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Abstract: The 27,000 km of railway track in France represents approximately 100 million tonnes of ballast. This ballast requires maintenance approximately every 7 years, screening and partial renewal every 20 years, and complete replacement every 40 years. Despite its shortcomings, ballast is still widely used on railways worldwide, as there is no better or more efficient solution currently available. In an effort to conserve resources, companies such as SNCF (French national railway company) are implementing initiatives to move towards zero waste. In order to achieve the goal of promoting the recycling and recovery of end-of-life material flows, it is necessary to develop specific studies and models for production, such as direct and reverse logistics systems. This article proposes a generic material flow analysis model applied to a track and ballast renewal site, aiming to fill a gap in the literature. It is based on data from eleven track and ballast renewal sites. A flow diagram generated by STAN software presents a detailed diagnosis of ballast inputs, outputs, and stocks, including data uncertainty. The distribution of the material flows through the model is characterized by transfer coefficients in various transformation processes. Furthermore, by varying the quantities in this model, it is possible to study different scenarios based on the current situation. This will facilitate the projection and analysis of future management strategies aimed at achieving zero waste and reducing the discharge of toxic substances based on specific performance indicators.

Keywords: railway track and ballast renewal site; material flow analysis (MFA); STAN free software appropriate for MFA; ballast recycling; waste management; strategic planning

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1. Introduction

a. Global context of TBR management in France

As indicated by the Organisation for Economic Cooperation and Development (OECD), the utilisation of raw materials is projected to nearly double globally by 2060, largely due to an escalation in human activity, which will exert twice the current level of pressure on the environment [1]. In order to ensure the continued availability of materials, it will be necessary to meet this growing demand in an environmentally sustainable manner, despite the potential challenges posed by factors such as global warming and the depletion of resources.

To illustrate, global materials use is projected to reach 167 Gt in 2060, representing a significant increase from the current level of 90 Gt. Non-metallic minerals, such as construction materials, are anticipated to experience a notable expansion in their use, rising from 35 Gt in 2011 to 82 Gt in 2060. This is attributed to the strong correlation between their utilisation and investment and construction requirements, coupled with the limited availability of high-value-added recycling options [2]. However, the recovery of materials is a developing field that is yet to become fully competitive. Consequently, it will continue to play a relatively minor role compared to the extraction of raw materials [3]. Nevertheless, the OECD has indicated that an expansion in the extraction and processing of raw materials, including biomass, fossil fuels, metals, and non-metallic minerals, will result in an increased demand for water and energy. Additionally, it will lead to a rise in air pollution (from 28 to 50 gigatonnes of CO_2 equivalent by 2060), water and soil contamination, and a notable contribution to climate change (GHG emissions) [1,4].

In 2015 at the United Nations Summit on Sustainable Development, the UN defined Goal 9 as modernising infrastructure (installations, equipment, transport, etc.) and adapting industries to make them more sustainable by 2030. This will be achieved through the more efficient utilisation of resources and the increased implementation of cleaner, more environmentally friendly industrial processes and technologies [5]. In this regard, the authors of [6] state that resource scarcity identified by the European Factory of the Future Research Association is one of seven critical trends for manufacturers.

However, as [7] notes, ensuring the sustainability of the supply of mineral resources is a highly complex undertaking. It requires a multifaceted approach that encompasses exploration, technology, economics, and social and environmental issues, as well as advances in scientific knowledge. The task of predicting future sustainability is inherently challenging. As posited by [8], the concept of sustainable development necessitates a long-term structural transformation within our economic system and society. This is to ensure a reduction in resource consumption and the promotion of environmental sustainability over the long term, while maintaining a well-functioning economy and a cohesive society. To illustrate, in order to satisfy the necessity for sustainable mineral resources, the construction industry is required to adapt its methods of production from the technical, economic, and environmental perspectives.

In order to achieve this, the initial steps are to develop a technological framework that includes processes and practices, and to raise awareness among stakeholders. This will facilitate a transition from the linear consumption of products to a circular mode [9–11]. Secondly, stakeholders must deal with legislation, such as the European Waste Framework Directive [12], which set recycling and recovery targets to be achieved by 2020 for household waste (50%) and construction and demolition waste (C&DW) (70%). At the present time, the majority of European countries are in compliance with the target set for the recycling of construction and demolition waste [13]. C&DW encompasses materials derived from the dismantling of railways and is categorised in EUROSTATS as W121 (EWC-Stat category) [14]. At last, at the company's initiative, as during the European Week for Waste Reduction Sncf (Société nationale des chemins de fer français) reiterated its commitment to a zero-waste trajectory within 15 years. This will be achieved by exploiting a range of strategies, including eco-design, the reuse of objects, and the recovery of materials that would otherwise be considered waste or end-of-life products.

In more precise terms, the concept of zero waste represents an approach that is designed to minimise the generation of waste and wastage of materials to the greatest extent possible.

To achieve this, the right strategies must be identified [15–17] we have placed these references] for consumption and production patterns specific to the studied systems, in order to reduce waste at the source and improve the reuse, recovery, and recycling of products at the end of their life cycles, taking into account the substances and energy consumed [18].To attain this, it is essential to have a detailed knowledge of the flows into and out of the production systems in order to characterise quantitative aspects, such as the material pool, and qualitative aspects, such as the nature of the material. The economic (e.g., treatment and transport costs) and environmental (e.g., waste, release of toxic substances, and energy) performance aspects are also very important. The first aspect concerns the production of recycled materials or the recovery of end-of-life products at attractive prices, while the second concerns the rate of recycled or recovered materials, as well as the CO_2 emissions linked to transport. Material flow analysis (MFA) is a method used to obtain this holistic view of flows and to analyse the results of different scenarios [19–21].

The objective of this article is to examine the potential for recycling 70% of the ballast extracted from a ballasted complex during rail track regeneration operations (French conventional line of IUR group 7 to 9; see Appendix A, International Un-ion of Railways). A further objective is to analyse the material flows of scenario 1, which incorporates 30% recycled ballast, and scenario 2, which incorporates 70% recycled ballast. The data used for this analysis come from a TBR worksite provided by Sncf Réseau, the French railway infrastructure manager. The aim of this analysis is also to compare the relative changes and differences between scenarios 1 and 2 in terms of material flows (input/output/stock), transport use, and the track renewal train (TRT) required when regenerating the track, based on performance indicators. This comparison enables the identification of the most effective methods of production, transport, ballast recycling, and end-of-life material recovery. The results, presented in the form of a SWOT matrix, indicate the effects of a high rate of in situ recycled ballast on the preservation of the resource, since there is a reduction in the supply of new ballast, transport, and means of production and a corresponding reduction in the quantity of end-of-life material to be transported. However, the absence of solutions for recovering materials at the end of their life cycle and for reducing toxic substances, such as the use of polluting industrial products, transport, and means of production, makes a zero-waste approach more complex, since it also involves releasing as few pollutants as possible into the environment [22].

b. Research plan strategy

Firstly, an overview of the literature on ballast recycling is presented.

This includes a review of the quality of recycled ballast, a study of the mechanical behaviour of a mixture of recycled and new ballast, and, finally, an analysis of the feasibility of reusing 70% of the recycled ballast in situ from the ballasted complex extracted during track regeneration. This analysis takes into account the environmental problems associated with the emission of toxic substances produced by the means of production and transport used for the works.

Secondly, there is a focus on track and ballast renewal (TBR) worksites, and more specifically on the logistical complexity of managing large quantities of ballast entering, leaving, stored on, and recycled on TBR worksites within a circular economy framework. In addition, the TBR operations of a worksite and of the works train (TRT), with its logistical aspects, are described in order to fully understand and identify the related flows.

A literature review is presented with the aim of identifying a relevant MFA model to finely characterise the material flows of a TBR worksite in a stochastic context, based on quantitative production databases of TBR worksites provided by Sncf Réseau. An original methodology is selected to plan and design the efficient (zero-waste) management of the inputs, outputs, and stocks of a TBR site throughout a direct and reverse supply chain, based on quantitative assumptions with a 95% confidence interval. This methodology is based on MFA [20,23], mapping (flow diagram), and data uncertainty (STAN software) [24–26].

A generic and innovative TBR flow diagram is proposed for the MFA. This MFA makes it possible to quantitatively monitor ballast and material flows, as well as their fate once they leave the TBR site (on-site recycling, other material recovery, or disposal). This MFA model developed on the basis of a TBR site, coupled with a powerful tool such as strategic planning, makes it possible to move from the linear consumption of materials (management model corresponding to the "current situation" with 30% recycled ballast) to a more circular consumption (new management model corresponding to a "future situation" with 70% recycled ballast), more conducive to a zero-waste strategy.

In addition, detailed knowledge of material inputs, stocks, and outputs enables a global development plan to be drawn up in which the quantities vary and are estimated with their confidence intervals (95%). The STAN software used for this purpose has a unique feature, as follows: the possibility of introducing tolerances (±) on the transformation transfer coefficients within the various processes of the industrial system. This makes it possible to highlight the instability and disorganisation of flows at the site logistics (TBR) level. Finally, to conclude, different flow management scenarios are presented and discussed, comparing the "current situation" (referred to as scenario 1 with 30% recycled ballast) with a "future" situation (referred to as scenario 2 with 70% recycled ballast), making the best decisions to achieve the zero-waste objective, as targeted by the railway companies.

c. Ballast recycling

Recycling ballast in situ is potentially more sustainable and less costly, because it minimises the disposal of this material. This means less material from quarries and less transport to supply construction sites with new ballast and to dispose of end-of-life products. This is why our work is based on the assumption that the recycling rate for uncontaminated ballast can be increased to 70%. However, to achieve this, we need to produce recycled ballast of an equivalent quality, at a lower production cost than new ballast and at an environmentally acceptable level. It is essential to check whether this proposal is viable.

Over time, railway ballast degrades, and the characteristics of ballast recovered during track renewal take the form of abraded ballast and roughness that can become detached.

The ballast bed then loses its performance as the finer material created gradually fouls the assembly.

The causes of these phenomena can be attributed to the following three primary factors: the frequency of train traffic, the tonnage transported, and the significant damage caused to the ballast by repeated maintenance operations, which typically involve 10 to 15 tampings over the course of a track's lifespan, which is typically from 20 to 30 years. These operations are conducted with the aim of restoring the track geometry and cleaning the ballast mid-life [27].

In general, there is no reason not to reuse ballast extracted from railway tracks during regeneration operations if it can be cleaned, screened, and supplied in a distribution that complies with the standards regulating ballast properties, such as granulometry, hardness, abrasion resistance, and mineral composition, comparable to that of new ballast (petrographic analysis). The objective remains to guarantee the performance qualities of the railway subgrade, given its heterogeneity due to the wide variety of materials that compose it (gravel, pebbles, sand, etc.) and the environmental conditions to which it is subjected, with poor drainage remaining a key cause of track deterioration [28].

d. The quality of recycled ballast

In order to envisage the reuse of used ballast on railway lines, the literature presents a series of research studies enabling the quality of used ballast to be compared with that of new ballast. For example, a study of the recycling of used ballast was carried out using the Southampton Railway Testing Facility (SRTF) and a large triaxial testing apparatus. The properties of individual ballast grains were characterised in terms of their shape and petrographic composition. The results showed that the obsolete ballast used in this study retained a good performance and strength similar to that of new ballast, despite a reduced surface roughness [27]. Moreover, in another comparative study conducted by [29] between used and new ballast collected under a switch, the geometric and strength characteristics were evaluated using the Los Angeles abrasion test, which provides data on resistance to fragmentation. The findings indicated that the degraded material remained suitable for its intended purpose, as its properties were retained and continued to meet the specified criteria for ballast material.

In addition, poor maintenance of the ballast bed leads to a non-linear or uneven load distribution and a loss of track stability, particularly in tight curves. Sharp-edged ballast elements provide a stable base for tracks. However, dynamic loads and tamping operations can round off or destroy the sharp edges of the ballast, resulting in a reduction in track stability. Nevertheless, in a case study of a 7.3 km line, ballast fouling was at 51%, and after tamping and ballast regeneration operations, the volume of recycled ballast was 14,100 m^3, compared with a total ballast volume of 17,853 m^3. Consequently, dirty and worn ballast can, therefore, be recycled and renewed on a regular basis using recycling machines or a recycling plant close to the railway line [30].

e. Mechanical behaviour of a mixture of recycled and new ballast

It is usual to apply a mixture of new and recycled ballast when regenerating railway tracks. The aim of one study was to characterise the mechanical behaviour of this mixture and to determine the weight proportions of recycled ballast. To achieve this, a series of large shear tests were carried out under different normal stresses (50, 100, and 200 kPa) with different weight proportions (0%, 10%, 20%, 30%, 40%, and 50%) of recycled ballast mixed with fresh ballast. The interlocking of recycled ballast was weaker than that of fresh ballast due to its loss of angularity and reduced surface texture. Therefore, increasing the proportion of recycled ballast mixed with fresh ballast caused a decrease in shear strength and friction angle, generating an increase in shear expansion. The experimental results showed that, when the proportion of recycled ballast was less than 30%, the reduction in shear stress was negligible [31].

In another case, based on tests using an abrasion machine, the results of the study showed that the strength properties of a ballast layer consisting of a mixture of new and recycled ballast depended on the initial abrasion level of the ballast.

Thus, for a mixture of 70% recycled ballast and 30% new ballast under 200 round trips in an abrasion machine, the strength properties of the ballast layer corresponded to the standard values for new ballast. However, whatever the percentage of the new ballast mix in relation to the ballast handled in the abrasion testing machine under a test of 800 round trips, the specific cohesion values were twice as low as those of the new ballast, even with a ratio of new and recycled ballast of 30/70% [32]. However, in this work, the research focused on studying the mechanical behaviour of fresh and used ballast grain assemblies using a combination of laboratory experiments and discrete element modelling (DEM). The results showed that assemblies of fresh and used ballast grains exhibited similar stress–strain curves compared with the fresh ballast assembly, which had a slightly higher shear strength (5%) in the residual state. In other words, fresh ballast grains had a better lateral resistance than used ballast. So, to reuse so-called used ballast in railway applications, it would be interesting to discover a method of increasing resistance to lateral deformation because of the almost equal vertical deformation of the two materials [33].

f. How can used ballast be recycled efficiently?

Firstly, today's track regeneration worksite policy is based on reuse, in order to reduce the supply of new material and waste. To achieve this, used ballast is collected, sieved according to grain size, and washed in factory trains. The ballast is reused either directly on site or via a nearby reprocessing platform.

Secondly, to ensure the quality and conformity of reused ballast, algorithms and optical analysis allow for its size and shape to be monitored in real time on the production line and the installation to be shut down in the event of non-compliance. On this subject, the literature reports research work that studied the morphological parameters (flatness, elongation, roundness, sphericity, and convexity) of fresh and used ballast materials using 3D scanning and image analysis techniques. To perform this, a machine learning algorithm was trained to automatically distinguish between fresh and used ballast (Los Angeles Abrasion Test). The results revealed that sphericity and convexity were crucial parameters for differentiating between fresh and used ballast [34,35]. In this way, digital technology can provide answers to one of the challenges of recycling used ballast—determining its useful life—because it makes it possible to anticipate deposits, monitor production in tonnage, and help in the decision to recycle ballast, reducing the demand for fresh ballast while maintaining track performance. In addition, this research carried out on the Austrian rail network showed that the laser scanning survey method provides precise geometric data on the profiles of ballast layers. Based on this new index, decision makers are able to make precise decisions on the priority of track segments to be renovated and their planning [36].

Thirdly, the assurance of industrial control of the supply chain is defined by a detailed knowledge of the material flows from upstream to downstream of the TBR site. Bottom-up MFA models [20] provide the most detailed knowledge of a system's input/output/stock flows. This tool makes it possible, on the one hand, to study the reuse potential of used materials from the site and to plan their transfer to internal or external recovery solutions, and, on the other hand, to measure supplies accordingly.

On another note, to improve the life of ballast and, thus, promote its recycling rate, the ballast bedrock can be adapted to local needs. In France, for example, the ballast standard can be relaxed to suit the needs of the railway. Similarly, in China, in order to remedy shortages of high-quality ballast, it is possible to use "first-class" ballast rather than "special-class" ballast [37].

Thus, until now, only 30% of the used ballast removed from tracks was likely to be reused. Now, the combination of a new approach based on real-time production control via continuous granulometry monitoring and a compact, mobile production tool consisting of factory trains and local reprocessing platforms has made it possible to return up to 72% of used ballast to the track on certain sites. Thanks to this "100% local" approach, greenhouse gas emissions and our transport costs have been reduced, Sncf Réseau, (Sncf Réseau is the French railway infrastructure manager). Every year, tonnes of material are replaced on the railways, and these kilometres of rail, sleepers, and tonnes of ballast can be reused for other purposes. However, the environmental cost generated by their secondary use is sometimes worse than the problems associated with their disposal. Research results show that the carbon footprint generated by an indirect process is almost a hundred times greater than that of a direct process of reusing track materials. Therefore, to reduce CO_2 levels, one solution would be to simplify the processing activities in the industry, which would save time and money. Another would be to give these materials direct uses close to their place of origin and reduce transport and processing operations [22].

The proposed local solution would entail the reuse of up to 70% of the recycled ballast in situ, as well as the reuse of the 'earth', a mixture of aggregates and ballast at the end of its life, as a sub-ballast layer for rail or road lines. For example, research conducted by [38,39] explored the potential utilisation of recycled fouled ballast waste stabilised with soil collected in the vicinity of the railway. The findings demonstrated that all mixtures incorporating recycled fouled ballast waste satisfied the mechanical and physical criteria for a railway sub-ballast layer subjected to high-load transportation.

In this instance, a scenario may be studied using an MFA model [20,23], which targets the absence of waste and toxic substances, based on a series of performance indicators, and provides for the recycling of 70% of used ballast.

g. Track Ballast Renewal worksites

The regeneration and maintenance of a national rail network requires around 1.5 Mt per year of new ballast. In 2018, around 7% of the new ballast delivered to construction sites was not used (approximately 100,000 t). In addition, from 30% to 40% of the 2 Mt of removed ballast is reused in situ, with the remainder being recycled in road engineering or sent to a materials recovery platform [40]. Recycling platforms are used to temporarily store end-of-life ballast, for example, so that it can be sorted and then recycled. They are equipped with crushing and screening facilities.

The construction work is performed using an automated mechanical chain known as a 'TRT' (Train Renewal Track) at a rate of 900 to 1000 metres per day. This 'TRT' is a 600-metre-long factory train consisting of several rail modules that are specific to each operation in the construction phase plan (see Figure 1 below).

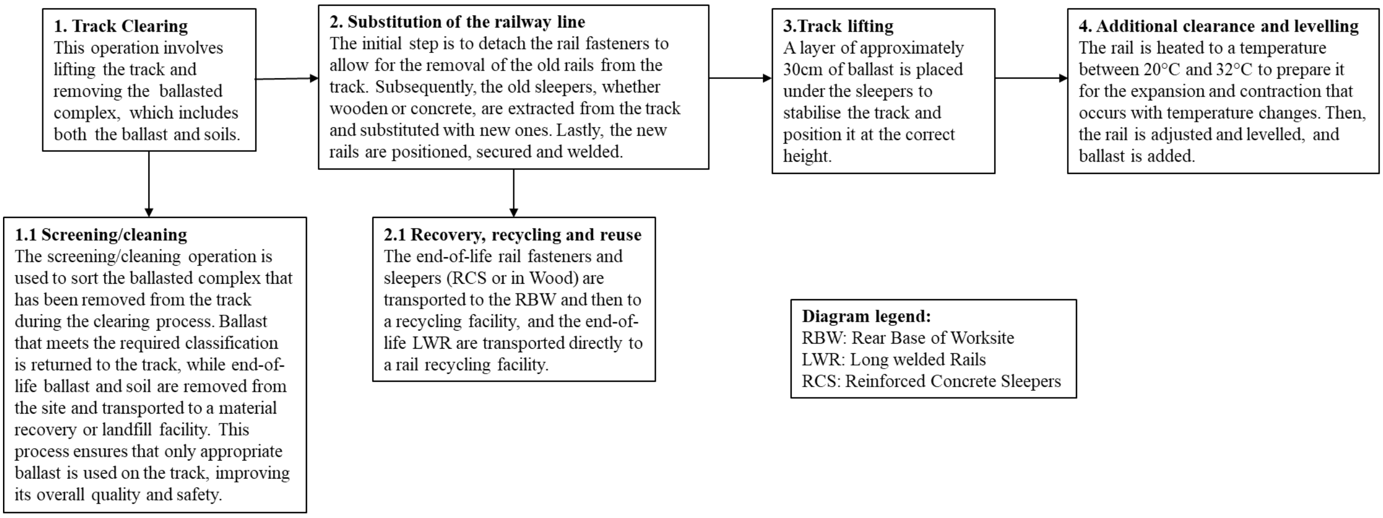

Figure 1. Main stages of the TBR works and intervention of the works train TRT.

However, certain rail infrastructures such as tunnels, bridges, and stations do not allow the use of the TRT, the factory train specially designed for track renovation. In these cases, lighter mechanised means are used, with a lower output (from 150 to 300 metres of work per day). According to Sncf Réseau, the average lifespan of a railway track is 40 years, depending on the intensity of traffic, the speed of trains, the tonnage transported, and maintenance operations such as tamping [41,42]. The components of the track wear out, particularly the ballast, whose corners eventually become rounded [37,43]. Depending on the segment of track to be regenerated, the flow values and scenarios can vary significantly. For instance, on some sites, up to 72% of recycled ballast was reused in the track (Sncf Réseau).

From a qualitative point of view, before each Track Ballast Renewal project, a chemical characterisation (herbicide, hydrocarbon, phenol, creosote, heavy metals, silica dust, etc.) of the ballasted complex (used ballast and earth) is carried out before it is removed from the track. Over the three years from 2012 to 2014, only around thirty worksites had non-inert ballast to manage (station and switch areas). This represents 7% of the worksites concerned and around 1% of the total ballast cleared [40]. Furthermore, on the Tours–Bordeaux TGV line, the phases of infrastructure production and maintenance accounted, on average, for 62% and 59% of the environmental impact, respectively, while the transportation phase contributed up to 18% of the total impact [44,45].

The work with the factory train is divided into four main stages of track clearing, substitution, track lifting, and additional clearance and levelling, as determined by Sncf Réseau.

h. Logistical flows of a TBR construction site

TBR generates major flows of goods, such as the supply of new materials (sleepers, new and recycled ballast, rails, etc.) and the disposal of end-of-life products and site waste (ballast, sleepers, rails, etc.). Sorting and treatment operations are used to direct end-of-life material flows towards material recovery or landfill. After screening (in situ), ~30–40% of ballast can be reused on the railway [31,37,40,46,47], and another part can be reused in road engineering [48,49] or directed to a material recovery platform. However, ~1% of the ballast will have to be depolluted (station platform), particularly in terms of the metal deposits caused by wear on the bearings and track or contamination of the ballast by hydrocarbons [50,51].

There is an average annual renewal rate of ~550 km per year, where, for each kilometre of track, 120 tonnes of rail, 1666 concrete sleepers, 6700 elastic sleepers, and 2500 tonnes of ballast are needed. In terms of the supply and removal of materials by the TRT for a 20 km project, this requires the organisation of 500 wagon rotations (200 for the ballast; 120 for the sleepers; 100 for the removal of excavated material; 50 for the removal of rails; and 30 for miscellaneous materials) (Sncf Réseau/Setra).

The sustainable development implications of an analysis of ballast flows are, therefore, significant and relevant. The sustainable development implications of analyzing ballast flows are thus both significant and relevant. Material Flow Analysis (MFA) supports improved resource efficiency and waste management [52,53], reduces costs and environmental impacts, and minimizes health risks associated with toxic materials [18]. Applied to TBR operations, MFA is useful for analysing and planning the flows of an industrial system [23], as it allows for quantifying the material flows involved in each production process and in the direct and reverse supply chain.

i. Literature on MFA models

Analysis of material flows enables a diagnosis of resource management in a given area at a given time [54–56]. It is based on an accounting approach for flows based on the first law of thermodynamics, which is linked to the conservation of matter. The MFA method makes it possible to assess and control the metabolic processes in anthropogenic systems and to improve resource use and environmental protection [20]. More specifically, this MFA method makes it possible to characterise the metabolism of an area by focusing on the following anthropogenic activities: feeding, cleaning, living and working, transporting, and communicating, broken down into processes. For example, the construction of a building belongs to the activity of living and working [20], while railway development belongs to the activities of working and transporting. The work activity involves building and maintaining the quality (aesthetics and operation) of the rail infrastructure and protecting the environment (waste management and treatment). The transport activity, in our case, involves transporting raw materials and products at the end of their life.

In addition, MFA is applicable in many areas, such as environmental management, industrial ecology [57–59], and resource and waste management [60–63]. It can also contribute to eco-design to facilitate the recycling of end-of-life products [20].

MFA is used by industrial and commercial entities such as shipbreaking yards [23] as a standard analytical tool in materials management to locate and examine inputs, stocks, outputs, and the source of waste [6,64,65]. The method is bottom-up [20], i.e., based on elementary data which are aggregated, unlike the method Eurostat developed by the European Statistical Office [66], which is more specific for the generation of national balances, where the quantification of material flows appears as a complement to the usual economic indicators [67]. This method is top-down, i.e., based on global data, which may be disaggregated [62]. The principle of this methodology is to count all the flows into the system, as well as all the flows out from it, without first analysing the processes that link them. The system is somewhat analogous to a black box, which will only be opened once a material balance has achieved.

The Material Flow Assessment in Manufacturing (MFAM) proposed by [6] assesses the material efficiency of production systems. Material efficiency is defined as the provision of a product or service with less material output [68]. In addition, it aims to improve the efficiency of production and reduce the environmental impact of material processing. The MFAM is a comprehensive tool for the manufacturing industry, as it integrates quantitative and qualitative information. The qualitative aspect at the disaggregated level allows for the measurement and characterisation of the environmental impact of a material flow in a production system during its transformation or combination in the manufacturing of a product, since, at the disaggregated level, all the constituents and transformation reactions involved in the manufacturing of a product can be characterised, and their environmental impacts studied and measured. This is also the principle of the definition of the Life Cycle Assessment (LCA) of a product, which aims to systematically evaluate the environmental effects of the life of a product from its "cradle to grave". That is to say, to assess the flows (of materials or energy) entering and leaving a product at each stage of its life, from the extraction of raw materials to its final disposal. Life Cycle Assessments (LCAs) are standardised in the ISO 14040 and ISO 14044 (For the European Union, the standard reference is: EN 15804).

In addition, the MFAM provides information on the recyclability rate of a product, which is the percentage of material that can be recycled (ISO 14021:2016). The quantity of materials in a production system is the result of a material balance (law of mass conservation) based on the inputs/stocks/outputs of a process, so that, at the aggregate level, it represents the quantity of raw materials consumed, products produced, recyclable materials, and waste. The MFAM framework was designed to focus clearly on the assessment of material flows in a manufacturing system in five phases (production system scope, material flow inventory, material flow assessment, improvement scenario modelling, and interpretation). This allows the decision maker to discover innovative improvement opportunities on these material flows, which would normally not have been discovered [6].

j. Selection of a relevant MFA model: Brunner and Rechberger (2004)

The literature allowed us to select an MFA methodology, a method for systematically assessing the input and output flows of a system defined in time and space [20]. Furthermore, the literature has shown us an application of this method for ship recycling [24]. MFA can be performed using the STAN software [24–26]. This software allows for the modelling of the material flow within a system (such as a TBR site) and the display of results in the form of a flow diagram. Additionally, it can be used to determine the quantities and types of materials that enter, are stored, or exit the system. The strategy of the method relies on the quality of the input data (accuracy, completeness, homogeneity, reliability, and timeliness). However, in the case of missing data or data reliability problems, the STAN software (the latest version is 2.7.101; released 2022-02-01), based on the principle of the law of mass conservation, allows for material and substance flow analyses (MFAs/AMSs) to be carried out, taking into account the uncertainty of the data. It is capable of performing non-linear data reconciliation based on the conventional weighted least squares minimisation and error propagation approach [27].

2. Materials and Methods

The quarry is generally located close to the worksite. New ballast, F7, is produced there, and trains (from 800 to 1100 tonnes) are loaded to supply the TBR site directly, at a rate of one or two trains per day depending on the requirements of the work (F7). In addition, F7, still coming from the quarry and transported by rail, makes it possible to build up a stock of new ballast at the rear base of the worksite to supply the "TRT". At the start of the works, new ballast is delivered to the rear base (e.g., 20,000 t) to ensure a safety stock and the start of the works, as well as for special works (e.g., track switches, station platforms, etc.). In this case, the TRT is supplied with new ballast, F7, from the rear base.

a. Flows and processes of a TBR supply chain

Table 1 (see below) contains the nomenclature of the MFA model, which was built based on the main material flows of a TBR construction site, which are the internal or production flows F1, F2, F3, F4, F5, and F6 and the external flow F7. From this base, all the solutions for the distribution of the flows coming directly from the building site (F2.1, F4.1, F5.1, and F8.5) or passing through the rear base (F2.3, F4.3, F4.4, F5.3, F8.2, F8.3, and F8.4) are carefully studied and associated with the different processes of the system. The aim of our model is to generate all the possibilities for recovering, storing, or treating products at the end of their lives, in order to move towards a zero-waste strategy.

The first material introduced into the system is the ballasted complex (the F1 flow) to be removed from the track. Each flow is associated with a material and treated by a process, and each process identified is introduced into the MFA developed. The processes are mainly the cleaning of the railway track (CRT), handling/transport (H/T), screening (Scr), storage (Sto), storage on the railway (SR), new ballast laid on the railway track, and recovery of the leftover material from new ballast (NBLRT, RLNB).

Table 1. Nomenclature of the material flow analysis of the TBR site.

Flow	Nature of Flow
F1	Worksite of Track and Ballast Renewal (TBR), Railway Ballasted Complex
F2	Worksite (TBR), End-of-Life (EOL) of Toxic Ballast and Soils
F2.1	Evacuation of End of Life of Toxic Ballast and Soils from the Worksite (TBR) to a Hazardous Waste Facility (HWF) by lorry or train
F2.2	Evacuation of EOL of Toxic Ballast and Soil from Worksite (TBR) to the Rear Base of the Worksite (RBW) by Track Renewal Train
F2.3	Evacuation of the EOL of Toxic Ballast and Soil from the Rear Base of the Worksite to a Hazardous Waste Facility by lorry or train
F3	Worksite (TBR), End-of-Life of Non-Toxic Ballast and Soil
F4	Worksite (TBR), End-of-Life of Non-Toxic Ballast
F4.1	Evacuation of End-of-Life of Non-Toxic Ballast from Worksite (TBR) to Material Recovery by lorry or train
F4.2	Evacuation of End-of-Life of Non-Toxic Ballast from Worksite (TBR) by TRT to the Rear Site Base of Worksite by TRT
F4.3	Evacuation of End-of-Life of Non-Toxic Ballast from the Rear Base of the Worksite to a Material Recovery by lorry or train
F4.4	Evacuation of End-of-Life of Non-Toxic Ballast from the Rear Base of the Worksite to a Material Recovery Platform by lorry or train
F5	Worksite (TBR), End-of-Life of Non-Toxic Soils
F5.1	Evacuation of End-of-Life of Non-Toxic Soils from Worksite (TBR) to an Inert Waste Storage Facility 1 by lorry or train
F5.2	Evacuation of End-of-Life of Non-Toxic Soils from Worksite (TBR) to the Rear Base of the Worksite by Track Renewal Train
F5.3	Evacuation of End-of-Life of Non-Toxic Soils from the Rear Base of Worksite to an Inert Waste Storage Facility 2 by lorry or train
F6	Worksite (TBR), Recycled Ballast
F7	Supply of New Ballast
F7.1	New Ballast Laid on the Railway Track
F8	Worksite (TBR), Leftover of New Ballast
F8.1	Evacuation, Leftover of New Ballast from the Worksite (TBR) to the Rear Base of the Worksite by TRT
F8.2	Evacuation, Leftover of New Ballast from the Rear Base of the Worksite to other Worksites (TBR) by lorry or train
F8.3	Evacuation, Leftover of New Ballast from the Rear Base of the Worksite to a Material Recovery Platform by lorry or train
F8.4	Evacuation, Leftover of New Ballast from the Rear Base of the Worksite to some Buffer Stocks * by lorry or train
F8.5	Evacuation, Leftover of New Ballast from the Worksite (TBR) to a Material Recovery by lorry or train

*Buffer Stock *: It is possible to place small quantities of ballast along the track. This is a particularly useful method for carrying out minor repairs to railway switches and other components.*

The process (P1, see Table 2 below) is the stripping operation, which consists of removing the old ballast from the track and the earth using a specific machine (stripper). This ballasted complex is automatically directed (with the exception of flow F2, the toxic waste) towards a process that enables the screening (process P3) of the flow of non-toxic materials at the end of their life (flow F3). At the end of this process (P3), the following three flows are generated: (F5) non-toxic soil, (F4) the non-toxic end-of-life ballast, and the flow (F6) of the ballast recycled in situ (granulometric conformity), which is accounted for in the "stock" of the process (P6).

Table 2. Process nomenclature of the worksite (Track Ballast Renewal).

Processus	Nature of the Process
P1	Worksite (Track and Ballast Renewal), Cleaning of the Railway Track
P2	Worksite (TBR), End-of-Life (EOL) of Toxic Ballast and Soil: Handling/Transport
P2.1	Storage of EOL of Toxic Ballast and Soil at the Rear Base of the Worksite (RBW): Handling/Transport
P3	Worksite (TBR), Screening
P4	Worksite (TBR), End-of-Life of Non-Toxic Ballast: Handling/Transport
P4.1	Storage of EOL of Non-Toxic Ballast at the Rear Base of the Worksite: Handling/Transport
P5	Worksite (TBR), End of Life of Non-Toxic Soils: Handling/Transport
P5.1	Worksite (TBR), End of Life of Non-Toxic Soils Storage at the Rear Base of the Worksite
P6 = F6 + F7.1	Worksite (TBR), Stock on the Railway (Recycled Ballast + New Ballast)
P7	Worksite (TBR), New Ballast Laid on the Railway Track and Recovery Leftover New Ballast
P8	Worksite (TBR), Leftover of New Ballast: Handling/Transport
P8.1	Storage, Leftover of New Ballast at the Rear Base of the Worksite

The transportation of end-of-life products from the site is accomplished through various processes. Toxic waste is transported using process (P2) to a hazardous waste landfill, while processes (P4) and (P5) are used to transport materials to a materials recovery solution or platform, or to a non-hazardous waste landfill. More specifically, materials can be transported directly to a local recovery solution (road technique) or, if there is no immediate solution, to a logistics platform for the short-term storage of materials while awaiting a solution.

In addition, flows F2.1, F4.1, and F5.1 are evacuated directly from the site, while flows F2.2, F4.2, and F5.2 pass through the rear base via processes P2.1, P4.1, and P5.1, before being directed towards a material recovery solution (see flows F2.3, F4.3, F4.4, and F5.3). The evacuation of flows F2.1, F4.1, and F5.1 from the site is only feasible if there is a solution close to the site for processing these used materials and road access. As a general rule, the logistics for transporting used materials from the site are organised via the rear base and by rail (TRT). The flows of end-of-life materials or waste are then mainly directed towards a local processing solution by road transport or, very rarely, towards an acceptable rail solution depending on the frequency, quantity, distance, cost, and path available on the rail network.

The second material input to the system, represented by flow F7, is the supply of new ballast transported by rail from a nearby quarry and placed on the track during the track-lifting operation (the P7 process). Flow F7.1 tells us the quantity of ballast placed on the track accounted for in the “stock” (see Table 2 process P6). However, residue of new ballast (flow F8) results from process P7. To avoid wasting leftover new ballast, which generally either remains along the tracks or is stored at the rear base, the P8 process proportionally distributes the evacuation of this new residual ballast, either directly from the worksite via flow F8.5, or from the rear base with flows F8.2, F8.3, and F8.4.

The rear base is a strategic location in the organisation of TBR worksites with the “TRT” works train. It is located close to the worksite (20 to 60 km) and serves as a logistics platform. The rear base enables the company to manage supplies, evacuate waste, and maintain the TRT. Every day, the TRT leaves the rear base loaded with the concrete sleepers and new F7 ballast needed for the site’s production, and returns with end-of-life materials and products, which the rear base is responsible for redistributing to material recovery solutions (flows: F4.3, F4.4, F8.2, F8.3, F8.4, and F8.5) or landfills (flows: F2.1 and F5.3). These flows result from the operation of stripping the ballasted track complex (see Figure 2, F1 flow in the TBR site rectangle and P1 process in Table 2 carried out on the TBR site, which generates flows F2, F3, F4, and F5.

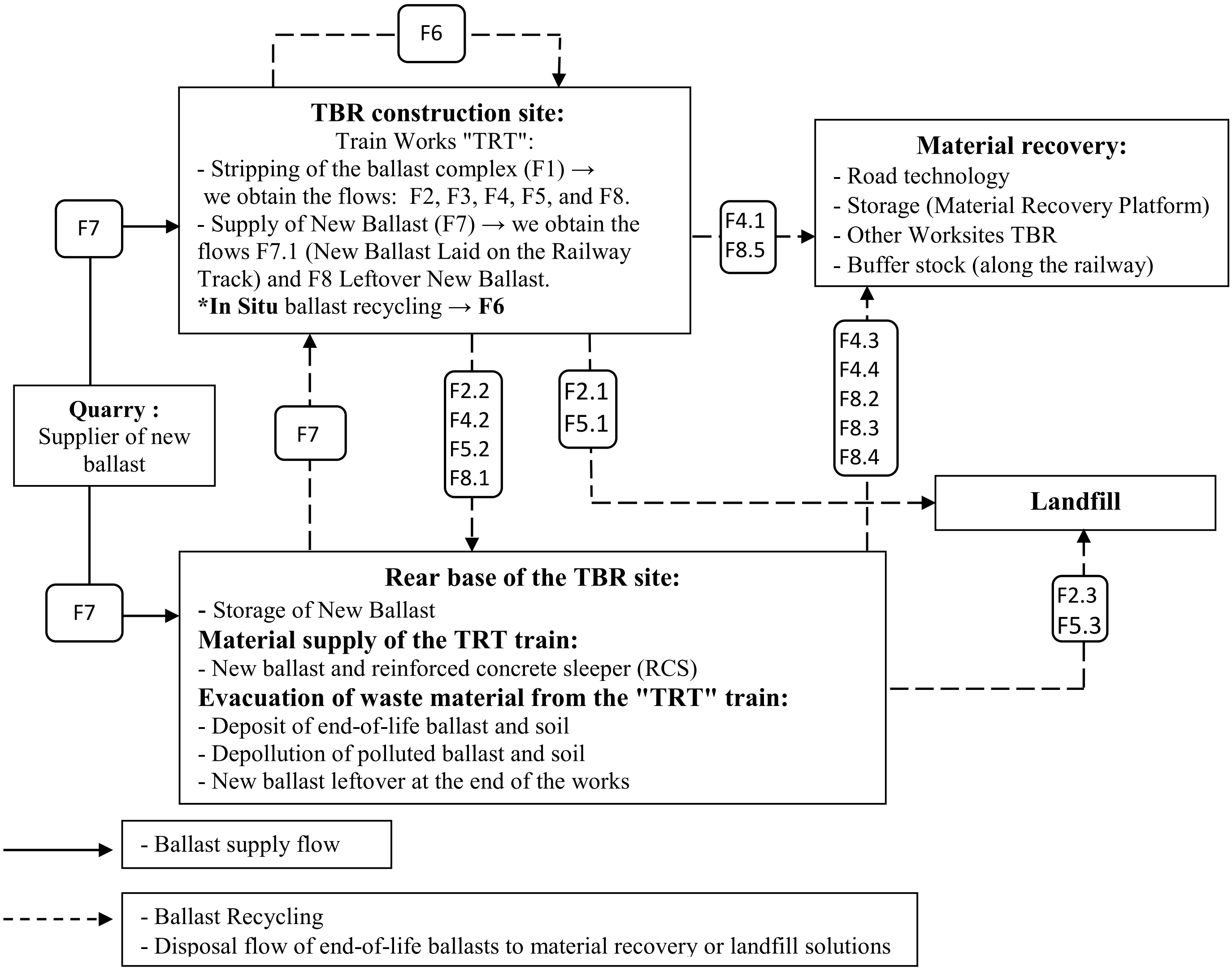

Figure 2. Diagram of the direct/reverse logistics chain of a TBR worksite.

Added to this is the F8 flow, the ballast residue resulting from the installation of new ballast, i.e., F7.1, the new ballast laid on the track. This is why the rear base enables end-of-life ballast F4 and new ballast residues F8 to be redistributed by road or rail towards material recovery solutions (flows: F4.3, F4.4, F8.2, F8.3, and F8.4), which represents the reverse open-loop logistics chain, since the materials do not return to the site's production cycle. Waste is directed to specific treatment units, for example. for flows F2.3 and F5.3. In addition, as far as possible, this end-of-life management of materials and waste, as well as ballast residues, can be carried out directly on the TBR site (F2.1, F4.1, F5.1, and F8.5). However, the most remarkable aspect of the TBR site organisation is the in situ recycling of ballast (see Figure 2, *F6, in the TBR site rectangle), which represents the inverted closed-loop supply chain [53,69], as the material is recycled and reused in the TBR production process and does not need to be transported. This is why a small star is placed above *F6 in the rectangle of the TBR site diagram (see Figure 2). The MFA presented in this document takes into account all these flows and their characteristics.

b. Material flows in processes (see Figure 3)—example of data from work site 1.

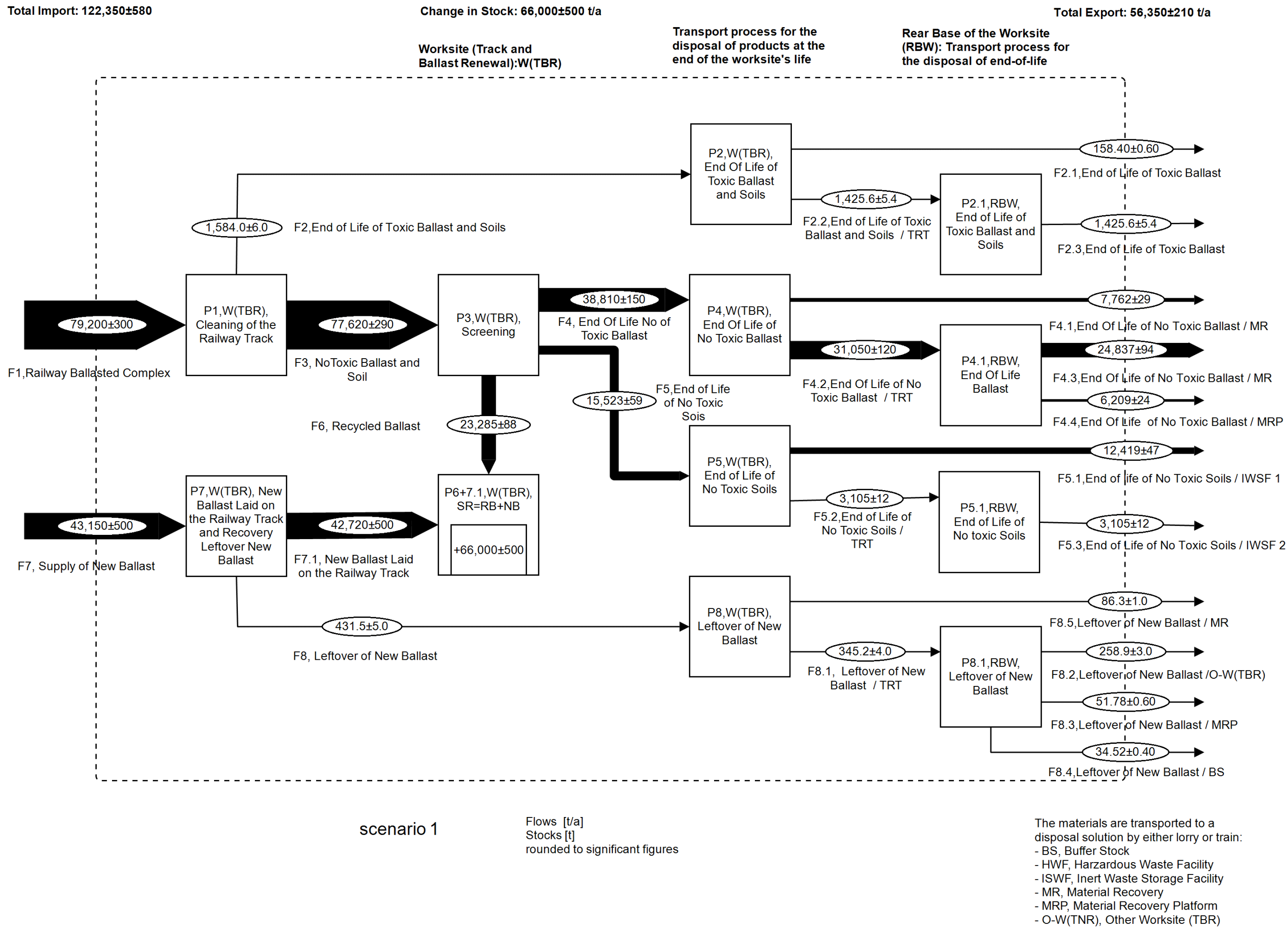

Figure 3. MFA of worksite 1, material flow diagram for TBR (see Tables 1 and 2)—scenario I "current situation".

The study was confined to the implementation of a static MFA [20,70] on the ballast flows of a TBR construction site, which serves as our reference site (designated as site 1). On this site, we established a transfer coefficient (TC) of 30% for F6 recycled ballast, as illustrated in Figure 3. The defined boundary shown in Figure 3 marks the limits of what is inside and outside the system. In our MFA model, we can see that there is no exchange of matter with the outside, so the system is closed. Site 1 was chosen because it had the most complete data of the eleven TBR sites supplied by Sncf Réseau, making it the most representative. This approach made it possible to develop the desired generic model, i.e., scenario 1 (see Figure 3) and scenario 2, which has a transfer coefficient (TC) of 70% for F6 recycled ballast (see Figure 4).

Worksite 1 consists mainly of 51 days of stripping (F1: ballasted complex) and track substitution operations over a total project duration of 74 days for 43,000 m of renewed track. This represents ~66,000 t of new ballast (F7), ~1.54 t/m, with an overall volume of 80 trains at a frequency of five trains/week with a format of 15 wagons loaded with 55 t (average), i.e., 825 t/train, (Sncf Réseau).

The ballasted complex (F1) is made up of approximately 66,000 tonnes of ballast, to which around 20% of earth (F5) is added, so F1 = 66,000 t × 0.2 + 66,000 t = 79,200 t, (see Figures 3 and 4). This ballasted complex (F1) of 79,200 t is extracted during the track stripping operation (i.e., ~1.84 t/m), with a "TRT" train advancing at a rate of 864 m per day, as planned by the works design organisation.

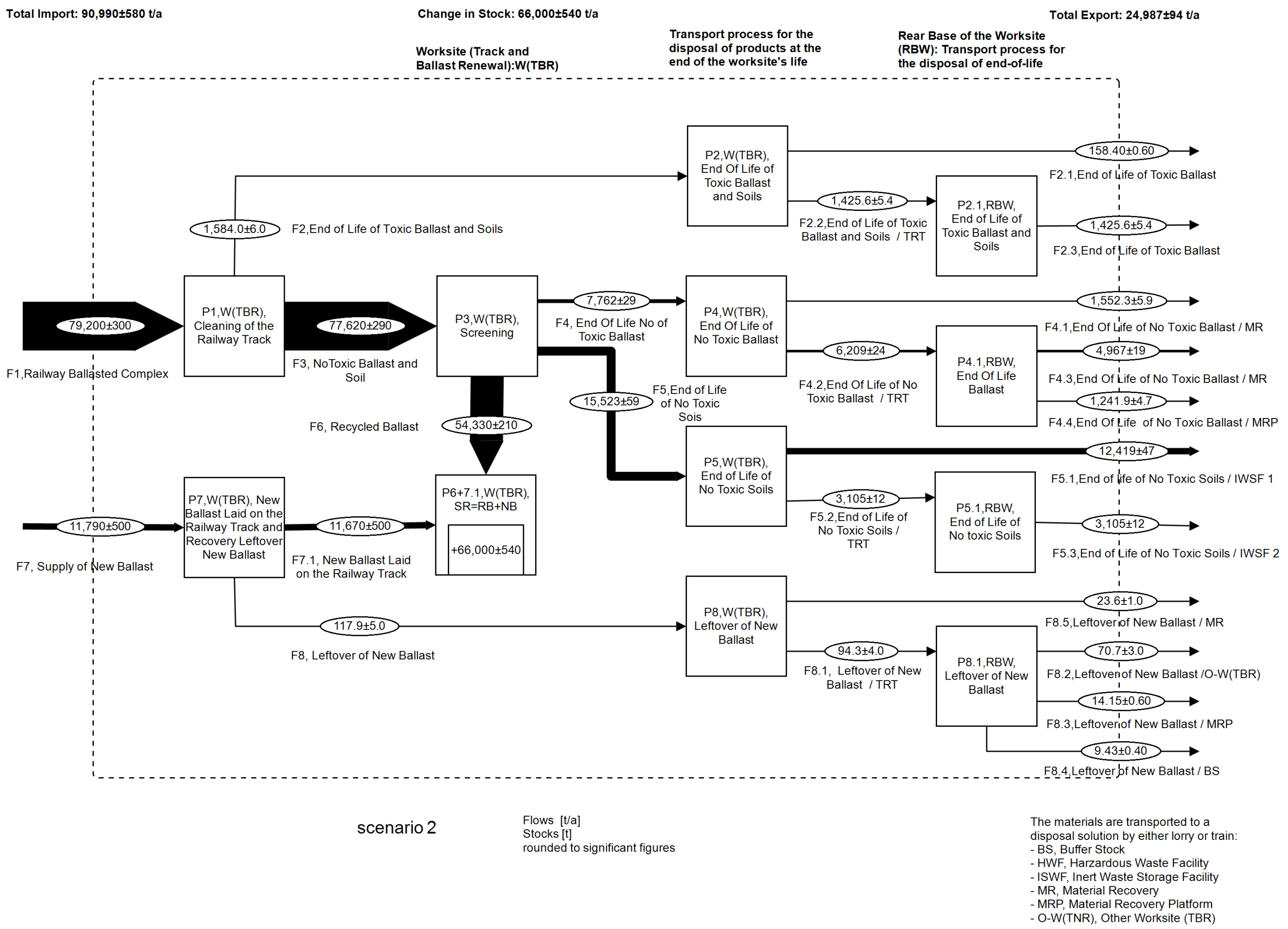

Figure 4. MFA of worksite 1, material flow diagram for TBR (see Tables 1 and 2)—scenario 2 "Future situation".

F1, the ballasted complex, is considered as an input in our MFA model, as it is the source of material for the worksite to produce F4 end-of-life ballast and F6 recycled ballast, whereas F7, the supply of new ballast, is a real input provided by Sncf Réseau. In addition, the transfer coefficients (TCs) used in the processes of our MFA model were obtained on the basis of information gathered from Sncf Réseau. This represents the basis for the construction of our MFA model presented in Figures 3 and 4.

c. Reliability of MFA data

Transfer coefficients (TCs), which are process parameters, are introduced with uncertainties. According to O. Cencic [26], a transfer coefficient indicates the proportion of a stream treated by a process that is transferred to an output stream (see Table 3a); this corresponds to a characteristic of the process. For example, process P3 (see Table 3a) represents the screening operation, which produces a recycling rate of 30% for ballast with a flux uncertainty of ±88 t (see Table 3a and Figure 3, flux F6), 20% for soil with an uncertainty of ±59 t (see Table 3a, flux F5), and 50% for end-of-life ballast with an uncertainty of ±150 t (see Table 3a, flux F4). These flow uncertainties are the result of the propagation of uncertainties due to the uncertainties in the input flows (F1 and F7, see Table 3a and Figure 3) and the uncertainties in the transfer coefficients.

Transfer coefficient values are accompanied by an uncertainty (±) due to the lack of accuracy of introduced values. According to O. Cencic, by using uncertainties in STAN (MFA software [24]), it is assumed that these uncertainties represent a random number and are normally distributed. The bell curve (Gauss curve) indicates how much the possible values could deviate from this mean value, where, in the middle, there is the mean value, which corresponds with the measurement. So, the bigger the uncertainty, the more the values can deviate from the mean value. This assumption must be considered when reconciling the data. In other words, the mean values remain the same and are affected by an uncertainty (±confidence interval): this means that a 10% uncertainty in a transfer coefficient results in a corresponding 10% uncertainty in the respective flow.

This information is essential for decision makers, because introducing an uncertainty on the mean value leads to having two times the standard error on the confidence interval. For example, with a transfer coefficient of 35% on an F3 flow of 77,620 t and an uncertainty of ±5%, we obtain an average value of 27,200 t on the F6 recycled ballast flow, with a low quantity of 19,556 t and a high quantity of 34,844 t (see Table 3b, process P3). This value is very significant, which underlines the importance of this information when building a plant or designing a supply chain. In addition, the MFA software (STAN [24]) is designed according to the logic of the law of conservation of mass in order to obtain a balanced system between input, stock, and output flows (sum of inputs = sum of outputs + change in stock). Consequently, when there is an error in the data, such as the quantities of matter, the transfer coefficients, or the uncertainties, the data reconciliation cannot be carried out during the matter balance calculation operation. STAN will then display a dialog box indicating the flows, transfer coefficients, or uncertainties that are in conflict.

Table 3. (**a**) of the transfer coefficients for the material flows in the TRB processes is constructed from the input data according to flow F1 and flow F7 (see Table 3a below). (**b**) of the transfer coefficients for the material flows in the TRB processes is constructed from uncertainty based on the information of ±1% on F2, ±1% on F3, ±5% on F6, and ±0.005% on F8 (see Table 3b below).

(**a**)

Input Flow In Process	Quantity Input (t)	Processus	Transfer Coefficient (%)	Output Flow of a Process	Analysis Chemical	Quantity Mean (t)	Standard Error		Confidence Interval		Error Margin %
							(t)	%	Low (t)	High (t)	
F1	**79,200**	**P1**			**X**	**79,200**	300	0.38	78,612	79,788	1.47
			0.02	F2	X	1584	6	0.38	1572	1596	1.47
			0.98	F3	X	77,620	290	0.37	77,052	78,188	1.45
F2	1584	P2	0.10	F2.1	X	158	0.6	0.38	157	159	1.48
			0.90	F2.2	X	1425	5.4	0.38	1414	1436	1.47
F2.2	1425	P 2.1	1	F2.3	X	1425	5.4	0.38	1414	1436	1.47
F3	77,620	P3	0.50	F4		38,810	150	0.39	38,516	39,104	1.50
			0.20	F5		15,523	59	0.38	15,407	15,639	1.48
			0.30	F6		23,285	88	0.38	23,113	23,457	1.47
F4	38,810	P4	0.20	F4.1		7762	29	0.37	7705	7819	1.45
			0.80	F4.2		31,050	120	0.39	30,815	31,285	1.50
F4.2	31,050	P4.1	0.80	F4.3		24,837	94	0.38	24,653	25,021	1.47
			0.20	F4.4		6209	24	0.39	6162	6256	1.50
F5	15,523	P5	0.20	F5.1		12,419	47	0.38	12,327	12,511	1.47
			0.80	F5.2		3105	12	0.39	3081	3129	1.50
F5.2	3105	P5.1	1	F5.3		3105	12	0.39	3081	3129	1.50
F6 + F7.1		P6				66,000	500	0.76	65	66,980	2.93
F7	**43,150**	P7				43,150	500	1.16	42	44,130	4.44
			0.99	F7.1		42,720	500	1.17	42	43,700	4.49
			0.01	F8		431	5	1.16	421	441	4.45
F8	431	P8	0.80	F8.1		345	4	1.16	337	353	4.44
			0.20	F8.5		86	1	1.16	84	88	4.44
F8.1	345	P8.1	0.75	F8.2		258	3	1.16	252	264	4.46
			0.15	F8.3		52	0.6	1.15	51	53	4.42
			0.10	F8.4		34	0.4	1.17	33	35	4.51

Table 3. *Cont.*

(**b**)

Input Flow in a Process	Quantity Input (t)	Processus	Transfer Coefficient (%)	Output Flow of a process	Analysis Chemical	Quantity Mean (t)	Standard Error		Confidence Interval		Error Margin %
							(t)	%	Low (t)	High (t)	
F1	**79,200**	P1				79,200	300	0.38	78,612	79,788	1.47
			0.02 ± 0.01	F2	X	1580	790	50	32	3128	98.98
			0.98 ± 0.01	F3	X	77,620	840	1.08	75,974	79,266	4.15
F2	1580	P2	0.10	F2.1	X	158	79	50	3	313	98.99
			0.90	F2.2	X	1420	710	50	28	2812	98.99
F2.2	1420	P 2.1	1	F2.3	X	1420	710	50	28	2812	98.99
F3	77,620	P3	0.45	F4		34,900	3900	11.17	27,256	42,544	35.93
			0.20	F5		15,520	170	1.10	15,187	15,853	4.20
			0.35 ± 0.05	F6		27,200	3900	14.34	19,556	34,844	43.87
F4	38,800	P4	0.20	F4.1		6990	780	11.16	5461	8519	35.89
			0.80	F4.2		27,900	3100	11.11	21,824	33,976	35.77
F4.2	31,000	P4.1	0.80	F4.3		22,400	2500	11.16	17,500	27,300	35.90
			0.20	F4.4		5990	620	10.35	4775	7205	33.73
F5	15,520	P5	0.20	F5.1		12,420	130	1.05	12,165	12,675	4.02
			0.80	F5.2		3105	34	1.10	30,380	3172	4.20
F5.2	3105	P5.1	1	F5.3		3105	34	1.10	30,380	3172	4.20
F6 + F7.1		P 6				66,000	3900	5.90	58,356	73,644	20.76
F7	**39,190**	P7				39,190	500	1.28	38,210	4017	4.88
			0.99	F7.1		38,800	530	1.36	37,761	39,838	5.22
			0.01 ± 0.005	F8		390	200	51.28	2	782	100.26
F8	430	P8	0.80	F8.1		310	160	51.61	4	624	100.58
			0.20	F8.5		78	39	50	2	154	98.99
F8.1	350	P8.1	0.75	F8.2		240	120	50	5	475	98.99
			0.15	F8.3		47	24	51.06	0	94	100.04
			0.10	F8.4		31	16	51.61	0	62	100.58

This table also shows the coefficient transfers, the standard error, and the margin of error for the material flows in the processes of scenario 1.

We present two tables of transfer coefficients in worksite processes (TBR). Table 3a represents a model where the standard error on quantities is low, varying from 0.38 to 1.18%, depending on the flows (see Table 3a). To achieve this, firstly, we introduced a standard error only on the F1 and F7 input streams (see Table 3a and Figure 3). Secondly, in the processes of our MFA model, we established only constant transfer coefficients. Thirdly, in order to detect erratic values, we used a 95% confidence interval. The result showed that all flux values were contained within the confidence interval, as presented in Table 3a and Figure 5a. It can, therefore, be concluded that the data set does not exhibit any significant discrepancies that would result in the calculated flux values falling outside the established confidence interval.

This confidence interval method assumes a normality of observations, based on the hypothesis that these observations follow a normal distribution [71]. In other words, the observations introduced into our MFA model follow a symmetrical distribution with respect to the mean (Gaussian curve).

However, according to information provided by Sncf Réseau [40], 35% of the ballasted complex removed from the track during renewal can be recycled, with an uncertainty of ±0.05 (see Table 3b, process P3, flow F6). Similarly, it is possible that from 1 to 2% (±0.01) of the ballast removed from the track is toxic (see Table 3b, process P1, flow F2) and generally, at the end of the worksite, there is a residue of new ballast of 1% (±0.005), (see Table 3b, process 7, flow F8). In this case, we introduced these information-based uncertainties into the transfer coefficients (see Table 3b), i.e., into the TC(s) of the site flow transfer processes. This is shown in our second Table 3b, where the uncertainties applied to the transfer coefficients gave rise to a very large standard error of 0.38 to 51.61% and a margin of error of the confidence intervals of 1.47 to 100.58%, depending on the TBR site flows. Under these conditions, the model is, therefore, highly uncertain, as shown by the disparity of the curve in Figure 5b, since 68% of the observations lie outside their confidence intervals and, therefore, do not follow a normal distribution. The ability to propagate uncertainties is one of the strengths of the STAN software, which provides the uncertainties of the quantities to be calculated. This also highlights the stochastic nature of the quantities of ballast recycled on TBR sites, since the quantity of ballast recycled depends on the segment of track being renovated, which can represent a difficulty in managing flows.

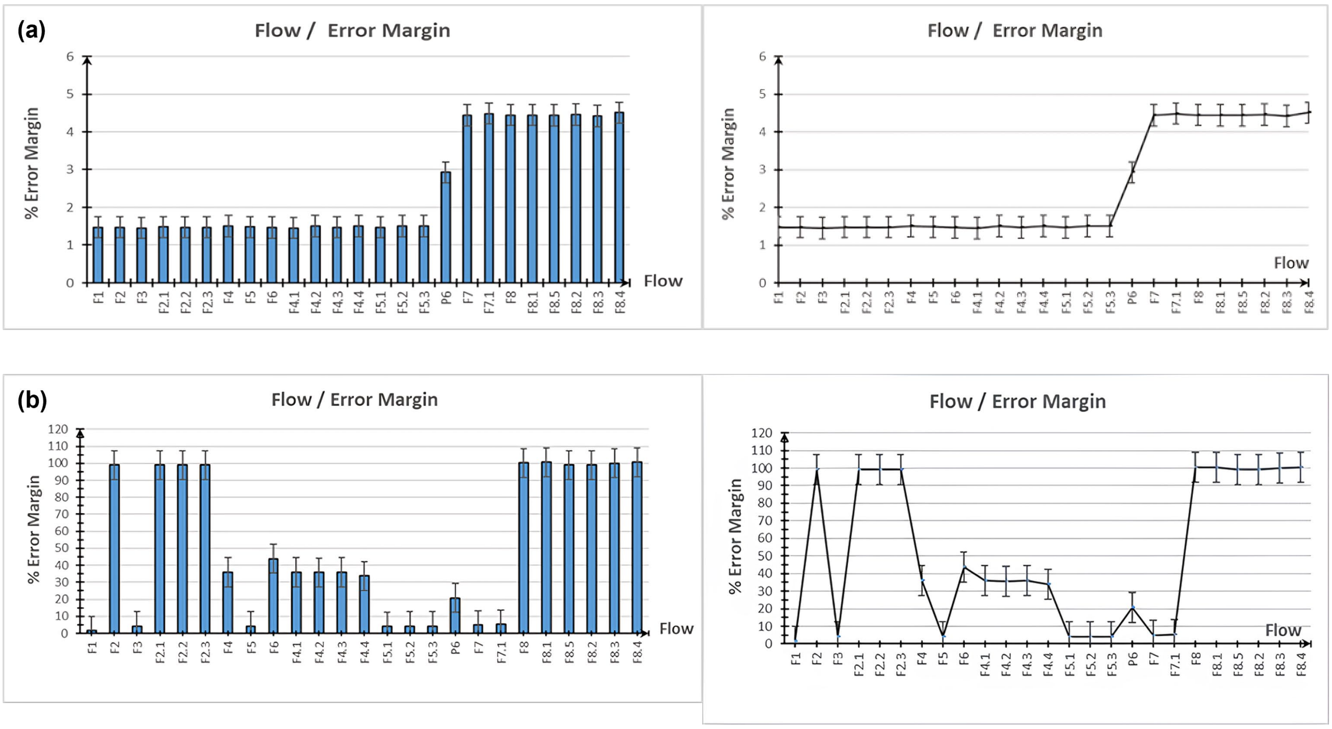

Figure 5. (**a**) Show the margin of error for each material flow from the construction site (TBR) in the scenario 1 processes; (**b**) Shows the margin of error for each material flow from the construction site (TBR) in the scenario 1 processes as a function of uncertainties based on information of ±1% on F2, ±1% on F3, ±5% on F6, and ± 0.005% on F8.

d. Flows and indicators

The results of our strategic plan are presented and discussed to highlight the characteristics of the ballasted complex (F1), such as the quantities recovered and recycled in situ from this complex. In the plan, key performance indicators are determined, which, on a large scale, make it possible to monitor the company's objectives of moving towards a zero-waste strategy. These indicators, derived from the main flows, are the quantities of toxic ballast (F2), old ballast (F4), and earth (F5) for the recovery of materials, recycled ballast (F6), the supply of new ballast (F7), the quantity of new ballast laid on the track (F7. 1), knowledge of the proportions of ballast in stock on the track established by the process P6 = F6 + F7.1 for forecasting future work, and, finally, the indicator of the amount of wastage of new ballast (F8).

Thus, Figures 6a and 7a, for scenarios 1 and 2, respectively, present a diagnosis of the input/output flows (F) and processes (P) in terms of the quantities of materials circulating in the system studied. Figures 6b and 7b provide the relative changes in the end-of-life ballast F4, soil F5, and recycled ballast F6 calculated in relation to the ballasted complex

F3. Table 4 presents a comparison between scenarios 1 and 2 of the proportions of and relative changes in new ballast (F7.1) and recycled ballast (F6) calculated in relation to the P6 processes, which represent the ballast stock present on the track of 66,000 t. It can be observed that, scenario 2, which represents 70% recycled ballast, results in the saving of 31,050 t of new ballast (F7.1), given that 31,045 t more recycled ballast (F6) is reused on the track than that in scenario 1.

Figure 6. (**a**) Shows the main flows from the TBR site in scenario 1 of our MFA with standard error (see Figure 3). (**b**) Composition of the F3 flow scenario 1. (**c**) The quantities are presented with a 95% confidence interval (CI).

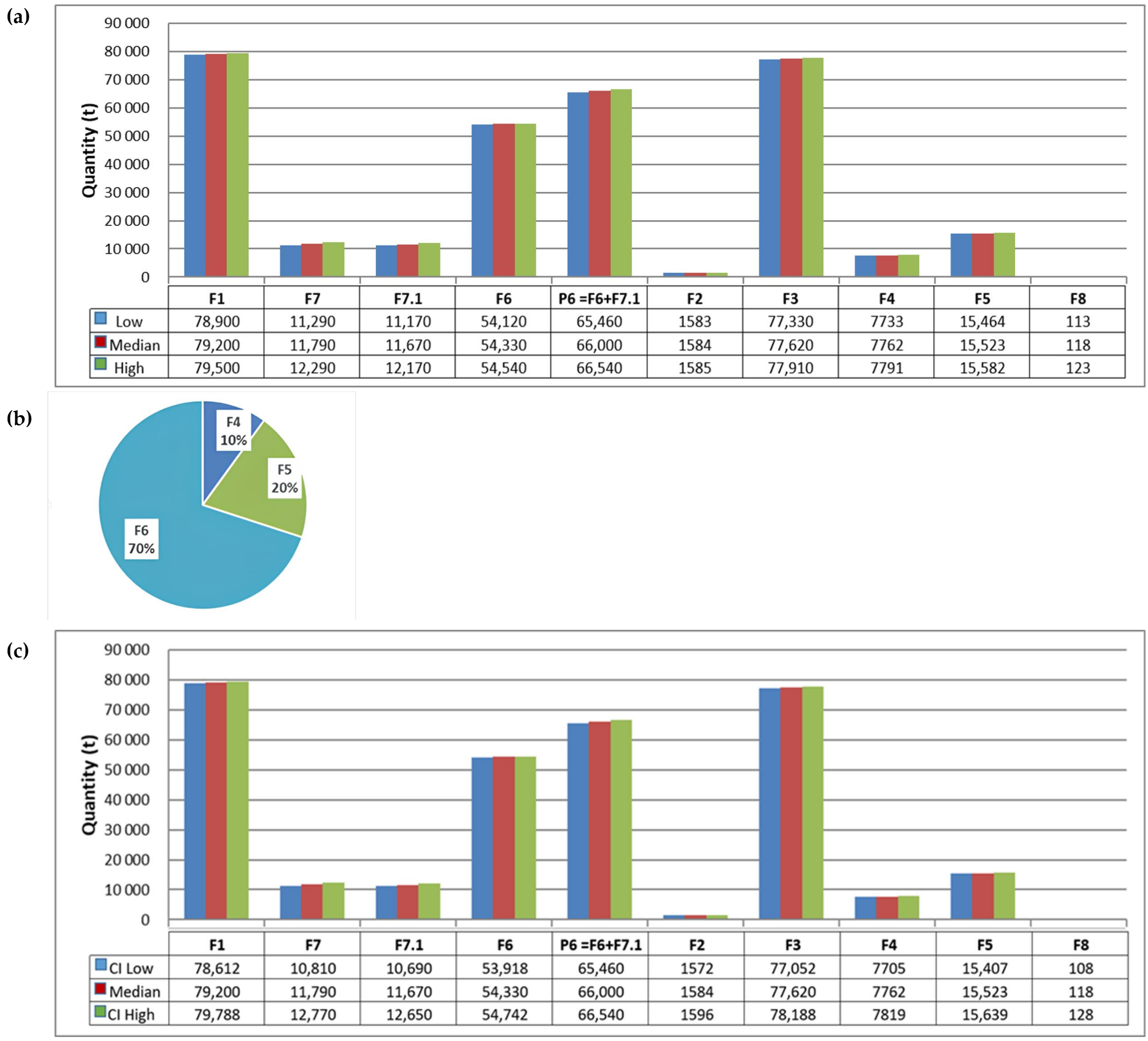

Figure 7. (**a**) Shows the main flows at the TBR site in scenario 2 with standard error (see Figure 4). (**b**) Composition of the F3 flow scenario 2. In this scenario, we have increased the quantity of recycled ballast (TC F6: 70%). (**c**) The quantities are presented with a 95% confidence interval (CI).

Table 4. Proportions of new ballast (F7.1) and recycled ballast (F6).

Scenario	Stock: P6 = F7.1 + F6 (t)	F7.1 (t)	F6 (t)	% F7.1	% F6
1	66,000	42,720	23,285	64	36
2	66,000	11,670	54,330	18	82
Difference		31,050	31,045	46	46

In addition, the overall results make it possible to compare and establish the differences in uses that exist in terms of the modes of transport (see Table 5a–c) and means of production used (see Table 6) during track regeneration between scenario 1, which represents 30% recycled ballast, and scenario 2, which represents 70% recycled ballast.

Table 5. (**a**) Diagnostic table of transport processes for input and output flows in scenarios 1 and 2. (**b**) Relative change and difference by mode of transport between scenarios 1 and 2. (**c**) Relative change and difference in total transportation by mode between scenarios 1 and 2.

(**a**)

		Scenario 1						**Scenario 2**					
Processus Worksite	**Flows**	**Input by Train (t)**	**Output by TRT Worksite (t)**	**Ouput by Train Worksite (t)**	**Ouput by Train Rear Base Worksite (t)**	**Ouput by Truck Worksite (t)**	**Ouput by Truck Rear Base Worksite (t)**	**Input by Train (t)**	**Output by TRT Worksite (t)**	**Ouput by Train Worksite (t)**	**Ouput by Train Rear Base Worksite (t)**	**Ouput by Truck Worksite (t)**	**Ouput by Truck Rear Base Worksite (t)**
P2	F2.1					158						158	
P2.1	F2.2		1426						1426				
	F2.3						1426						1426
P4	F4.1				7762						1552		
P4.1	F4.2		31,050						6209				
	F4.3				24,837						4967		
	F4.4					6209						1241	
P5	F5.1			12,419						12,419			
P5.1	F5.2		3105						3105				
	F5.3						3105						3105
P7	F7	43,150						11,790					
P8	F8.5					86						24	
P8.1	F8.1		345						94				
	F8.2						258						71
	F8.3						52						14
	F8.4						34						10
Total in (t)		**43,150**	**35,926**	**12,419**	**32,599**	**6453**	**4875**	**11,790**	**10,834**	**12,419**	**6519**	**1423**	**4626**

(**b**)

	Input by Train (t)	**Ouput by TRT Worksite (t)**	**Ouput by Train Worksite (t)**	**Ouput by Train Rear Base Worksite (t)**	**Ouput by Truck Worksite (t)**	**Ouput by Truck Rear Base Worksite (t)**
SCN 1	43,150	35,926	12,419	32,599	6453	4875
SCN 2	11,790	10,834	12,419	6519	1423	4626
Relative Change (%)	**27**	**30**	**0**	**20**	**22**	**95**
Difference (%)	**73**	**70**	**0**	**80**	**78**	**5**

(**c**)

Total Transport Rate by Mode	**SCN 1 (t)**	**SCN 2 (t)**	**Relative Change %**	**Difference %**
Train	**76,998**	**30,728**	**40**	**60**
TRT	**35,926**	**10,834**	**30**	**70**
Truck	**11,328**	**6049**	**53**	**47**

Examples include the use of rail transport to supply the site with new ballast (F7) and TRT to remove materials at the end of their lives from the site (flow: F2.2, F4.2, F5.2, and F8.1). Examples also include the use of transport by truck (flow: F2.1, F2.3, F4.1, F4.4, F5.1, F5.3, F8.2, F8.3, F8.4, and F8.5) or by train to transport end-of-life materials (F4.3) to treatment or recovery facilities (see Table 5a,b and Figures 3 and 4). Table 5c shows an overall representation of transport use. Similarly, Table 6 shows the utilisation rate of the work train (TRT), e.g., for the removal of the ballasted track complex (flow F1 and process P1) and its screening (flow F3 and process P3).

Table 6. Rates and differences in the use of TRT between scenarios 1 and 2.

Process Worksite	Flows	TRT Work SCN 1 Quantity (t)	TRT Work SCN 1 in %	TRT Work SCN 1 Quantity (t)	TRT Work SCN 2 in %	Difference in t SCN1/SCN2	Difference in % SCN1/SCN2
P1	F1	79,200	100	79,200	100	0	0
	F2	1584	2	1584	2	0	0
P3	F3	77,620	98	77,620	98	0	0
	F4	38,810	50	77,620	10	31,048	40
	F5	15,523	20	15,523	20	0	0
	F6	23,285	30	54,330	70	31,045	40
P6	F6 + F7.1	66,000	100	66,000	100	0	0
P7	F7.1	42,720	65	11,670	18	31,050	47
P8	F8	431	1	118	1	313	0

Thus, Tables 5a–c and 6 allow us to visualise the impacts of recycled ballast between scenarios 1 and 2 on the use of transport, means of production, and ultimately on the prospect of reducing transport costs, means of production, and toxic emissions into the environment.

In addition, the key indicators derived from the main flows enable us to develop Table 7, the aim of which is to provide us with information on the proportions of the site flows studied in relation to an allocated percentage (TC) of recycled ballast (F6), e.g., on the composition of the stock P6 = F7.1+ F6 (see Figures 3 and 4). Similarly, on the basis of the key indicators derived from the main flows, we present eleven TBR sites treated according to scenario 1 (see Table 8a) and scenario 2 (see Table 8b), together with a comparison of the P6 stock (see Table 8c). This initiative enabled us to compare the quantities of materials in each stream over a year of rail track renovation on a national scale between scenarios 1 and 2. From this, it would appear that our scenario 2, which represents 70% recycled ballast, is more in line with a strategy of significantly reducing waste.

Table 7. Impact of the recycled ballast rate (F6) on the main flows.

F7 Supply of New Ballast/F6 Recycled Ballast Supply Table										
F7 (t)	**F3 (t)**	**% F4**	**F4 (t)**	**F5 (t)**	**% F6**	**F6 (t)**	**F7.1 (t)**	**F8 (t)**	**P6 = F7.1 + F6 (t)**	
58,831	77,620	0.70	54,334	15,523	0.10	7762	58,243	588	66,005	
50,990	77,620	0.60	46,572	15,523	0.20	15,524	50,480	510	66,004	
43,150	77,620	0.50	38,810	15,523	0.30	23,285	42,719	432	66,004	**Scenario 1**
35,308	77,620	0.40	31,048	15,523	0.40	31,048	34,955	353	66,003	
27,467	77,620	0.30	23,286	15,523	0.50	38,810	27,192	275	66,002	
19,626	77,620	0.20	15,524	15,523	0.60	46,572	19,430	196	66,002	
11,789	77,620	0.10	7,762	15,523	0.70	11,671	11,671	118	66,001	**Scenario 2**

Table 8. (**a**) (scn 1): Values of the main flows from a mass balance drawn up for each site TBR. (**b**) (scn2): Values of the main flows from a mass balance drawn up for each site TBR. (**c**) Values of the proportions of new ballast (F7.1) and recycled ballast (F6) stored on railway lines representing 11 TBR sites (group 7 to 9 IUR) over one year on a national scale.

(**a**)

Worksite	Lenght (m)	F1 (t)	F2 (t)	F3 (t)	F4 (t)	F5 (t)	F6 (t)	SNB Planned (t)	F7 (t)	F7.1 (t)	P6 = F7.1 + F6 (t)	F8 (t)
1	42,926	79,200	1584	77,620	38,810	15,523	23,285	66,000	43,150	42,720	66,005	431
2	44,746	82,558	1681	80,911	40,455	16,181	24,272	68,798	44,979	44,531	68,803	449
3	80,070	147,732	2,955	144,785	73,392	28,955	43,434	123,110	80,488	79,685	123,118	804
4	33,290	61,421	1228	60,196	30,098	12,038	18,058	51,184	33,464	33,310	51,188	334
5	70,327	129,756	2595	127,167	63,584	25,432	38,149	108,130	70,694	69,989	108,137	706
6	39,504	72,886	1458	71,432	35,716	14,286	21,429	60,739	39,710	39,314	60,743	397
7	35,368	62,255	1305	63,953	31,977	12,790	19,185	54,379	35,553	35,198	54,383	355
8	19,785	36,504	730	35,776	17,888	7155	10,732	30,420	19,888	19,690	30,422	199
9	67,094	123,791	2476	121,321	60,661	24,263	36,395	103,159	67,444	66,771	103,166	674
10	49,016	90,436	1806	88,632	44,316	17,725	26,588	75,364	49,272	48,780	75,369	492
11	58,382	107,717	2154	105,568	52,784	21,112	31,662	89,764	58,687	58,101	89,763	586
Total	**540,508**	**997,257**	**19,945**	**977,362**	**488,681**	**195,460**	**293,189**	**831,047**	**543,329**	**537,908**	**831,097**	**5433**

(**b**)

Worksite	Lenght (m)	F1 (t)	F2 (t)	F3 (t)	F4 (t)	F5 (t)	F6 (t)	SNB Planned (t)	F7 (t)	F7.1 (t)	P6 = F7.1 + F6 (t)	F8 (t)
1	42,926	79,200	1584	77,620	7762	15,523	54,330	66,000	11,790	11,670	66,000	118
2	44,746	82,558	1651	80,911	8091	16,181	56,634	68,798	12,290	12,165	68,798	123
3	80,070	147,732	2955	144,785	14,478	28,955	101,342	123,110	21,992	21,768	123,110	22
4	33,290	61,421	1228	60,196	6020	12,038	42,134	51,184	9143	9050	51,184	92
5	70,327	129,756	2595	127,167	12,717	25,432	89,011	108,130	19,316	19,119	108,129	193
6	39,504	72,886	1458	71,432	7143	14,286	49,999	60,739	10,850	10,739	60,738	109
7	35,368	65,255	1305	63,953	6395	12,790	44,764	54,379	9174	9615	54,379	97
8	19,785	36,504	730	35,776	3578	7155	25,041	30,420	5434	5379	30,420	54
9	67,094	123,791	2476	121,321	12,132	24,263	84,919	103,159	18,428	18,240	103,159	184
10	49,016	90,436	1809	88,632	8863	17,725	62,038	75,364	13,463	13,325	75,363	135
11	58,382	107,717	2154	10,568	10,557	21,112	73,892	89,764	16,035	15,872	89,764	160
Total	**540,508**	**997,257**	**19,945**	**977,362**	**97,736**	**195,460**	**684,103**	**831,047**	**148,455**	**146,941**	**831,044**	**1486**

(**c**)

Total Worksite	Lenght (m)	F1 (t)	F2 (t)	F3 (t)	F4 (t)	F5 (t)	F6 (t)	SNB Planned (t)	F7 (t)	F7.1 (t)	P6 = F7.1 + F6 (t)	F8 (t)
SCN 1	540,508	997,257	19,945	977,362	488,681	195,460	293,189	831,037	543,329	537,908	831,097	5433
SCN 2	540,508	997,257	19,945	977,362	97,736	195,460	684,103	831,037	148,455	146,941	831,044	1486
Relative change SCN 1 and SCN 2 (%)					**20**		**43**		**27**	**27**		**27**
Difference					**390,945**		**390,914**		**394,873**	**390,967**		**3948**

3. Results and Discussion

3.1. From the Supply Chain to the Material Flow Diagram Using Software (STAN) to Generate Scenarios

a. Generic MFA diagram for TBR worksites

The material flow diagram presented in this article is a major innovative contribution to the state of the art of MFAs of railway track and ballast renewal site. The flows, process structures, and links are generic. The values of the flows may vary depending on the data available and the TBR site studied. On this basis, the following two scenarios were analysed: a "current situation" (Figure 3) corresponding to the real use case described above and a "future situation" (Figure 4). Comparing the results of the two scenarios will allow decision makers (site managers) to make decisions based on circular economy objectives.

The first scenario represents a recycling rate of 30% (see Figure 3, process P3, flow F6) of the non-toxic ballasted complex (flow F3) with a distribution of end-of-life material flows towards a material recovery solution or directly to a landfill. This distribution is carried out from the site (see Figure 3, flows: F2.1, F4.1, F5.1, and F8.5) or via the rear base (see Figure 3, flows: F2.2, F4.2, F5.2, F8.1). The latter represents the transport needed to move these flows to the rear base, which is used as a temporary storage base for the redistribution of materials to suitable material recovery or landfill solutions, as shown in Figure 4 for the flows (F2.3, F4.3, F4.4, F5.3, F8.2, F8.3, and F8.4).

Thus, the MFA model established according to scenarios 1 and 2 provides a representation of the flows and stock of materials in the logistics organisation of a TBR site. The distribution of flows in the system is based on transfer coefficients, which are process parameters. The flows represent the mean with their standard deviation, for which the confidence interval (95%) for scenario 1 (Figure 3) is calculated in Table 3a. In our model, the F1 flow, which represents the ballasted complex, is made up of used ballast (F4) and earth (F5) consisting of small stones, sand, and earth. This F1 flow is considered as an input flow to the worksite and not as an import flow, because this F1 flow extracted from the railway track is the source of material for the worksite study. The F2 flow, which represents toxic ballast (station platform and track switchgear, etc.), is notified by specific analyses before the start of the worksite. F2 is specifically extracted from the track by train (TRT) if possible or by other lighter means. F7 is an import flow, since it brings new ballast into the system, from which the 0.01% residual F8 must be removed. This is why the flow of new ballast put on the track is called F7.1. Therefore, the small rectangle that appears in process P6 (see Figures 3 and 4) represents the net accumulation of materials, i.e., the "stock" on the track. This stock consists of the ballast recycled in situ (F6) and the addition of new ballast laid on the track (F7.1).

b. Scenario comparisons of the main MFA ballast flows

The results (main flows) of scenarios 1 "current situation" and 2 "future situation" are presented in Figure 6a,b and Figure 7a,b. The main difference between scenarios 1 (Figure 3) and 2 (Figure 4) is the recycling rate, which is 30% for the former and 70% for the latter.

c. Analysis of the main MFA ballast flows in scenarios 1 and 2

For scenario 1, the main results of the MFA (Figure 6a) show that, for the quantities, the ballasted complex (F1) of 79,200 t is made up of 1584 t of ballast and toxic soil (F2), i.e., 2%, and 77,620 t of ballast and non-toxic soil (F3), i.e., 98%.

3.2. Scenario I

The flow F3 breaks down into 38,810 t of end-of-life ballast (F4), i.e., 50% (indicator of the rate of end-of-life ballast to be recovered), 15,523 t of soil (F5), i.e., 20%, and 23,285 t of recycled ballast (F6), i.e., 30% (performance indicator of the rate of recycled ballast), (see Figure 6b). In addition, there is 431 t of new ballast remaining (F8), i.e., 1% of the 43,150 t of new ballast (F7).

3.3. Scenario 2

Compared to scenario 1 (see Figure 6a,b), the main changes in the breakdown of the F1 flow in scenario 2 are as follows: the flow (F3), which breaks down into 7762 t of end-of-life ballast (F4), i.e., 10% (material recovery indicator), 15,523 t of earth (F5), i.e., 20%, and 54,330 t of recycled ballast (F6), i.e., 70% (recycled ballast rate performance indicator) (see Figure 7a,b). In addition, there is 118 t of residual new ballast (F8), i.e., 1% of the 11,790 t of new ballast (F7).

Table 4 shows the composition of the ballast stock (P6 = F7.1 + F6) between scenarios 1 and 2, so that the proportions of the stock, i.e., the quantities of new ballast (F7.1) and recycled ballast (F6), respectively, are as follows:

d. Diagnostic Table of Transport Processes and TRT Utilisation Rate for Input and Output Flows for Scenarios 1 and 2

Table 5a presents the diagnosis of the transport flow processes (input/output) for scenarios 1 and 2 (see Figures 3 and 4), indicating the quantity of materials transported to supply the site with ballast or to remove end-of-life products. From this, Table 5b shows the relative changes and differences by mode of transport between scenarios 1 and 2. Similarly, Table 5c shows the relative changes and differences in total transport by mode between scenarios 1 and 2. Table 6 provides a comparison between scenarios 1 and 2 of the amount the track renewal train is used to carry out work, recycle ballast, and process end-of-life products.

The choice of a mode of transport depends on a number of factors, in particular, its feasibility and the economic conditions for providing the transport operation, such as accessibility to infrastructure, the quantity transported, and the journey distance and frequency.

Nevertheless, in order to preserve the environment in the face of transport constraints, it is first necessary to limit the release of noxious substances (carbon dioxide, CO_2). The most effective strategy is linked to the use of less polluting vehicles (electric, hydrogen, etc.). Secondly, another approach would be to reduce the deterioration of road and rail infrastructure and the consumption of operating equipment due to the heavy use of transport. To achieve this, recycling materials in situ is an interesting lever, since it reduces the use of transport. The results in Table 5b show a difference in the use of transport between scenarios 1 and 2, based on the rate of recycled ballast (TC_F6). For example, for flow F7, supplies of new ballast, there is a 73% reduction in the use of trains and a 70% reduction in the use of TRT for the evacuation of end-of-life materials from the worksite to its rear base (F2.2, F4.2, F5.2, and F8.1). Furthermore, for the transport of end-of-life materials to recovery or industrial treatment solutions from the rear base, there is an 80% reduction in the use of trains (F4.1 and F4.3), a 5% reduction in the use of lorries (F2.1, F4.4, and F8.5), and a 78% reduction in the use of lorries from the site (F2.3, F5.3, F8.2, F8.3, and F8.4).

In Table 6, the most significant results concerning the use of the TRT train for on-site production are the flows F1 and F3 (scn 1 and 2), F6 (scn 2), and F7.1 (scn1). However, the F7 flow is not included, because the train delivers the new ballast.

The F1 flow is a feature common to both scenarios and represents the stripping of the track (P1 process, see Figures 3 and 4) with a TRT utilisation of 100%, of which approximately 2% of the toxic ballast (F2) is eliminated by the P2 process. The flow of clean ballast (F3), which represents a TRT utilisation rate of 98% for the scenarios 1 and 2, is directed to the screening/cleaning operation (process P3), which produces end-of-life ballast (F4), earth (F5), and recycled ballast (F6). This operation has a major impact on the utilisation rate of the TRT train. It can be observed that, for the end-of-life ballast flow (F4), the TRT utilisation rate calculated in relation to the F3 flow is 50% for scenario 1 and 10% for scenario 2, which means a difference of 40%. Similarly, for the F5 flow, the rate is 20% for both scenarios. Finally, for the recycled ballast (F6), the rate is 30% for scenario 1 and 70% for scenario 2, which means a difference of 40% (see Table 6). Thus, the higher the rate of recycled ballast, the more work the TRT has to perform, since it is responsible for returning the recycled ballast (F6) to the track following the flow screening operation (F3). Conversely, the TRT necessitates less work for surfacing the track with new ballast (F7.1) due to its utilisation rate of 18% for scenario 2, which recycles 70% of the ballast. These aspects of the machine utilisation rate are not to be neglected, because they have an impact on maintenance such as the consumption of cleaning and operating products (oils) and the consumption of energy of petroleum origin and electricity, which represents the discharge of toxic substances.

e. Impact of the recycled ballast rate (F6) on the main flows

Table 7 shows the impact of the recycled ballast rate (F6) on main flows such as the new ballast supply flow (F7) and the end-of-life ballast flow (F4) as a function of the recycled ballast rate (F6). The soil flow (F5) is weighted by a constant of 20% of the non-toxic ballast flow (F3) from track stripping and the residual new ballast flow (F8) at 1% of the F7 flow. Table 7 also shows the quantity of new ballast (F7.1) and recycled ballast (F6) contained in the stock P6 = F7.1 + F6.

However, we note that, in Table 7, the flow of recycled ballast (F6) stops at 70% because, beyond this limit, we have to take into account the 10% of end-of-life ballast (F4) and the 20% of earth (F5) extracted from the ballasted complex (F3), as presented in scenario 2 (see Figure 4). We reach the maximum limit of recycled ballast because the P6 stockpile = 66,001 t, which corresponds approximately to the 66,000 t of ballast planned for the track. However, it would be possible to recycle 80% of the ballasted complex, provided that the 10% F4 end-of-life ballast from scenario 2 (see Table 7) can be incorporated into ballasted railway track construction standards for reuse, e.g., as a track sub-ballast layer [39]. Finally, it can be seen that the values increase linearly with the weighting applied to the recycled ballast flow F6 and decrease linearly for the flows of (F4) end-of-life ballast and (F7.1) supply of new ballast. This flow (F7.1) is obtained by the following calculation: (F7) supply of new ballast ~(66,000 t − F6) * 0.01 + (66,000 t − F6), or more directly, F7.1 = P6 − F6, from which we can obtain F7 = F7.1/(1 − 0.01). Note that 0.01 corresponds to 1% residual ballast F8.

f. Eleven TBR sites treated according to scenario 1 (Table 8a) and scenario 2 (Table 8b)

The study of each site was based exactly on the MFA model, as presented in Figure 3 for scenario 1 with 30% F6 recycled ballast (see Table 8a scn 1) and in Figure 4 for scenario 2 with 70% recycled ballast (see Table 8b scn 2). Similarly, this study of the main flows during a year of track renovation was carried out with the transfer coefficients established in each process of the MFA model corresponding to scn 1 and 2, respectively. Sncf Réseau provided the input data for the eleven worksites, such as the lengths of renovation per worksite and the supplies of new ballast. Table 8c shows the proportions of new and recycled ballast in the stock for the eleven sites.

The results of the mass balance in Table 8a,b show that, for a total of eleven TBR worksites over one year, the length treated is 540,508 m. This represents a total of 997,257 t of ballasted complex (the flow, F1), i.e., the old ballast removed from the track, of which ~1% of toxic ballast (F2) is extracted to obtain 977,362 t of clean ballast (F3), of which ~20% of earth (F5) is extracted. The other flows are considered as variables, such as end-of-life ballast (F4), the supply of new ballast (F7), and new ballast placed on the track (F7.1), as well as ballast remaining at the end of the worksite (F8). These flows are controlled by the percentage of ballast recycled (F6) and by the P6 process, the stock of ballast placed on the track, which represents a mixture of new ballast (F7.1) and recycled ballast in proportion to the rate of recycled ballast (F6).

Thus, because of the effect of scale, the results of scenario 2 (see Table 8b) at the national level are important and tend to help us progress towards a "zero-waste" policy and a reduction in the release of toxic substances. Compared with the results for scenario 1 in Table 8a, there is less waste to be removed from the site and, therefore, less transport (see Table 5a,b). For example, for the end-of-life ballast stream (F4), this represents a difference of 390,945 t between scn 1 and 2. In addition, the ballast recycling rate (F6), with a difference of 390,914 t between scenarios 1 and 2 (see Table 8c), shows a saving of 394,873 t of new ballast (F7) and 3948 t for the flow (F8) of new ballast remaining at the end of the project (see Table 8a,b).

Thus, scenario 2 makes it possible, on the one hand, to preserve the resources and, on the other hand, to reduce ecological damage to the environment, since less raw material is extracted.

This is an interesting indication for extracting statistics on the lifespan of tracks renovated with a mixture of recycled and new ballast or on track segments where only recycled ballast is used [45].

g. Proposal of a SWOT analysis to orientate decision

Several measures could be taken after this MFA analysis and scenario comparison. Regarding the production/site organisation, these measures could be as follows: (1) maximising in situ ballast recycling on TBR sites, (2) developing material recovery channels at the local, regional, and national levels, (3) reusing end-of-life products and soil 100%, and (4) eliminating the waste of new ballast. For transport, the identified measures were as follows: (1) studying the possibility of using empty returns from new ballast supply trains to transport end-of-life materials (flow F4), soil (F5), and wasted new ballast (F8) and (2) limiting the use of road transport to a radius of 50 km. For environmental measures, the following are proposed: (1) targeting and listing all the toxic products present in transport, railways, and TBR worksites and (2) developing research programmes to reduce these toxic elements in order to protect the environment and people's health.

In addition, extending the life of ballast to reduce the need for track renewal would reduce the impact of traffic disruption and environmental pollution. To achieve this, several lines of research need to converge in order to reduce the degradation of railway track due to ballast wear [72–79].

A SWOT analysis of scenarios 1 and 2 (see Table 9) is an approach that enables targeting a series of actions adapted to the new objectives proposed (zero waste and a reduction in toxic substances).

Table 9. SWOT analysis of scenarios 1 and 2—"0", i.e., no variation estimated; "−" smallest impact of scenario for strength, weakness; "+" highest impact of scenario for strength, weakness.

SWOT / **Criteria**	**Strengths**		**Weaknesses**		**Opportunities**		**Threats**	
	SCN 1	**SCN 2**	**SCN 1**	**SCN 2**	**SCN 1**	**SCN 2**	**SCN 1**	**SCN 2**
Production/site organisation								
Dimensioning and characterisation of flows (input, output, and stock)	+	+						
Rate of ballast and toxic soil (F2)			−	−				
Identify solutions to reduce the flow of toxic ballast					+	+		
Rate of ballast at end of life (F4)		+	−					
Rate of land (F5)			−	−				
Facilitate the search for solutions to recover material flows at the end of the site's life at local, regional, and national levels					+	+		
Ballast recycling rate (F6)		+	−					
Identify ways of increasing ballast recycling					+	+		
Rate of supply of new ballast (F7)		+	−					
Stock rate P6 = % (F7.1) + % (F6)		+	−					
Ballast wastage reduction rate (F8)		+	−					
Identify solutions for eliminating new ballast residues					+	+		
Determining which processes are most stressed on the site					+	+		
Transport								
Total transport rate TRT		+	−					
Total truck transport rate		+	−					
Total transport rate by train		+	−					

Table 9. *Cont.*

SWOT / Criteria	Strengths		Weaknesses		Opportunities		Threats	
	SCN 1	**SCN 2**	**SCN 1**	**SCN 2**	**SCN 1**	**SCN 2**	**SCN 1**	**SCN 2**
Environment								
Development of a strategy to reduce the use of new ballast in order to preserve resources		+	–					
The absence of solutions for recycling material flows leaving the site does not promote a zero-waste strategy							–	–
Encourage the use of energy and maintenance products for works equipment and less polluting transport					+	+		
The lack of solutions for eliminating toxic discharges is not an argument in favour of a "zero toxic discharges" strategy							–	–
Developing a strategy for preserving the landscape due to the use of new ballast					+	+		
Development of a strategy for road deterioration caused by road transport		+	–					

This SWOT analysis of scenarios 1 and 2 is useful for identifying the immediate impacts of a high rate of in situ recycled ballast. This automatically minimises supplies of new ballast, end-of-life material outflows, and, finally, transport operations, as was achieved in scenario 2 compared with scenario 1 (see SWOT analysis of scenarios 1 and 2, column strength scn 2 and weakness scn 2). However, research must be undertaken to reduce the toxic substances present on railways (weed killers, hydrocarbons, etc.) and in transport (CO_2). The use of biodegradable and less polluting products would be an interesting avenue to explore. In addition, it would be desirable to know more about the recovery of end-of-life products and soil, as for flows (F4) and (F5), because the absence of a solution represents a very significant threat in a zero-waste strategy.

4. Conclusions

As shown in the literature, it is now possible to reuse up to 70% of the ballast recycled in situ and to reuse the "earth", which is a mixture of aggregate and ballast at the end of its life, for a layer of sub-ballast for railway or road lines (see Section f. How can used ballast be recycled efficiently? p5). This in-situ recycling solution for end-of-life materials aims to achieve zero waste and reduce toxic substances, based on a range of performance indicators.

To explore this, two scenarios were compared based on material flow analysis and strategic planning. This combination enabled us to establish a representation of the current situation of a TBR site—scn 1, with a rate of ballast recycled in situ (TC_F6) of 30%, and scn 2 of 70%, representing the future situation.

The ballast recycled in situ (F6) comes from the screening process (P3), which treats the old ballast flow and the non-toxic soil (F3) (see MFA scn 1 and 2, Figures 3 and 4). Although this is a zero-waste strategy, it does not rely solely on a high ballast recycling rate. However, scenario 2 shows the impact of a high in situ ballast recycling rate (TC_F6 of 70%) on all main flows (see Figure 7a,b and Table 7) and on direct and reverse logistics structures. In the case of scenario 2 (see Figure 4), there was a significant reduction in the quantity of end-of-life ballast F4 compared with scenario 1. Respectively, there was 7762 t for scn2 and 38,810 t for scn 1, i.e., a difference of 31,048 t. Similarly, for the supply of new ballast F7, there was a quantity of 43,150 t for scn1 and 11,790 t for scn2, i.e., a difference of 31,360 t. For transport, there was a relative change of 20% for F4, i.e., a difference of 80%, and 27% for F7, i.e., a difference of 73%. So, overall, this strategy of a high recycling rate promotes "zero-waste" management and reduces toxic substances (e.g., CO_2 for transport).

However, the reuse of toxic ballast (F2) depends on the development of low-pollution treatment methods at attractive prices. Another line of research would be to identify ways of reducing the flow of earth or spoil (F5), which represents ~20% of the tonnage of the ballasted complex (F1) (see Figures 6a,b and 7a,b). First, this depends on the type of track renewal work to be carried out. It may be a total renewal of the ballast, in which case, the spoil is made up of ballast and earth residue, or ballast screening, which results in a spoil of end-of-life ballast and earth residue as well. In the same way, it can be a rehabilitation of the infrastructure with a total clearing, and in this case, all the ballast and the infrastructure are cleared together, or it can also be a separate clearing, and in this configuration, the excavated material represents part of the ballast, the infrastructure, and the subsoil material.

The subgrade is the mineral waterproofing layer that extends below the ballast bed, which is composed of bitumen and a mixture of gravel. Soil, also known as spoil, is a mixture of minerals (ballast residue, gravel, sand, and earth) contained in the ballast bed, the subgrade, and the subsoil [80]. Thus, washing earth or spoil in situ with a water recovery system is a method that eliminates landfill, and storage costs and produces reusable materials such as sand or local recycled aggregates. Clean soil can be used to revegetate the landscape along railway lines, unlike earth or spoil, which is used as fill to support the tracks.

In addition, for future track renovation work, knowing the rate of recycled ballast (F6) makes it possible to know the proportion of new ballast (F7.1) in the stock (P6 = F6 + F7.1) (see Tables 4 and 8c). This knowledge of the stockpile can also be useful in determining forecasts for new ballast (F7) in future works. However, the research needs to clarify whether the life of recycled ballast is equivalent to that of new ballast. More specifically, the aim is to confirm that recycled ballast or a mixture with fresh ballast placed on a track does not require twice as much track regeneration work as new ballast (see Section e. Mechanical behaviour of a mixture of recycled and new ballast, p5).

Scenarios 1 and 2 of our study were based on an MFA model. These MFA models of a TRB worksite were used to model the flows in the various production and transport processes, both for the supply and disposal of materials, based on the principle of the first law of thermodynamics and data reconciliation.

However, in order not to spread too many uncertainties due to the wear of the track and, in particular, the ballast, which is not the same according to the traffic and the tonnage transported, the study was limited to a TBR worksite of IUR group 7 to 9 (see Appendix A, International Union of Railways). More specifically, these are lightly loaded lines, with or without passengers, which generally correspond to the capillary network and are most often regional. In addition, the model does not take into account geographical aspects (e.g., mountainous and maritime regions) and meteorological aspects (scorching or negative temperatures and rainfall), which also lead to the more rapid erosion and ageing of railway lines and ballast in particular.

In our publication, we also wanted to show the effects of scale. This is why we presented the results obtained between scenarios 1 and 2 on a national scale (see Table 8a,b) based on one year's regeneration of 540,508 m of track spread over a total of 11 worksites. The impact in terms of material savings at national level between scenarios 1 and 2 mainly showed a relative change of 20% and a difference of 80% in the flow of F4, end-of-life ballast, between scenario 1,488,681 t, and scenario 2,97,736 t. Similarly, there was a relative change of 27% and a difference of 73% in the supply of new ballast, F7, between scenario 1,543,329 t, and scenario 2,148,455 t. In addition, there was a relative change of 43% and a difference of 67% in recycled ballast, F6, between scenario 1,293,189 t, and scenario 2, 684,103 t.

A high rate of in situ ballast recycling, therefore, makes it possible to preserve resources (see Table 7, flows F6 and F7) and reduce the environmental impact of transporting materials (CO_2) and ballast quarrying, which degrade the environment. On the other hand, ballast recycling leads to a reduction in quarrying. So, one of the challenges for TBR projects is to find ways of increasing the quantities of ballast recycled, so as to reduce the need for new ballast, minimise waste and transport operations, and minimise the toxic substances present on (TBR) sites and railways. Another challenge would be to move towards zero-waste management and a reduction in toxic substances, while trying to preserve the economic activity of quarrymen and hauliers. One solution would be to involve them in a circular economy project to manage end-of-life products from TBR sites.

Through scenarios 1 and 2, it is demonstrated that Material Flow Analysis (MFA), combined with a strategic planning model based on a reliable forecasting framework, enables companies to project their futures and integrate new objectives that support their sustainability.These include preserving resources and the environment, securing supplies, and recovering end-of-life products by adopting new operating methods such as reducing waste and toxic substances. From this point of view, at the quantitative level and for the characterisation of inter-flow exchanges between the different production processes of an industrial centre (TRT), the MFA methodology (bottom-up) of Brunner and Rechberger 2004 [20], combined with the use of the STAN software [24], is a tool that could be classified as a reference. It allows for modelling a flow diagram for a construction site (TBR) and propagating the uncertainties in the model. In particular, it allowed us to appreciate the degree of uncertainty associated with assigning a tolerance of $\pm$ 5% to the 35% transfer coefficient from the process (P3) to the recycled ballast flow (F6), since the standard error was 3900 t for an average flow of 23,300 t, i.e., a margin error of 43.88% (see Table 3b, process P3, flow F6).

Finally, by combining this MFA tool with a planning and forecasting model, a new project can be built from an existing situation. From a strategic point of view, this combination enables a company to describe its future objectives and, in particular, to develop an action plan to move from the current situation to a situation where future objectives are targeted. However, in order to develop a strategic plan aimed at zero waste, it is important to consider the impacts of toxic substances on the environment and human safety (Brunner and Bacinni SFA 1991, [54]).

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Abbreviations

C&DW	Construction and Demolition Waste
CO_2	Carbon Dioxide
ETC/WMGE	European Topic Centre on Waste and Materials in a Green Economy
EWC-Stat category	Explanation of Waste Catégories
EFFRA	European Factories of the Future Research Association
EWWR	European Week for Waste Reduction
GHG	A greenhouse gas (GHG or GhG)
UIC	International Union of Railways
IRP	International Resource Panel
MFA	Material Flow Analysis
OECD	Organisation for Economic Cooperation and Development
SFA	Substance Flow Analysis
SETRA	Service étude sur les transports, les routes et leurs aménagements, (service for studies on transport, roads, and their development)
SNCF	Société Nationale des Chemins de Fer Français: French national railway company
SNCF Réseau	The French railway infrastructure manager. A public limited company and subsidiary of the SNCF, it is responsible for the operation, maintenance, and development of rail infrastructure in France.
STAN	Short for subSTance flow ANalysis
SWOT	Strengths, Weaknesses, Opportunities, and Threats
TC	Transfer coefficient
TBR	Track and Ballast Renewal
TRT	Track Renewal Train
UNEP	United Nations Environment Program
UN	United Nations (United Nations Summit on Sustainable Development)

Appendix A

Appendix A.1. IUR Classification of Railway Lines

The International Union of Railways (IUR) has established a classification of lines according to the traffic loads borne by the infrastructure and the type of traffic (see the table below). IUR group 1 corresponds to very busy lines and, on the other hand, IUR group 9 corresponds to very lightly loaded lines. The high-speed lines and main lines of the national rail network belong, in principle, to IUR groups 1 to 4, except for certain routes, particularly transverse ones, which belong to IUR groups 5 and 6. The lightly loaded lines of IUR groups 7 to 9, with passengers or without passengers, generally correspond to the capillary network and are generally regional. This IUR classification is used to define the maintenance policy of the railway network.

The classification of railways is based on a notional traffic (Tf) calculated according to the daily tonnage of passengers, goods, the type of traction units, and the armament of the line (the capacity of a railway to support a defined amount of traffic).

The lines have been classified into the nine groups defined by these thresholds as follows:

Group IUR	Characteristic Value Tf
Group 1	$Tf \geq 120{,}000$
Group 2	$120{,}000 \geq Tf \geq 85{,}000$
Group 3	$85{,}000 \geq Tf \geq 50{,}000$
Group 4	$50{,}000 \geq Tf \geq 28{,}000$
Group 5	$28{,}000 \geq Tf \geq 14{,}000$

Group IUR	Characteristic Value Tf
Group 6	14,000 ≥ Tf ≥ 7000
Group 7	7000 ≥ Tf ≥ 3500
Group 8	3500 ≥ Tf ≥ 1500
Group 9	1500 ≥ Tf

Source: SNCF RESEAU/Directions Techniques Réseau/DGOP PI SRMN: Directions Générale des Opérations et de Production DPI—Département Suites Rapides et Marchés Nationaux.

Classification table of railway tracks.

References

1. OECD. Global Material Resources Outlook to 2060 Economic Drivers and Environmental Consequences. 2018. Available online: https://www.oecd.org/environment/waste/highlights-global-material-resources-outlook-to-2060.pdf (accessed on 6 March 2023).
2. UNEP. *Global Material Flows and Resource Productivity. An Assessment Study of the UNEP International Resource Panel*; Schandl, H., Fischer-Kowalski, M., West, J., Giljum, S., Dittrich, M., Eisenmenger, N., Geschke, A., Lieber, M., Wieland, H.P., Schaffartzik, A., et al., Eds.; United Nations Environment Programme: Paris, France, 2016.
3. Lorang, E. Ressources, déchets et climat: Essais sur l'économie du recyclage. *INRAE Sci. Soc.* **2021**, *2021*, 1–2.
4. OECD. *Policy Guidance on Resource Efficiency*; OECD Publishing: Paris, France, 2016. [CrossRef]
5. UN. *Transforming Our World: The 2030 Agenda for Sustainable Development*; United Nations: New York, NY, USA, 2015; Resolution adopted by the General Assembly on 25 September 2015.
6. Gould, O.; Colwill, J. A framework for material flow assessment in manufacturingsystems. *J. Ind. Prod. Eng.* **2015**, *32*, 55–66. [CrossRef]
7. Mudd, G.M. The "Limits to Growth" and 'Finite' Mineral Resources: Re-Visiting the Assumptions and Drinking from That Half-Capacity Glass. In Proceedings of the 4th International Conference on Sustainability Engineering & Science: Transitions to Sustainability, Auckland, New Zealand, 30 November–3 December 2010. Available online: https://www.thesustainabilitysociety.org.nz/conference/2010/papers/Mudd.pdf (accessed on 2 January 2023).
8. Brundtland. Report of the World Commission on Environment and Development: Our Common Future; présidée par Gro Harlem Brundtland; 1987. Available online: https://www.are.admin.ch/dam/are/en/dokumente/nachhaltige_entwicklung/dokumente/bericht/our_common_futurebrundtlandreport1987.pdf.download.pdf/our_common_futurebrundtlandreport1987.pdf (accessed on 2 January 2023).
9. Delgado, B.G.; da Fonseca, A.V.; Fortunato, E.; Paixão, A.; Alves, R. Geomechanical assessment of an inert steel slag aggregate as analternative ballast material for heavy haul rail tracks. *Constr. Build. Mater.* **2021**, *279*, 122438. [CrossRef]
10. Khong, S.C.; Yee, J.J.; Doh, S.I.; Chin, S.C. A review of agro-potential waste as a constituent in railway sleepers. *Phys. Chem. Earth Parts A/B/C* **2022**, *128*, 103238. [CrossRef]
11. Doğan-Sağlamtimur, N.; Bilgil, A.; Öztürk, B. Reusability of ashes for the building sector to strengthen the sustainability of waste management. In *Handbook of Research on Supply Chain Management for Sustainable Development*; IGI Global: Hershey, PA, USA, 2018; pp. 265–281. [CrossRef]
12. Directive 2008/98/C, Législation Européenne Sur la Gestion des Déchets. Available online: https://eur-lex.europa.eu/FR/legal-content/summary/eu-waste-management-law.html (accessed on 21 December 2022).
13. Eionet Report—ETC/WMGE 2020/1. Construction and Demolition Waste: Challenges and Opportunities in a Circular Economy. Available online: https://www.eionet.europa.eu/etcs/etc-wmge/products/etc-wmge-reports/construction-and-demolition-waste-challenges-and-opportunities-in-a-circular-economy/@@download/file/Clean%20Version_CDW%20and%20CE%20Report%20version%20January%2010%202020_final.pdf (accessed on 8 March 2023).
14. Reporting on Material Recovery of C&D Waste: Guidance for the Reporting of the Data According to Commission Decision 2011/753/EU and Commission Implementing Decision (EU) 2019/1004 Version of May 2022. Available online: https://ec.europa.eu/eurostat/documents/342366/351811/C&D+-+Guidance+on+Construction+and+Demolition+waste+reporting.pdf/6063625b-e9f0-8d24-be25-c3fa88aed0f1?t=1622469335376 (accessed on 7 March 2023).
15. Pásztai, Z.; Branner, F.; Hübner, K.; Apostol, T.; Stan, C.; Cocârță, D.M. A Romanian Zero Waste Strategy: Salacea and Cociuba Mare Case Study. In Proceedings of the 2019 International Conference on Energy and Environment (CIEM), Timisoara, Romania, 17–18 October 2019. [CrossRef]
16. Iqbal, M.W.; Kang, Y.; Jeon, H.W. Zero waste strategy for green supply chain management with minimization of energy consumption. *J. Clean. Prod.* **2020**, *245*, 118827. [CrossRef]
17. Gao, Q.; Li, X.-g.; Jiang, S.-q.; Lyu, X.-j.; Gao, X.; Zhu, X.-n.; Zhang, Y.-q. Review on zero waste strategy for urban construction and demolition waste: Full component resource utilization approach for sustainable and low-carbon. *Constr. Build. Mater.* **2023**, *395*, 132354. [CrossRef]
18. Allesch, A.; Brunner, P.H. Material Flow Analysis as a Decision Support Tool for Waste Management: A Literature Review. *J. Ind. Ecol.* **2015**, *19*, 753–764. [CrossRef]

19. Lederer, J.; Gassner, A.; Fellner, J.; Mollay, U.; Schremmer, C. Raw materials consumption and demolition waste generation of the urban building sector 2016e2050: A scenario-based material flow analysis of Vienna. *J. Clean. Prod.* **2020**, *288*, 125566. [CrossRef]
20. Brunner, P.H.; Rechberger, P. *Practical Handbook of Material Flow Analysis*; Lewis Publisher: Boca Raton, FL, USA, 2004.
21. Cochran, K.M.; Townsend, T.G. Estimating construction and demolition debris generation using a materials flow analysis approach. *Waste Manag.* **2010**, *30*, 2247–2254. [CrossRef]
22. Sañudo, R.; Goswami, R.R.; Ricci, S.; Miranda, M. Efficient Reuse of Railway Track Waste Materials. *Sustainability* **2022**, *14*, 11721. [CrossRef]
23. Jain, K.P.; Pruyn, J.F.J.; Hopman, J.J. Material flow analysis (MFA) as a tool to improve ship recycling. *Ocean. Eng.* **2017**, *130*, 674–683. [CrossRef]
24. Software STAN (Short for subSTance Flow ANalysis) Is a Freeware That Helps to Perform Material Flow Analysis According to the Austrian Standard ÖNorm S 2096 (Material Flow Analysis—Application in Waste Management) The Latest Version is 2.7.101; Released 2022-02-01. Available online: https://www.stan2web.net/ (accessed on 21 December 2022).
25. Cencic, O.; Rechberger, H. Material Flow Analysis with Software STAN. *J. Environ. Eng. Manag.* **2008**, *18*, 3–7. Available online: https://sswm.info/sites/default/files/reference_attachments/CENCIC%20and%20RECHBERGER%202008%20Material%20Flow%20Analysis%20with%20Software%20STAN.pdf (accessed on 20 October 2020).
26. Cencic, O. Nonlinear data reconciliation in material flow analysis with software STAN. *Sustain. Environ. Res.* **2016**, *26*, 291–298. [CrossRef]
27. Abadi, T.; Madhusudhan, B.N.; Li, H.; Le Pen, L. Reusing Life-Expired Railway Ballast: Laboratory Testing, Shape Analysis, and Petrographic Evaluation. *J. Geotech. Geoenvironmental Eng.* **2023**, *149*, 1. [CrossRef]
28. Trinh, V.-N.; Tang, A.-M.; Cui, Y.-J.; Canou, J.; Dupla, J.-C.; Calon, N.; Lambert, L.; Robinet, A.; Schoen, O. Caractérisation des matériaux constitutifs de plate-forme ferroviaire ancienne. *Rev. Française Géotechnique* **2011**, *134–135*, 65–74. [CrossRef]
29. Cescon, J.T.A.M.; Silva, B.-H.d.A.e.; Marques, M.E.S.; Santos, R.P.d. Evaluation of the viability of recycling railroad ballast for reusing in railroads. *Res. Soc. Dev.* **2021**, *10*, e277101321231. [CrossRef]
30. Ciotlaus, M.; Kollo, G. Ballast bed cleaning and recycling—Influence on stability of continuously welded rail track. *Procedia Manuf.* **2018**, *22*, 294–300. [CrossRef]
31. Jia, W.; Markine, V.; Guo, Y.; Jing, G. Experimental and numerical investigations on the shear behaviour of recycled railway ballast. *Constr. Build. Mater.* **2019**, *217*, 310–320. [CrossRef]
32. Leus, O.; Pidal, I.M.; Kolos, A.; Klishch, S. Strength properties of ballast layer, created from new and recycled crushed stone ballast. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *942*, 012026. [CrossRef]
33. Binaree, T.; Kwunjai, S.; Jitsangiam, P.; Azéma, E.; Jing, G. Assessment of macro and micro mechanical properties of fresh and deteriorated ballast combining laboratory tests and 2D-discrete element methods. *Constr. Build. Mater.* **2024**, *420*, 135525. [CrossRef]
34. Kwunjai, S.; Somsri, T.; Jitsangiam, P.; Binaree, T.; Qian, Y.; Jing, G. Characterization of deteriorated railway ballast morphological changes using 3D scanning and supervised machine learning data analytics. *Constr. Build. Mater.* **2023**, *398*, 132445. [CrossRef]
35. Varuntanya, K.; Kwunjai, S.; Binaree, T.; Jitsangiam, P.; Jing, G.; Aela, P. Laboratory investigation of railway-used ballast morphology using 3D imaging data analyses. *Case Stud. Constr. Mater.* **2023**, *19*, e02272. [CrossRef]
36. Sadeghi, J.; Motieyan Najar, M.E.; Zakeri, J.A.; Kuttelwascher, C. Development of railway ballast geometry index using automated measurement system. *Measurement* **2019**, *138*, 132–142. [CrossRef]
37. Yunlong, G.; Xie, J.; Fan, Z.; Markine, V.; Connolly, D.P.; Jing, G. Railway ballast material selection and evaluation: A review. *Constr. Build. Mater.* **2022**, *344*, 128218. [CrossRef]
38. Saico, J.H.; Castro, G.B.; Motta, R.; de Moura, E.; Bernucci, L.B.; Oliveira, L. Evaluation of the Behavior of Recycled Ballast Waste Applied in Subballast Railway Track Layer Rehabilitation. 2023. Available online: https://www.researchgate.net/publication/375594178 (accessed on 14 May 2024).
39. Castro, G.; Saico, J.; deMoura, E.; Motta, R.; Bernucci, L.; Paixão, A.; Fortunato, E.; Oliveira, L. Evaluating Different Track Sub-Ballast Solutions Considering Traffic Loads and Sustainability. *Infrastructures* **2024**, *9*, 54. [CrossRef]
40. Blard, C. Sncf Réseau. Réutilisation du ballast de dépose des Voies Ferries. OPTIGEDE-Ademe: Resource Centre Circular Economy and Waste. 2016. Available online: https://optigede.ademe.fr/fiche/reutilisation-du-ballast-de-depose-des-voies-ferrees (accessed on 12 October 2020).
41. Lidén, T. Railway infrastructure maintenance—A survey of planning problems and conducted research. *Transp. Res. Procedia* **2015**, *10*, 574–583. [CrossRef]
42. Lazorenko, G.; Kasprzhitskii, A.; Khakiev, Z.; Yavna, V. Dynamic behavior and stability of soil foundation in heavy haul railway tracks: A review. *Constr. Build. Mater.* **2019**, *205*, 111–136. [CrossRef]
43. de Abreu Corrêa, L.; Quezada, J.C.; Cottereau, R.; d'Aguiar, S.C.; Voivret, C. Randomly fluctuating heterogeneous continuum model of a ballasted railway track. *Comput. Mech.* **2017**, *60*, 845–861. [CrossRef]
44. de Bortoli, A.; Bouhaya, L.; Feraille, A. Roadways and Infrastructure: A life cycle model for high-speed rail infrastructure: Environmental inventories and assessment of the T ours-Bordeaux railway in France. *Int. J. Life Cycle Assess.* **2020**, *25*, 814–830. [CrossRef]
45. Huang, J.; Yin, Y.; Zheng, L.; Zhang, S.; Zhao, Q.; Chen, H. Life Cycle Assessment of Construction and Demolition Waste from Railway Engineering Projects. *Comput. Intell. Neurosci.* **2022**, *2022*, 6145755. [CrossRef]

46. Quintanilla, I.D. Multi-Scale Study of the Degradation of Railway Ballast. Doctoral Thesis, Université Grenoble Alpes. 2018. Available online: https://tel.archives-ouvertes.fr/tel-01858650 (accessed on 6 November 2018).
47. Bassey, D.; Ngene, B.; Akinwumi, I.; Akpan, V.; Bamigboye, G. Ballast Contamination Mechanisms: A Criterial Review of Characterisation and Performance Indicators. *Infrastructures* **2020**, *5*, 94. [CrossRef]
48. Han, J.; Thakur, J.K. Sustainable roadway construction using recycled aggregates with geosynthetics. *Sustain. Cities Soc.* **2015**, *14*, 342–350. [CrossRef]
49. Ramos, M.; Martinho, G. Relation between construction company size and the use of recycled materials. *J. Build. Eng.* **2021**, *45*, 103523. [CrossRef]
50. Samarska, A.; Zelenko, Y.; Kovrov, O. Investigation of Heavy Metal Sources on Railways: Ballast Layer and Herbicides. *J. Ecol. Eng.* **2020**, *21*, 32–46. [CrossRef]
51. Rak, A.; Klosok-Bazan, I.; Zimoch, I.; Machnik-Slomka, J. Analysis of railway ballast contamination in terms of its potential reuse. *J. Clean. Prod.* **2021**, *378*, 134440. [CrossRef]
52. Mutha, N.H.; Patel, M.; Premnath, V. Plastics materials flow analysis for India. *Resour. Conserv. Recycl.* **2005**, *47*, 222–244. [CrossRef]
53. Nacef, T.; Rachida, I.; AmorBen, F. Sustainable reverse logistic of construction and demolition wastes in French regions: Towards sustainable practices. *Procedia CIRP* **2020**, *90*, 712–717. [CrossRef]
54. Baccini, P.; Brunner, H.P. *Metabolism of the Anthroposphere*; Springer: Berlin, Germany, 1991; 157p.
55. Hendriks, C.; Obernosterer, R.; Müller, D.; Kytzia, S.; Baccini, P.; Brunner, P.H. Material Flow Analysis: A tool to support environmental policy decision making. Case studies on the city of Vienna and the Swiss lowlands. *Local Environ.* **2000**, *5*, 311–328. [CrossRef]
56. Woodward, R.; Duffy, N. Cement and concrete flow analysis in a rapidly expanding economy: Ireland as a case study. *Resour. Conserv. Recycl.* **2010**, *55*, 448–455. [CrossRef]
57. Naohiro, G.; Tachibana, J.; Fujie, K. Environmental Management System Based on Material Flow Analaysis to Etablish and Maintain Eco Town. *J. Ind. Eng. Chem.* **2005**, *11*, 818–825.
58. Sendra, C.; Gabarrell, X.; Vicent, T. Material flow analysis adapted to an industrial area. *J. Clean. Prod.* **2007**, *15*, 1706–1715. [CrossRef]
59. Manderson, E.; Considine, T. An Economic Perspective on Industrial Ecology. *Rev. Environ. Econ. Policy* **2018**, *12*, 304–323. [CrossRef]
60. Arena, U.; Di Gregorio, F. A waste management planning based on substance flow analysis. *Resour. Conserv. Recycl.* **2014**, *85*, 54–66. [CrossRef]
61. Brunner, P.H.; Rechberger, H. Waste to energy—Key element for sustainable waste management. *Waste Manag.* **2015**, *37*, 3–12. [CrossRef]
62. Tang, J.; Brunner, P.H. *Globalising MFA—Decision Support for Waste Management in Cities Based on the Software STAN*; International Solid Waste Association (ISWA): Rotterdam, The Netherlands, 2013. Available online: http://hdl.handle.net/20.500.12708/38012 (accessed on 6 November 2023).
63. Makarichi, L.; Techato, K.-a.; Jutidamrongphan, W. Material flow analysis as a support tool for multi-criteria analysis in solid waste management decision-making. *Resour. Conserv. Recycl.* **2018**, *139*, 351–365. [CrossRef]
64. Allen, F.W.; Halloran, P.A.; Leith, A.H.; Lindsay, M.C. Using Material Flow Analysis for Sustainable Materials Management. *J. Ind. Ecol.* **2009**, *13*, 662–665. [CrossRef]
65. Hashimoto, S.; Tanikawa, H.; Moriguchi, Y. Where will large amounts of materials accumulated within the economy go?—A material flow analysis of construction minerals for Japan. *Waste Manag.* **2007**, *27*, 1725–1738. [CrossRef]
66. Economy-Wide Material Flow Accounts and Derived Indicators. A Methodological Guide. Eurostat. 2001. Available online: https://ec.europa.eu/eurostat/documents/3859598/5855193/KS-34-00-536-EN.PDF.pdf/411cd453-6d11-40a0-b65a-a33805327616?t=1414780409000 (accessed on 21 December 2022).
67. UNEP. The Use of Natural Resources in the Economy: A Global Manual on Economy Wide Material Flow Accounting. 2021. Available online: https://wedocs.unep.org/20.500.11822/36253 (accessed on 20 November 2023).
68. Allwood, J.M.; Ashby, M.F.; Gutowski, T.G.; Worrell, E. Material efficiency: A white paper. *Resour. Conserv. Recycl.* **2011**, *55*, 362–381. [CrossRef]
69. Fleischmann, M.; Bloemhof-Ruwaard, J.M.; Dekker, R.; van der Laan, E.; van Nunen, J.A.E.E.; Van Wassenhove, L.N. Quantitative models for reverse logistics: A review. *Eur. J. Oper. Res.* **1997**, *103*, 1–17. [CrossRef]
70. Laner, D.; Rechberger, H.; Astrup, T. Systematic Evaluation of Uncertainty in Material Flow Analysis. *J. Ind. Ecol.* **2014**, *18*, 859–870. [CrossRef]
71. Bourbonnais, R.; Usunier, J.C. *Prévision des Ventes*, 4th ed.; Economica: Paris, France, 2007; p. 35.
72. Sol-Sánchez, M.; D'Angelo, G. Review of the design and maintenance technologies used to decelerate the deterioration of ballasted railway tracks. *Constr. Build. Mater.* **2017**, *157*, 402–415. [CrossRef]
73. D'Angelo, G.; Thom, N.; Lo Presti, D. Bitumen stabilized ballast: A potential solution for railway track-bed. *Constr. Build. Mater.* **2016**, *124*, 118–126. [CrossRef]
74. D'Angelo, G.; Bressi, S.; Giunta, M.; Lo Presti, D.; Thom, D. Novel performance-based technique for predicting maintenance strategy of bitumen stabilised ballast. *Constr. Build. Mater.* **2018**, *161*, 1–8. [CrossRef]

75. Giunta, M.; Bressi, S.; D'Angelo, G. Life cycle cost assessment of bitumen-stabilised ballast: A novel maintenance strategy for railway track-bed. *Constr. Build. Mater.* **2018**, *172*, 751–759. [CrossRef]
76. Bressi, S.; D'Angelo, G.; Santo, J.; Giunta, M. Environmental performance analysis of bitumen stabilized ballast for railway track-bed using life-cycle assessment. *Constr. Build. Mater.* **2018**, *188*, 1050–1064. [CrossRef]
77. Pons, J.J.; Villalba Sanchis, I.; Francoa, R.I.; Yepes, V. Life cycle assessment of a railway tracks substructures: Comparison of ballast and ballastless rail tracks. *Environ. Impact Assess. Rev.* **2020**, *85*, 106444. [CrossRef]
78. Ngamkhanong, C.; Kaewunruen, S.; Baniotopoulos, C. Influences of ballast degradation on railway track buckling. *Eng. Fail. Anal.* **2021**, *122*, 105252. [CrossRef]
79. Sainz-Aja, J.; Carrascal, I.; Polanco, J.A.; Thomas, C.; Sosa, I.; Casado, J.; Diego, S. Self-compacting recycled aggregate concrete using out-of-service railway superstructure wastes. *J. Clean. Prod.* **2019**, *230*, 945–955. [CrossRef]
80. Département Fédéral de l'Environnement, des Transports et de l'énergie et de la Communication (DETEC); Office Federal des Tranports (OFT). Directive sur les Déblais de Voie. Planification de Travaux d'Excavation, évaluation et élimination des Déblais de Voie. Réfé-rence: BAV-522.450-2/3/23/4/10. 2023; (Unpublished reference). Available online: https://www.bav.admin.ch/dam/bav/fr/dokumente/richtlinien/eisenbahn/gleisaushubrichtlinie.pdf.download.pdf/directive_sur_lesdeblaisdevoie.pdf (accessed on 12 July 2024).