce noise nuisance usually found in traditional ballast placement. It also should decrease dust generation.

• **Behaviour of the material in situ**

The material in situ will be observed and tested. Charges will be applied to simulate the traffic and the maintenance. If there is not enough traffic to get results, the use of a stabilizer will be required.

To observe and test the behaviour of the material to any maintenance process, it will be important to check what goes one when tamping or ballast regulators are used.

• **Long-term observation**

More reliable results can be established within long term observation, when rail traffic and weather conditions really happen. Those conditions can always be complemented with the results observed in the previous subtask, simulating the charges with a stabilizer.

• **Simulation model**

In order to have a tool to contrast the results obtained during the tests, a simulation model using Plaxis, attempting to describe the behaviour of the track structure, which will be calibrated as tests are conducted and that will be used as measurements are obtained in the experimental section. Figure 27 shows a type of ballast bed model using different sized spheres.

![Figure 27: Modelling of roadbed for simulation analysis](image)
2.1.12.3 Neoballast added value to the railway track

The present research project seeks to provide greater benefits to the ballast. The friction between the different particles of the ballast are wearing their faces gradually losing part of the main properties required to ballast bedding (mainly lateral stability and vertical settlements), having to conduct periodic tamping actions and finally partial or total renewal. In addition ballast natural attrition during their cycle life is also polluting it with fines, causing the ballast to lose its properties (Figure 28). The main objective of the project will treat ballast for durability and thus able to reduce operating and maintenance costs, this being applicable to existing and future railway lines.

Another important objective is to provide the highest possible ballast performance, not only in terms of durability as the previous point, but in terms of performance against noise and vibration. It is well known the importance that has been taking in railway infrastructure (as the increases of the maximum speeds are also generating higher dynamic forces that result in increased noise and vibration). This has imposed to develop elements to be incorporated in the track section as elastomeric blankets, low cross soles, tie plates, etc. By introducing the mixed ballast wrapping rubber powder particles (from ELT), the behaviour in this regard should improve apparently, and then it is expected to reduce the above elements necessity.
It also aims to improve environmental awareness, so the search for materials should be reducing the use of quarries, resulting in leverage and reuse all resources available to the industry.

In Spain, aggregate and recycled materials are used. However, the recovery of natural and industrial resources is still low and poor in quality. This project goes in the right direction to improve both on line with the State regulations.

Among the most important benefits introduced by Neoballast are:

- The noise reduction.
- The ability to geometrically correct the track by tamping it.
- The reduction of vibrations caused by train circulation.
- The less deterioration of the ballast and therefore the durability of the ballast bed.
- The lower cost of maintenance.
- The conservation of the permeability of the ballast bed to drain rainwater.
- A substantial increase in the shear.
- The ability to reuse NFU contributing to plan promoted by the Spanish Ministry of Environment.
- The possible reuse of recycled aggregate ballast and previously rejected stones.
- Decreased flight ballast and the damage this causes.

2.1.12.3.1 Noise reduction

To get an idea of the possible impact that may cause the use of ELT in the ballasted track, we will refer to the recent use of rubber for the road construction.

The use of ELT in bituminous mixtures has allowed reducing the noise level on roads. In various European countries and in the U.S. and Canada, a lower noise level measured has been measured with the use of rubber mixtures with bitumen. The reductions observed are of the order of 3 to 4 dB compared to conventional asphalt mixtures. The first measures made in Spain about the loudness on surfaces containing ELT are in line with these experiences. Thus, the noise measurements performed by the CEDEX in different sections of a highway through the proximity method (CPX). The obtained results indicate that the bituminous mixture with a binder made with ELT has reductions in between 2 dB (v = 50 km/h) and 4 dB (v = 110 km/h) compared the traditional mixtures.

It can be expected that the effect of the coating of the ballast crushed stones with rubber powder, could have a very positive outcome in regard to the noise of the passing trains. This improvement could even partially avoid the works of sound insulation required nearby high-speed lines, where the noise coming from the passage of trains exceeds the acceptable decibels level.
2.1.12.3.2 Correction geometry by tamping

Unlike products that generate a rigid mesh between the ballast and the polymers, the use of Neoballast not conditions at all the possibility of tamping the track to correct the geometrical defects originated by the train circulation and platform defects, as it preserves the structure of the traditional ballast. The stones are not linked and thus immersion and tampers movement is possible.

Being able to retain the conventional track maintenance procedures and specialized machinery, prevents more costly methods or the need to completely change the affected section when the defects appear.

2.1.12.3.3 Less vibration

As discussed throughout section 2.1.7, the influence of the vibrations in the vertical deformation of the ballast bed is determinant on the railway lines with speeds above 150 km/h.

Then, the interest of narrowing vibrations generated in such a kind of lines is increasing. Also the use of rubber as an element to reduce vibrations is increasing in general in different sectors is increasing, ranging from small items to farm machinery and public works.

The application of elastic plate seats, low cross and soles rubber blankets (Figure 29) to reduce vibrations has been very successful in ballasted tracks. Application of these rubber blankets reduced between 15 dBV and 25 dBV (CDM) the existing vibrations in the ballast bed.

![Diagram showing three levels of vibration reduction](image-url)
The good results obtained by employing the ELT as vibration reducer highlights how important can Neoballast be.

12.1.12.3.4 Less ballast deterioration and extended track durability

Analyzing the generation of the irregularities on the track, as by Sato equation, we have:

\[ S = \alpha T^{0.31} M^{1.1} L^{0.21} P^{0.26} V^{0.98} \]

Which represents the increasing track irregularities with the passage of time (S), depending on: the tonnage supported by the track (T), a variable vertical resistance of the track (M), the continuity of the rails (L), the quality of infrastructure (P) and the speed of movement (V).

The role of ballast within this equation is reflected in the parameters that provide the vertical track resistance (M) and the overall track quality (P).

In the comparison between the performance of traditional ballast and Neoballast and in regard to the generation of track irregularities, it is evident that the improvement in the parameters M and P, introduced by the Neoballast, will result in lower generation irregularities (S) and therefore extended track durability.

2.1.12.3.5 Permeability of the ballast bed

By the analysis of the previous history of binder use in ballast, we find out a limiting factor to perform the track irregularities correction by tamping.

As mentioned in section 2.1.11.2, the application of XiTRACK\textsubscript{R} in the ballast bed result in a better quality in terms of geometrical deterioration compared with the traditional ballast, but this innovation has an important constraint when it is necessary to restore the track geometrical quality. The ballast and polyurethane together prevent tamping, so track deterioration imposes full track renewal.

Neoballast, in this sense, does not has any limitations as the ballast stones are not linked together and then the tampers can enter the ballast bed to recover the geometry and to ensure a proper train circulation.
2.1.12.3.6 Increased bearing capacity of the ballast bed

Taking into account the increase of the internal friction angle of the Neoballast and using the methodology based on the bearing capacity of a footing to consider the allowable stresses of the ballast, as recommended for high-speed lines, it is possible to conclude that the Neoballast acceptable stress can be greater.

2.1.12.3.7 Recycled ELT contribution to the plan promoted by the Spanish Ministry of Environment

One of the biggest achievements of Neoballast is the contribution to the plan promoted by the Spanish Ministry of Environment to promote the reuse of end of life tires.

The possibility of incorporating rubber powder (from ELT) within the rail infrastructure presents a major attraction considering the kilometers of ballasted track existing in the world and the possibility of using a smaller amount of quarried stones.

The average ballast stone size is around 50 mm and that the particles do not have planar geometry, but rather the ballast stones resemble a sphere. This sphere has approximately a 50 mm diameter for a conventional stone and 51 mm diameter for the rubber-coated one. The calculation shows that the volume previously occupied by a stone of ballast will increase by 6% when it is covered by in rubber and the porosity of the layer does not vary as the particle shape is unchanged but scaled.

As a consequence, if the Spanish Infrastructure Manager expects the utilization of 264.000 tons of ballast for the maintenance plans within two years, around 16.000 tons could be saved and then replaced by the rubber surrounding the stones. Since investment in this case would be 6,5 million Euros, the potential savings would be approximately 400.000 Euros.

Such a measure has a double positive impact on environmental levels: first it reduces the extraction of quarry rock (which is very positive in terms of environmental damage) on top of that reuses the waste today largely located in landfills and causing contamination.

2.1.12.3.8 Reutilization of recycled aggregate ballast and previously rejected materials

The improvement of the properties of the ballast with the implementation of Neoballast, suggests the possibility of using more recycled ballast thus allowing the reutilization of materials that today do not meet 100% of the specifications.
2.1.12.3.9 Decreased flight ballast and the damage this causes

Currently flying ballast is one of the serious problems faced by the high speed railway lines. The circulation of trains above 300 km/h causes the stones being in the surface to “fly” causing rolling stock damage (Figure 30).

![Figure 30: Ballast flight](image)

Tests have been conducted with the train ICE-3 DB Siemens in Belgium and France on this issue. They have led to limit the speed of the ICE-3 trains at 250 km/h in single units and 230 km/h in multiple units. In Spain, dynamic tests made with trains of 102 Talgo series up to and above 280 km/h and specifically above 300-320 km/h have demonstrated the same problem.

By using Neoballast in railway infrastructure, the damage that would occur would be less important but what is more important is that the higher friction will make more difficult the stones to be detached. This is due to a higher coefficient of static friction ($\mu_e=1$), compared with the one in traditional ballast ($\mu_e=0,3$).

2.1.12.3.10 Quick curing time

The application of a binder on ballast has a drawback that has been seen in the study of Elastrack® and refers to the cure time that is needed to get good resistance. In the tests conducted by Dersch, it has established that at least 14 days are needed to acquire acceptable resistance. Since time is one of the most
important cost variables within the construction sector, a long cure time results in a higher costs.

In the first samples taken from Neoballast the cure times required to obtain the final product was 6 hours at 23 °C which puts the curing time of Neoballast about 50 times faster than other products. This would allow coating the ballast stones on the same day of using them on the track maintenance or construction site, avoiding unnecessary storage costs.

2.12.3.11 Lower maintenance and environmental costs

As mentioned throughout before, the ballast deterioration results in the necessary maintenance to restore the geometric track quality. Those operations represent a significant cost that could be mitigated.

With the benefits provided by Neoballast and described throughout this section, there is expectable a notable reduction of maintenance and environmental costs. The factors with the greatest impact on the cost reduction are:

- The durability of the ballast bed.
- The savings generated by reducing the extraction quarry rock.
- Less damage caused by the flying ballast problem.
- The utilization of End of Life Tires.

Other benefits include contribution to the noise reduction, which involves expensive works of sound protection in urban areas, and the vibration attenuation, which avoids the necessity of incorporating rubber blankets which represent huge cost.
3. Goal definition

LCA continues to be a topic of growing interest to the industry, but has not been used very much in the construction industry, and even less in the railroad construction industry. The railway construction industry is strongly affected by the fact that there is not huge volume of new railways lines being built and its environmental effects are normally analysed under the perspective of the more common road construction.

Nevertheless there are many aspects of the railway construction and maintenance that need to be addressed under the environmental perspective. The very traditional ballast has been used since the beginning of the railroad construction and in a very few occasions analysis have been developed in order to minimize its effect.

All the improvements regarding the potential substitution of the traditional ballast bed by any other solution have appeared as a result of the interest of the railway’s engineers in reducing maintenance cost and delay the necessity of materials substitution.

Opposite to this approach the primary goal of this LCA is to analyse the environmental impact of the new product Neoballast, and more important, to compare this impact with the existing one, the so called conventional ballast, in accordance with ISO 14040:2006 and ISO 14044:2006 standards. The analysis is also focused in choosing the best product, process or service with the least effect on human health and the environment. The differential fact, in which is paid specific attention in this document is the positive increment in useful life of the Neoballast in contrast to the additional processes that are needed to produce it (additional materials and recovering of the ballast original particles).

Secondary goals are the rank in relative contribution of individual steps or processes. The LCA provides detailed data regarding the individual contributions of each step in the system studied. The data can provide information to address the efforts for improvement by showing which steps contribute the most pollutants or which consume most energy and resources.

This LCA is also interested to showing industry and governments these effects in order to provide information and direction to decision-makers between the two products in comparison.
4. Scope of study

4.1 General

The scope of the LCA is outlined in the following sections, and among other things outlines the functions, functional unit, system boundaries and cut-off criteria of the study.

As a comparison, it is crucial the equivalence between different products being compared. The definition for the functional unit and systems boundaries are the same in order to allow do the comparison in terms of equality, as if not could be a critical difference in the results. For the methodological processes and raw materials in common, the same specification is used for each analysis. As some other facts are analysed in following parts of these study, any differences between systems regarding these parameters are indentified and reported.

4.2 Functional unit

For the study, the functional unit is the extraction, construction, maintenance and restitution of the ballast in a double track railway line, for a length of 1 Km. In this LCA the time period is considered 50 years (lifetime of the Neoballast, 2 times the lifetime of conventional ballast, Appendix 2). As upstream and downstream are considered, the data provided is called cradle-to-gate data.

Where the data includes end-of-life recycling, the function includes the limits of the re-utilisation and recycling of the product and the credits associated with the end-of-life recycling of the ballast and Neoballast.

As there are different types of railway lines cross-sections and then ballast layer can also be different from one case to the other, the type and dimensions used belongs to the ones used in a high speed line, according to the interest of European governments to implement them. They are designed for passenger (and in some cases freight) railway transport; with double track (in normal operational conditions one track is used for each train direction). As the analysis pretends to be as much representative as possible for the EU, the gauge of the railway line in consideration is 1.435 mm. In the case of the results needing to be extrapolate to any other country with different track gauge (as Spain, where standard track gauge is 1.668 mm), there won’t be problems as it will be just necessary to readjust the factor of ballast quantity in the ballast layer.

As is the more common cases, there is not going to be ballast over asphalt or concrete and the studied has just considered the ballast to be placed over an embankment. The study of the material under the ballast bed is not a goal of this
analysis, it will be considered of having enough good properties for railway superstructure (ballast, sleepers, tracks, overhead and catenary).

The detailed specifications of the railway section are in the Appendix 1.

It has to be taken into account that Neoballast shows better resisting properties than the conventional ballast, so thickness of ballast layer could be reduced, in order to minimise material utilisation. But this fact is not considered, as this study intends only to consider the increase of the ballast bed lifetime using Neoballast with the same thickness of the ballast layer.

4.3 System boundaries

The study is a cradle-to-gate LCA study with the end-of-life recycling of ballast. That covers all the production steps from raw materials in the earth (i.e. the cradle) to finished product installed in the railway. The end-of-life recycling is included in the LCA but it does not consider the manufacturing of the recycled products or their use.

There were no data at LCI available of most processes for ballast and Neoballast, which led to extensive data collection for different processes and raw materials. Measuring, calculating and averaging the measurements for inputs of each process and sub processes. Similar process was used for taking into account the appropriate outputs compatibles to the available ones in the LCI.

In addition, cradle-to-gate (with recycling) inventories do not include the following: R&D, business travel, commercialization and decommissioning, repair and maintenance of the machinery used, cleaning, legal services, marketing, operation of administration offices, etc.
4.3.1 Flow diagrams

Ballast system overview:

![Ballast system overview](image1)

Figure 31: Ballast system overview

Neoballast system overview:

![Neoballast system overview](image2)

Figure 32: Neoballast system overview

As seen in Figures 31 and 32, the system boundaries involves all the processes from raw material provision to the product end-of-life and recycling. In addition to the recovery and use of the ballast co-products outside of the railway construction industry are taken into account. As shown in Figure 32, for cradle-to-gate data with end-of-life recycling, the upstream burdens from obtaining all raw materials (not just the ballast, also the binder and the rubber powder) are included in the system boundaries, as are the credits for recycling ballast or Neoballast at the end of final product life.
4.3.2 Time coverage

The majority of data were derived from the period 2013 to 2014 and is believed to be representative during this frame, recent past years and expect to be so for next coming years.

4.3.3 Geographic coverage

Most data for this project was collected from Spain or estimated according to Spain standards, utilising information coming from the experience of building new railway standard gauge double track lines. Thus these standards accomplish the EU ones and all data was checked also according to EU requirements and interests, as the objective is to include representativeness of the as larger number of countries as possible for this project, in order to be this project representative for them.

Nevertheless the results are not representative for other continents, as notable differences will be observed from the raw material provision to the different end-of-life recycling and reusing. The differences in the railway construction technologies and railroads design could also affect the result of this study when applied in other continents, even if in a minor grade.

In order to assess the consistency, methodology applied is as uniform as for the various components of the analysis; avoiding as much as possible the introduction of irregularities.

4.3.4 Technology coverage

Modern railway technology has been used as well as modern production data of the railway. Normal but high quality materials have also been assumed. For the material production the existing LCA data has been used for the different materials, when possible. These data covers normal environmental good but ordinary production in a specific plant or European average.

Is has to be considered that some hypothesis have been made regarding the no already existing machines necessary to produce the materials utilised (Neoballast). The information has been obtained in close contact with other industries having similar machines and being utilised in similar processes.
4.4 Data collection

The LCI model has been created in GaBi 6. It is based on the similar models utilized for aggregates and uses information from previous studies dedicated to similar processes, related and not related with railway track construction and maintenance.

4.4.1 Transport

The environmental burden of internal transport is very small, mainly limited to raw materials, to the transport between processes and end-of-life transport.

For external transport, of transport systems and the distances of the main raw materials (in terms of tonnage) to the railway, from railway to landfill site or other external process transports have been recorded, calculated or estimated appropriately.

The models and information for these transport options come from GaBi 6 database; the diesel mix supply (based on EU27) and the electricity supply come also from the GaBi 6 database.

The functional unit for all transport models is kg.km. Transport includes ballast, ballast fines, binder, rubber powder, Neoballast and fines according to the case; which represent the total tonnage of inputs and outputs transported in the analysis.

For the appropriated transport distances from available departing locations all over Spain to the working sites, and for the diverse transport systems, a particular approach has been necessary. In principle, for the road transport in between the quarries and the stocks (where the ballast is transferred to trains), an average distance has been utilised, considering the situation of the different quarries (homologated by ADIF) and the most common stock sites. For rubber dust and binder transports same approach has been done.

For the rail transport between those stocks sites and the working sites along the railway track, also an average has been calculated; for this purpose the experience of COMSA project managers and engineers has been very useful, as there are no official records. Same process was utilised for the distance estimation of reused material transport. As the already utilised ballast (no reused) coming from the track is considered to be deposited in landfills, average distance has been utilised, considering the situation of the different landfills.

Neoballast recycled material transport distance from site it has been adopted as the transport distance to site.
4.4.2 Energy supply

For all energy inputs (e.g. electricity, diesel for internal transport), the country/region-specific upstream inventories have been taken into account. All upstream data have been updated. For electricity, further detail is provided in the following section.

4.4.2.1 Electricity

The grid electricity production associated with individual sites can have a significant effect on the LCI, particularly with regard to CO₂ emissions. Therefore, this has been customised and specified according to major electricity supply at Spain and so on the Nuclear energy has been chosen. For each data, the country specific electricity grid mix is used, as defined in the GaBi 6 database.

The LCI profiles for electricity taken from the GaBi 6 database quantify the related environmental burden on the basis of the consumption mix analysis for the related cradle-to-gate system. This includes domestic production and the most important imports for a certain country.

![Electricity Mix - ES](image)

Figure 33: Electricity mix (Spain)

4.4.3 Raw and process material

Data for processes outside the railway industry, e.g. upstream raw material production, were obtained for use in the study. To ensure a high level of data quality, the acquired data for those upstream processes was appropriately judged and analysed.

Where possible, data were taken or calculated directly from some providers. Otherwise, data have been taken from the GaBi 6 Professional database.
methodology for the derivation of these datasets is out of the scope of this project but the major methodological and data quality aspects are consistent with the ones of ballast and Neoballast.

4.4.3.1 Aggregate extraction

For the data encompassed in this process, the EVA 025 project has been used. In this project a detailed analysis has been done for the LCA of aggregates, with different LCA according to its grain size. So the data coming from the appropriate one, assimilated to ballast, has been used. Further check has been made on consistency and compatibility with the rest of the data inventories.

To avoid unknown data when detailed information has not been available, an average for each case was done, taking a logical intermediate value between the maximum and the minimum values, it has been considered the most appropriated value for ballast. A deeper analysis has been realized in each case to assure clearance and consistency in accordance to the railway industry.

4.4.3.2 Binder

The data for this upstream raw material process was taken from GaBi 6 professional database, as this material does not come from railway industry; no changes into data of this process have been introduced. The binder chosen has been the binder which description is the closest to the one used for Neoballast recovering. Verifications have been done to assure consistency of inventory data and the results.

4.4.3.3 Rubber powder

Provision of rubber powder, as explained in previous chapters, comes from ELT tires. The usage of rubber powder for covering the ballast avoids the ELT incineration, deposition in landfills or spilling and its damaging impacts, but introduces additional triturating steps in the ELT triturating, for obtaining the appropriated diameter for rubber powder particles.

The recycling of ELT in Neoballast usage would influence in a positive way the tonnes of ELT that are incinerated, deposited in landfills or spilled. In this study the fact of avoiding these environmental impacts is not taking into account, moreover the environmental impacts considered are the ones coming from additional steps in triturating ELT for obtaining rubber powder. As the alteration of tires Life Cycle is not considered in this study, but such a good repercussion in Life Cycle of tires must represent some positive environmental impacts compensating the negative
ones taking into account in this study. This choice is a conservatory decision to not underestimate the negative environmental impacts of rubber powder provision.

4.4.3.4 Neoballast manufacture

Neoballast manufacture process is divided in two processes in the GaBi model, Neoballast SR process and Neoballast SRS process. In Neoballast SR it is considered the process of applying the first binder layer, later on the rubber powder and then the considered time for the curing of the binder on conveyor belts. After curing is complete, the Neoballast SRS process begins, which consists only the covering of the previous Neoballast SR stones with the final binder layer and it’s curing on conveyor belts.

This division in the Neoballast manufacture process is also adopted due to recycling facts. Neoballast which lost part of the recovering can be recycled just covering them with the last binder layer used in the Neoballast manufacture process.

Neoballast is not yet produced in big scale and so on the corresponding industrial machinery. Machinery examples from other industries were consulted and analysed in order to obtain machinery emissions and consumptions similar to the ones of the Neoballast performing machine. Once the chosen machine was selected for assimilating Neoballast manufacture, equivalence between the production of the machine and Neoballast volume was realized for extrapolating the corresponding inputs and outputs of the process. These assumptions and calculations were done in collaboration with GASER industrial machinery.

4.4.3.5 Landfill

For the data encompassed in this process, the EVA 025 project has been used. In this project detailed analysis has been done for the LCA of aggregates, with different LCA according to its gain size. So the data coming from the appropriate one, assimilated to ballast fines, has been used. Further check has been made on consistency and compatibility with the rest of the data inventories.

To avoid unknown data when detailed information has not been available, an average for each case was done, taking a logical intermediate value between the maximum and the minimum values, it has been considered the most appropriated value for ballast. A deeper analysis has been realized in each case to assure clearance and consistency in accordance to the railway industry.
4.4.4 Emissions

A list of all known emissions has been defined and drawn up for each process stage and included in the data collection. The availability of data has been sometimes limited as on certain sites and emission values were unknown; techniques of measurement are more advanced for some sites than others. Where sites are not able to provide the data for such flows, and to avoid artificially reducing the average values for them (as the value for sites that do not know the data is zero), average data has been assigned to the sites with 'missing data' when averaging it is possible. Average values are therefore not assigned to all sites with missing data. This average value is calculated based on those sites that have submitted data for each of the accounted flows below and is based on average value.

4.4.5 Data quality requirements

To ensure that this LCA can provide the most accurate and representative data for railway industry, the quality of the data used in both models must be as high as possible. To achieve this, industry data collected directly from the producers has been used whenever possible. For all other data, primary data were used when possible, and finally upstream LCA data from the GaBi 6 professional database.

4.5 Methodological details

4.5.1 Characterization

For CML 2001, a Microsoft Excel spreadsheet with characterisation factors for more than 1700 different flows can be downloaded from CML website. The characterization factors are updated when new knowledge on substance level is available. Several additional characterization factors are calculated by PE and LBP-GaBi following the principles described in the CML 2001 methodology documents.

4.5.2 Normalisation

Normalisation factors for CML 2001 are available for the EU. The normalisation factors are calculated via total substance emissions and characterisation factors per substance, and are hence following the substance level updates.
4.5.3 Averaging

Average has been calculated using weighted average, based on the average multiplying factor which has been obtained proportionally to the corresponding production quantity over the total production quantities.

4.5.4 Software and database

The models for ballast and Neoballast LCA have been made using the GaBi 6 software system for life cycle engineering, developed by PE International GmbH (most recent version available at the beginning of the LCA's). The data has been imported to GaBi 6 model following the indicated steps and in accordance to existing data and processes.

4.5.5 Interpretation

Results have been interpreted in accordance to goal and scope. The interpretation focus on the following topics:

- Identification of the main contributors to a certain impact and to overall results
- Sensibility evaluation of the main contributors
- Conclusions, limitations and recommendations of the impacts, flows and processes

4.5.6 The end-of-life phase

Ballast is partially reused, recycled and disposed in landfill. Therefore it is important to consider recycling in LCA study involving ballast, namely the crushed ballast no more useful for railway but still useful for other construction purposes. Furthermore the reuse of ballast in the track is an important process, which reduces ballast extraction substantially. In the other hand for Neoballast we are facing the no recycling of Neoballast for other construction purposes yet. Despite this fact, Neoballast recycling is in the own railway industry, for aggregates that lost its covering can be recycled just recovering them. As for ballast the reuse of Neoballast it's a crucial fact for reducing materials provision and production. The adopted methodology considers all previous mentioned factors.

Ballast recycling is not a fixed percentage of ballast implemented in the ballast bed; this quantity varies with the construction works carried out in the period of ballast restitution. An approach can therefore be applied for the recycling and its transport; considering the experience in recycling of some railway construction and maintenance companies, a weighted average value of the ballast recycled in other lines, in recent years.
5. Data quality

The data that have been used for this study can be classified in three ways:

- Primary data collected from railway companies (gate-to-gate data)
- Primary data from GaBi 6 Professional database
- Primary data from similar studies or analysis

The overall quality of the data is considered to be representative of the system described in terms of technological coverage and furthermore some checks have been done to assure it.

All data from GaBi 6 Professional database was revised in order to assure consistency in the system boundaries and the upstream data. Expert judgement and advice were used to select the appropriate data and boundaries to be chosen. Detailed database documentation for GaBi datasets can be accessed at http://documentation.gabi-software.com/.

Data collection pretends to be representative of all the steps in the ballast provision, maintenance and restitution; the inclusion of all processes is a crucial fact for assuring this.

For further analysis, a deeper data collection can be done, in a way to amplify the inputs and outputs spectrum to obtain a more detailed analysis but more locally dependant on each geographic and technologic precise location and period of data collection.

5.1 Raw data

All information provided has been checked individually. General plausibility checks were applied as well as benchmarking checks. The data collector was able to specify the data in their preferred units within the data collection system to avoid human error when entering the data, for the conversion from one unit to another. For example, electricity consumption could be entered in MJ, KWh, etc.

Following visual inspections suspected out-of-range data and missing information has been analysed and detected, where data were missing or suspected to be erroneous clarification was sought with the site or provider until all necessary information is in accordance. Some manual import was necessary, additional inspections have been done to avoid errors in conversion or typing.
5.2 Data gaps

Where there were gaps in the data, for any missing data it has been a strict collaboration to provide any missing data. Where this was not possible, the average value, based on data collected from other providers of railway industry was incorporated into the datasets where it was missing. If neither other providers have been capable of contributing to missing data, averaged data from providers and analysis from other industries was introduced to avoid data gaps, which represent a zero value.
6. Life Cycle Assessments results and analysis

6.1 Environmental impact categories

The impact assessment is based on the methods and data compiled and includes the following LCIA categories, for its relevance in the environment and the human health.

- **GWP (Global Warming Potential)** is a warming of the atmosphere, which causes climate changes, which may include increased global average temperatures in the lower atmosphere and sudden regional climatic changes.
- **AP (Acidification potential)** is caused by acids and compounds which can be converted into acids. When emitted to atmosphere and deposited in water and soil, may eventually result in a decrease of the pH, and so an increase in acidity. Mainly affects the environment in a regional scale.
- **EP (Eutrophication Potential)** is also called nutrient enrichment; it affects the function and structures of the ecosystems by exerting toxic effects on the organisms that live in them. Predominantly it affects local and regional scales.
- **HTP (Human Toxicity Potential)** covers a number of different effects (acute toxicity, irritation effects, allergic effects, etc) and exposure via different media (air, water and soil) related with human health. It does not include indoor consumer exposure or work environment.

6.1.1 Global warming potential 100 years

![Global warming potential 100 years (GWP)](image)

Figure 34: Global warming potential 100 years (CO\(_2\) eq) of ballast and Neoballast processes

The GWP is dominated by carbon dioxide (CO\(_2\)) emissions and methane (CH\(_4\)) emissions, which represent almost all the emissions of all Green House Gases...
(GHG) emissions for the ballast industry. Processes with more GWP are the more contributors to carbon dioxide and methane emissions.

In accordance with Appendix 4, for Neoballast it is appreciated a reduction of 7.31% of kilograms carbon dioxide equivalent in respect to conventional ballast for the GWP.

### 6.1.2 Acidification potential

The AP for ballast and Neoballast products is dominated by emissions to air, which contribute for nearly the totality of this impact.
In accordance with Appendix 4, for Neoballast it is appreciated a reduction of 20.21% of kilograms sulphur dioxide equivalent in respect to conventional ballast for AP.

### 6.1.3 Eutrophication potential

The EP for ballast and Neoballast products is predominated by emissions to air; the main contributor is nitrogen oxide.
In accordance with Appendix 4, for Neoballast it is appreciated a reduction of 17.23% of kilograms phosphate equivalent in respect to conventional ballast for EP.

6.1.4 Human toxicity potential

HTP is based on both the inherent toxicity of a compound and its potential dose.
In accordance with Appendix 4, for Neoballast it is appreciated a reduction of 39.34% of kilograms dichlorobenzene equivalent in respect to conventional ballast for HTP.
7. Life cycle interpretation

This section of the report summarizes the key aspects of the life cycle study in terms of the life cycle data developed, impact assessment and each of the categories included in the data.

7.1 Identification of significant issues

The following figures represent different contributions to diverse impact categories (in %). The addition of the percentages shown below, per category, is equal to the total emissions (100%).

![Figure 42: Life cycle contributions to impact categories for ballast](image)

In the first case (ballast), similitude between GWP, AP and EP lifecycle contributions is basically due to the fact that the main contributor to this categories are certain GHG emitted to air.

In Figure 42 Maintenance highlights for being the main contributor of the ballast in all impact categories, representing an impact from the 29% to the 41% for different cases. Both construction and transport to site processes are the two followers main contributors for GWP, AP an EP with percentages in between 15% and 25%. Therefore for Human Toxicity Potential category, aggregate extraction is distinguished for being the second main contributor (24%) after the maintenance (34%). This is explained due to the fact that inherit toxic compounds in the aggregate extraction is enormous despite the fact that its toxic potential dose is not one of the biggest.

Maintenance process is so important due to its machinery emission to air of different GHG, as some of them are the main responsible of more than the 90% of the impacts for some categories. Same phenomenon happens with construction and transport processes, but its impacts result lower because of the different machinery utilised, machinery specifications and efficiencies.

Regarding to transport from site, its impact for different categories it is between 8% and 14%, thus being part of the transport to site process unit, the transported...
material from site is smaller due to non transported and reused material, which directly in restitution goes back to the ballast bed.

In regard to landfill process, which represents a minor impact under 3% in all categories, clearly represents the small environmental repercussion of ballast end of life.

In the second case (Neoballast), binder represents the most important contribution to almost all categories (GWP, AP and EP) for Neoballast lifecycle contributions (Figure 43), specially importance over the rest in Global warming potential 100 years. In reference to other Neoballast specific processes: the process of Neoballast manufacture represents a very small contribution to the overall emissions of Neoballast for all categories. In addition the rubber powder process is more significant due to its increased consumption of electricity for the additional triturating needed for acquiring the wanted particle diameters, but still representing less than 5% of the total impact for Neoballast lifecycle contributions in each category.

All processes in common with ballast and Neoballast lifecycles, suffer a significant reduction due to the fact that Neoballast lifetime is two times the lifetime of conventional ballast. This represents a smaller required quantity of aggregates from quarries, for the period of analysis, and so the tonnage transported. The reduction of the construction works, maintenance works and restitution works, for the same period, affects in a reduction of its emissions in all the categories. Otherwise the appearance of new processes, specific for Neoballast, which contribute increasing the total Neoballast emissions in each category, compensates in some way the previous reductions.
7.2 Completeness and consistency checks

7.2.1 Completeness

Within the LCA model, completeness checks were carried out in order to analyse:

- Completeness of each process
- Coverage of relevant energy and material inputs of each product
- Coverage of the significant outputs (accounted emissions)

7.2.2 Consistency

For checking consistency of the data provided, different balances were carried out on a process level, for each site. Additionally, benchmarking checks were made of the data, on a horizontal level, for example on tampers comparison.

7.3 Conclusion, limitations and recommendations

7.3.1 Conclusion

- This study shows that for all the environmental categories considered, Neoballast behaviour is better than conventional ballast one. That applies to GWP (Global Warming Potential), AP (Acidification potential, EP (Eutrophication Potential) and HTP (Human Toxicity Potential). Which means Neoballast is a better product, in reference to the environment.
- But it also shows the very big impact of the binder processes in the case of Neoballast. This has two main reasons. First, the enormous amount of binder material required to ensure a proper protection of the original ballast particles. Second, because binder utilisation for this purposes is brand new and there is room for huge improvements in obtaining and implementing it. To study how to optimise those processes seems to be the next step recommended to be taken into account.
- As maintenance is a key factor in railway operation, both from the technical and economical points of view, Neoballast appears to be an interesting material, as reduces the necessity of aggregate material, increases the life cycle for the full track system and improves the efforts and vibrations transmission to the platform. LCIA results show that, on top of that, from the Impact Assessment perspective, Neoballast has even a better performance than the conventional ballast, mainly due to the extension of the life cycle and despite the high binder consumption.
7.3.2 Limitations

In regarding to the goal and scope that have been defined at the early stage of this LCA in accordance with the appropriated ISO standards, this project do not pretends to be representative of the whole superstructure of the rail track, it focus only on the ballast bed lifecycle with determined specifications. So this results cannot be taken for railway lifecycle representativeness.

Thus the corresponding geographic, time coverage and technology coverage has to be taken into account when it is pretended to utilise those results.

Furthermore for the usage of this data for future analysis and comparisons, all verifications done and criteria adopted must be fulfilled in other product analysis and comparisons.

7.3.3 Recommendations

In last recent years, different countries and companies have been working on new methodologies for reducing the maintenance of rail tracks, with Neoballast it is acquired the reduction of the maintenance in a substantial way and furthermore it opens a new line of investigation which is the binder product investigation. This analysis recommends the corresponding investigation and development in the binder components (for example, the usage of organic compounds in its performance) and its manufacturing optimization for the railway industry.

Still related with the binder, this analysis considers interesting the fact of the possible reduction of binder quantity usage for the corresponding coverings. As this will directly affect the reduction of binder environmental impact in the LCIA.
Appendices

Appendix 1
Type section of main line double track (straight)

Different sections of ballast layer are utilised all along the railway. By the way, as said in the explicit functional unit, double track railway in land layer (straight line). In that case, ballast layer is dimensioned as in the following figure.

![Figure 44: Ballast section for double railway on land platform (straight line)](image)

The area of this ballast section will be the one used from now on in ballast and Neoballast sections. Volume = 4,44 m³/m.

The apparent ballast density is depending on the quarry, so it is accorded to use the average of the apparent densities of the principal quarries in Spain supporting ballast type 1 (V≥200 km/h). This data has been provided by the specialized inspection organism which does the quality control of the quarries in Spain, working for Adif. As the quarries quality certificate must be renewed every 5 years, the information considered refers to the years 2009-2014. The result obtained is an average density of 1,4g/cm³.

For this type of section, the considered length and the average density utilised, the resulting weight of ballast are 6220 tones.
Lifetime is a critical fact when doing a comparative LCA of two products with different lifetimes. In this LCA is clear that for the same functional unit the one with lowest lifetime, when computing environmental impacts more material quantity should be taken into consideration.

For the conventional ballast lifetime, different European countries estimate the appropriate time for ballast restitution with different procedures. Divergence in procedures represents also divergence in the appropriate time to do ballast restitution. According to ballast theory, the tamping has to be done in shorter periods as ballast lifetime increases, till getting into a point in which the tamping is so frequent (with corresponding traffic interruptions) that it is economically better to proceed to ballast restitution than to keep tamping. This fact is shown in figure below:

![Figure 45: Tamping effectiveness over time](source: ALAF)

According to the figure and its corresponding ballast theory (ALAF) that assumes ballast lifetime for 25 years and the large experience in railways constructions, maintenances and restitutions from COMSAEMTE; the lifetime of ballast is assumed to be 25 years.

As Neoballast is a new type of ballast, it is not yet implemented in railways, neither for long distances nor long time. The estimation of its lifetime has been done
according to different laboratory tests. The different parameters are obtained from laboratory tests, realized in accordance with UNE.

The main problem with ballast is the percentage of fines, when the percentage of fines rises a value of 20% ballast restitution should be done (ballast cleaning process). So there is a big interest in avoiding the fragmentation of the ballast. In order to analyse this phenomenon the coefficient of Los Angles (CLA), is very relevant. The less fragmentation of Neoballast implies approximately a resulting CLA coefficient 10 times smaller than the one of conventional ballast. The other test interesting this issue is the Microdeval test, which is representative of the aggregates particles collision in a water media. The tests already done with the Neoballast, shows an obtained a Microdeval coefficient 2 times smaller than the one of conventional ballast; that means, better properties for the Neoballast for this test and so on for this comparison.

There is no linear relation between those two parameters and the ballast lifetime, theories about the relation of those coefficients with respect to ballast lifetime have not been yet globally proved and accepted. Furthermore this is not the main objective of this study so an assumption about that particular matter has been done. According to CLA, the estimated Neoballast lifetime can be almost an order of magnitude bigger. Thus the Microdeval results give us proper and lower value for the approximation of Neoballast lifetime, which can be assumed a lifetime of twice the normal one of the conventional ballast. It can be said that to adopt for the Neoballast to adopt a lifetime of 2 times the life of conventional ballast is quite a conservative criteria, even if further track tests have to be done to guarantee its validity.

So, as explained before, lifetime of the Neoballast (50 years) is supposed to be twice the lifetime of conventional ballast (25 years). As said in chapter 4.2, a reduction of Neoballast layer thickness could be done (due to better resisting properties of the Neoballast in various tests), even in the case of this project the same thickness has been considered for both the Neoballast and conventional ballast. Therefore once those better properties are confirmed after more laboratory and on site tests, the ballast layer optimization could be achieved.
Appendix 3
Ballast and Neoballast GaBi 6 model

Figure 46: Ballast GaBi model

Figure 47: Neoballast GaBi model
# Appendix 4

## LCA results

<table>
<thead>
<tr>
<th></th>
<th>Global warming potential 100 years</th>
<th>Acidification potential</th>
<th>Eutrophication potential</th>
<th>Human toxicity</th>
</tr>
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<tr>
<td></td>
<td>Kg CO\textsubscript{2} equivalent</td>
<td>Kg SO\textsubscript{2} equivalent</td>
<td>Kg phosphate equivalent</td>
<td>kg DCB equivalent</td>
</tr>
<tr>
<td></td>
<td>Ballast</td>
<td>Neoballast</td>
<td>Ballast</td>
<td>Neoballast</td>
</tr>
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<td>Aggregate production</td>
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<td>161,00</td>
<td>92,00</td>
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<td>589,46</td>
<td>321,02</td>
</tr>
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<td>Neoballast manufacture</td>
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<tr>
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<td>47.175,30</td>
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<td>Restitution</td>
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<td>6.168,10</td>
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<td>0,00</td>
<td>20,21</td>
</tr>
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</table>

Table 12: LCA results
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