Waste Management 75 (2018) 187–204

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Investigating the feasibility of a reuse scenario for textile fibres recovered from end-of-life tyres

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ARTICLE INFO

Article history:
Received 19 July 2017
Revised 29 January 2018
Accepted 9 February 2018
Available online 14 February 2018

Keywords:
Circular economy
End-of-life tyres
Reuse scenario
Cost–benefit analysis
Feasibility evaluation

ABSTRACT

The management of end-of-life tyres (ELTs) is regulated by several national and international legislations aiming to promote the recovery of materials and energy from this waste. The three main materials used in tyres are considered: rubber (main product), which is currently reused in other closed-loop applications; steel, which is used for the production of virgin materials; and textile fibres (approximately 10% by weight of ELTs), which are mainly incinerated for energy recovery (open-loop scenario).

This study aims to propose and validate a new closed-loop scenario for textile fibres based on material reuse for bituminous conglomerates. The final objective is to verify the technical, environmental, financial, and economic feasibility of the proposed treatment process and reuse scenario. After characterization of the textile material, which is required to determine the technological feasibility, a specific process has been developed to clean, compact, and prepare the fibres for subsequent reuse. A life cycle assessment (LCA) has been carried out to quantify the environmental benefits of reusing the fibres. Finally, a cost benefit analysis based on the LCA results was conducted to establish the long-term financial and economic sustainability.

From a technological point of view, the tyre textile fibres could be a promising substitute to the reinforcement cellulose commonly used in asphalts as long as the fibres are properly prepared (compaction and pellet production) for application in the standard bituminous conglomerate production process. From an environmental point of view, relevant benefits in terms of global warming potential and acidification potential reduction were observed in comparison with the standard incineration for energy recovery (respectively −86% and −45%). Moreover, the proposed scenario can be considered as financially viable in the medium to long term (cumulative generated cash flow is positive after the 5th year) and economically sustainable (expected net present value of more than €3,000,000 and economic rate of return of approximately 30%). Finally, the sensitivity and risk analyses show that no specific issues are foreseen for the future implementation in real industrial applications.

1. Introduction

Waste and waste management are primary issues that modern society has to address in order to ensure a liveable Earth for future generations (Hanifzadeh et al., 2017). The European Union (EU) drafted several plans to favour the transition towards a resource-efficient economy where wastes become resources to exploit instead of problems to manage (European Parliament and Council, 2013; European Commission, 2015).

End-of-life vehicles (ELVs) and end-of-life tyres (ELTs) represent a relevant percentage of solid wastes and thus are a priority in the EU waste legislation framework which includes specific directives for this sector (European Parliament and Council (2000)). European and national legislations are clearly inspired by the extended producer responsibility concept which identifies producers (and importers) as polluters, involving them in the responsibility of waste management of products they produce and commercialize (European Commission - DG Environment, 2014). For instance, in Italy, ELT dismantling is managed by different consortiums created by tyre producers operating nationwide and by several authorized recycling companies as regulated by the specific legal framework (DL 2006; DM 2011; DM 2012).

According to the European Tyre and Rubber Manufacturers Association (ETRMA) statistics in 2013, the quantity of used tyres in EU was approximately 3.6 million tonnes, mostly collected in Germany, United Kingdom, France and Italy. Figures highlight that the EU directives are effective, because most of the collected ELTs

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https://doi.org/10.1016/j.wasman.2018.02.018
0956-053X/

are correctly managed and dismantled. Only 2% of the residual wastes produced in EU28 are landfilled (4% including Norway, Switzerland, and Turkey) and most of the EU countries (e.g. Germany, Spain, and Italy) reached the 100% recovery of ELTs in 2013. However, the quickest route for recovered tyres is certainly their use for energy recovery. From 32% registered in 1994, the percentage of ELTs used for material recovery is slowly increasing but in recent years there is only a 50/50 mix that can be observed (EASME, 2015; ETRMA, 2015). This means that a large fraction of materials coming from the ELT treatment are used in open-loop scenarios which do not constitute the best option according to the environmental hierarchy (Favi et al., 2017).

The ELT treatment process essentially consists of ambient or cryogenic grinding and primarily aims at recovering triturated rubber in various sizes and types which represents the main portion of ELT materials (WBCSD, 2010). The separation of different compounds (mainly rubber and elastomers) is a very difficult or impossible task (ERTMA, 2015); thus, the granulated or pulverized rubber fraction is used for the production of other products/materials such as plastic compounds, concrete, asphalts, rails, or athletics tracks (Fornai et al., 2016). Generally, the incorporation of rubber leads to a positive effect in terms of weight, mechanical performance, durability, noise, and environmental sustainability (Aliapur, 2010; Ramarad et al., 2015; Aoudia et al., 2017; Nazzal et al., 2017).

During the treatment of tyres, two other sub-products are generated in substantial quantities which are namely steel and textile fibre (Pacheco-Torgal et al., 2012; Ecopneus, 2013). According to the ERTMA report, steel recovered from ELTs is generally a high-quality material with a large demand by the steel industry where it is used for the production of new virgin steel. However, textile fibres represent a challenge for ELT recycling companies, because they strongly contribute to the generation of dust in the working environment, which can result in health problems for operators (ETRMA, 2015). In addition, textile fibres are classified as special wastes (European Waste Catalogue – EWC code 19.12.08) to be disposed or incinerated.

After the tyre grinding process, the output fibres are contaminated with rubber (Re Depaolini et al., 2017) and have several unfavourable characteristics: (i) they take the form of soft bundles that cannot be uniformly mixed with other materials, such as plastic compounds or bituminous conglomerates; (ii) they accumulate electrostatic charges within the bundles, which limit the possibility of extruding them in combination with a compound; and (iii) they have a high volume and a low specific weight (approximately 140 kg/m^3) which makes the transportation very expensive. However, studies have investigated the use of waste tyre fibres for different applications in particular for reinforced cement (Flores Medina et al., 2017; Sofi, 2017; Sousa et al., 2017). Li et al. (2004) evaluated the influence of waste tyre fibres on the strength and stiffness of concrete. Yadaw and Tiwari (2017) proved the applicability of waste rubber fibres as fill materials in cement stabilized clays. Van de Lindt et al. (2008) applied scrap tyre fibres in building insulation panels to increase efficiency. Landi et al. (2016) provided a comparison between different second life applications of fibrous materials in terms of environmental benefits and waste disposal reduction.

The current study aims to integrate the above-mentioned studies by proposing and evaluating the economic and environmental feasibility of an alternative tyre textile fibre end-of-life scenario. Through the development of a specific treatment process, the textile materials can be reused for the preparation of reinforced bituminous conglomerates with improved mechanical performances in comparison with the standard ones. Even if this is one of the most common applications for the ELT rubber fraction (Sienkiewicz et al., 2017), reuse of ELT fibres in this sector has never been thoroughly investigated. The final objective is to quantitatively demonstrate that the new reuse scenario based on fibre cleaning could lead to economic revenues as well as environmental benefits. As a consequence, the ELT recycling chain will be improved, as a larger fraction of recovered materials could potentially have a closed-loop scenario, according to circular economy principles. In addition, a longer lifetime of asphalts realized by using tyre textile fibres is expected (Gonzalez et al., 2012; Liang et al., 2015) which will lead to cost reduction in road rehabilitation and maintenance (Blessen et al., 2016).

The paper is organized as follows. Section 2 describes the textile material characterization and the technical issues related to its application in bituminous conglomerates. Section 3 provides a detailed description of all the required processes for fibre cleaning, preparation, and reuse. Section 4 presents the life cycle assessment (LCA) study which is carried out to verify the environmental sustainability of the proposed scenario. Section 5 presents the cost–benefit analysis (CBA) conducted to establish the financial and economic feasibility. Section 6 discusses the obtained results and presents sensitivity and risk analyses which complete the feasibility study. Finally, Section 7 reports the conclusions and related future work.

2. Textile material characterization and valorisation

The technical and sustainable feasibility evaluation of the second life application firstly requires to define how to use the waste material as a subsequent raw material.

2.1. Textile material characterization

Tyres are made up of four main parts: (i) tread, which is designed for contact with the ground and to ensure proper friction; (ii) carcass, which is the structural part of the tyre on which the tread is vulcanized; (iii) shoulder, which minimizes the effects of irregularities of the terrain and transfers the load due to braking and oversteering under acceleration; and (iv) heels, which is used to fit the casing to the rim. Regarding the constituent materials, tyres have mixed compositions of carbon black, elastomer compounds, steel cord, and fibres, in addition to several other organic and inorganic components. Each material contributes to the particular characteristics of a tyre which promote longer life and attain a specific level of friction (Wei et al., 2005; Yang and He, 2013; Torretta et al., 2015). Table 1 presents a brief overview of this composition (ETRMA, 2015).

The following sub-sections describe the tests carried out on the textile material to establish its composition and the most important characteristics. Each test was repeated on 5 different lots of textile materials in order to ensure statistical significance.

2.1.1. Apparent density and thermal conductivity

Apparent (or bulk) density is defined as the ratio between mass and the volume occupied. This volume occupied by the fibres includes the space between the solid parts in addition to the one occupied by them. Apparent density is often used in the study of powders or fibres, which are generally formed by a mixture of air and solid particles. In order to obtain a repeatable and comparable measurement with various tests, the density measurement was associated with the measurement of the thermal properties of the fibre such as thermal conductivity, specific heat, and diffusivity. These parameters are influenced by the density of the material being analysed.

In this study, the thermal properties were measured using the ISOMET 2104 system equipped with a 'needle probe'. Five series of thermal measurements were carried out at three different density values (Table 2).

Table 1
Average composition of a tyre.

Ingredient	Rubber elastomers	Carbon black	Metal	Textile	Zinc oxide	Others
Passenger Car	47%	21.5%	16.5%	5.5%	1%	8.5%
Lorry	45%	22%	23%	3%	2%	5%
Off Road	47%	22%	12%	10%	2%	7%

Table 2
Apparent density and thermal conductivity test.

Test no	Weight [g]	Volume [cm^3]	Density [g/cm^3]	Thermal conductivity [W/m·K]	Specific heat [J/kg·K]	Diffusivity [m^2/s]
1	120	1737	0.069	0.0548	0.120	0.457
				0.0548	0.121	0.448
				0.0548	0.120	0.447
				0.0548	0.122	0.446
				0.0548	0.121	0.448
2	200	1737	0.115	0.0549	0.151	0.364
				0.0571	0.148	0.378
				0.0551	0.150	0.366
				0.0566	0.151	0.380
				0.0571	0.151	0.383
3	300	1737	0.173	0.0650	0.198	0.333
				0.0640	0.195	0.335
				0.0613	0.197	0.324
				0.0629	0.197	0.318
				0.0621	0.198	0.320
4	400	1737	0.230	0.0601	0.187	0.323
				0.0595	0.194	0.321
				0.0600	0.193	0.312
				0.0621	0.194	0.321
				0.0611	0.197	0.366
5	500	1737	0.287	0.0611	0.178	0.314
				0.0612	0.194	0.333
				0.0628	0.195	0.334
				0.0613	0.197	0.351
				0.0632	0.197	0.342

2.1.2. Thermogravimetric analysis (TGA)

Five dynamic scans of nitrogen were performed from 30 °C to 900 °C at 20 °C/min on four different samples detected by the 5 lots of ELT fibres. The right part of Fig. 1 shows the trends of the results obtained for the thermogravimetric curve (TG). A comparison with the TG curves derived from the literature showed that the textile material is mainly composed of Nylon 6.6 (TG curve on the left of Fig. 1).

2.1.3. Morphological analysis of fibre

Micrographic analyses were carried out on 3 different samples from each lot of textile material (two sample images are shown in Fig. 2). Table 3 provides the fibre diameters obtained with the measurement campaign. The average diameter is approximately 22.5 μm, comparable to commercially available fibre diameters (e.g. cellulose fibres), which have variable diameters, usually in the range between 20 and 40 μm.

2.1.4. Sifting of the fibre

The dirty fibre coming from the ELT grinder was passed in a 5 mm mesh sieve to separate most of the residual rubber. Fig. 3 shows the fibre before passing to the sieve and after cleaning while Table 4 presents the obtained quantities of materials. Approximately 40% by weight of clean fibres can be obtained from the dirty fibres.

2.2. Textile material reuse

The above analyses show that the fibres are essentially composed of Nylon 6.6. Therefore, to apply it as a reinforcement, it will be necessary to use a matrix with a process temperature lower than the melting temperature of Nylon 6.6 which is identified in the literature as 259 °C (Wong et al., 2002). Thus, the reinforcement of polymers, such as polyethylene terephthalate (PET) or polyesters, is substantially prevented as most commercial polymers have working temperatures close to the melting temperature of Nylon 6.6 or even higher (e.g. the PET melting temperature is 260 °C). The fibre can be used for reinforcement of low-density polyamides or polyolefins (e.g. polypropylene, polyethylene), subject to chemical compatibility. Conversely, the fibre can be used in all cold-reinforced materials such as cement and/or bituminous reinforcement. This study is focused on this latter application.

2.2.1. Application in bituminous conglomerates

The consumption of bituminous conglomerates in Europe amounts to approximately 325 million tonnes (ERF, 2017). This market segment represents a very large portion for ELT fibre uptake. ELT fibres might replace for instance more expensive reinforcements, such as cellulose fibres, reducing the use of virgin raw materials.

An experimental study showed that the use of reinforcement fibres as additive to bituminous conglomerates leads to a significant increase in the tensile modulus and fatigue strength (6–7 times higher than those of standard conglomerates) and therefore, in the useful lifetime of the pavement (Fazaeli et al., 2016). The conventional fibres (Xiong et al., 2015) used in the production of porous asphalt concrete consist of cellulose fibres (Fig. 4).

Table 5 reports the comparison, obtained through experimental tests, between the main characteristics of bituminous conglomer-

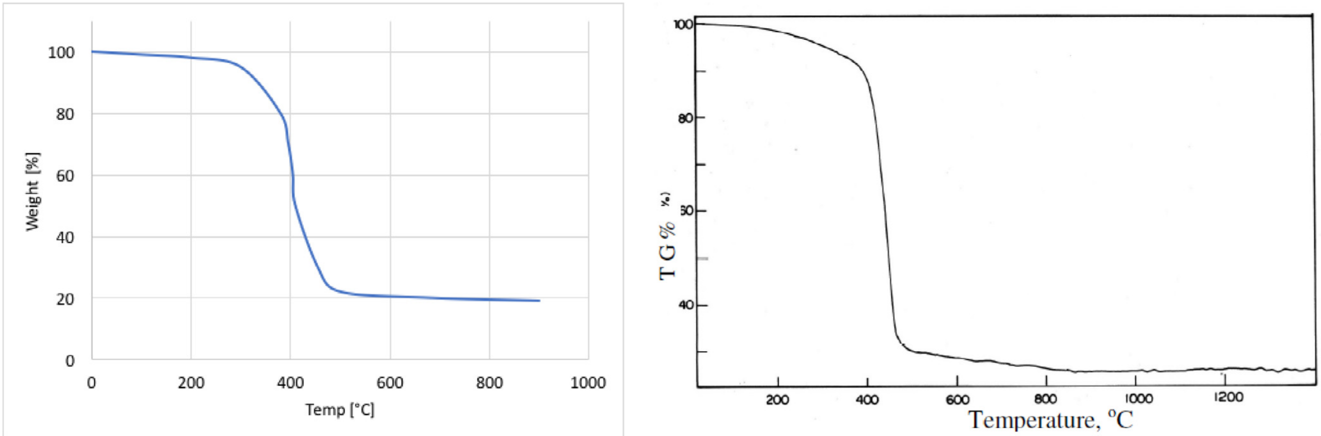

Fig. 1. TGA of textile material (right) and Nylon 6.6.

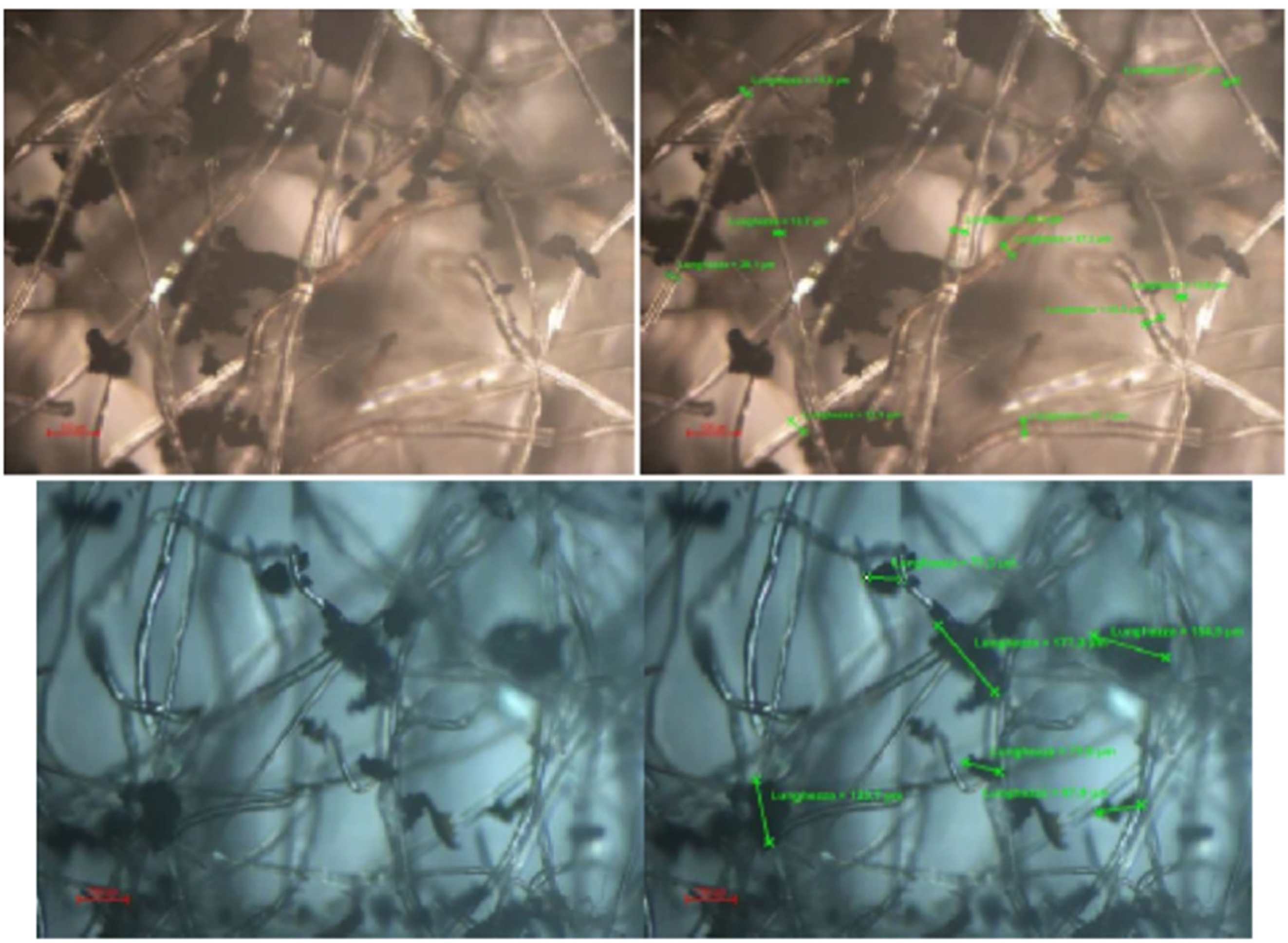

Fig. 2. Morphological analysis of the 1st (on the top) and 5th (on the bottom) sample of fibres.

ates prepared by using cellulose fibres (the standard reinforcement fibres) and ELT fibres. It is worth to notice that the indirect tensile strength values are similar for the two types of asphalt and higher than the common limit (1.35 MPa) fixed by the main tender dossier in Italy. In addition, the presence of ELT fibres determines an increase of more than 15% of the indirect tensile module as well as a relevant improvement of fatigue (i.e. number of cycles to failure).

In particular, this study involved the application in the binder (medium part of an asphalt). The binder is a polymer-modified bitumen (PMB) with a high content of polymers (hard modification) classified as PMB 45-80/60 according to EN 14023. The bitumen has a penetration ranging between 45 and 80 dmm (Class 4) and a softening point higher than 60 °C (Class 6).

In order to optimize the job mix formula, different bitumen and filler contents were investigated, starting from the typical mix

Table 3
Measured fibre diameters.

Test No	Lot 1	Lot 2	Lot 3	Lot 4	Lot 5
	Diameter [μm]	Diameter [μm]	Diameter [μm]	Diameter [μm]	Diameter [μm]
1	10.8	13.7	17.9	14.8	10.7
2	13.9	13.8	18.0	15.6	16.8
3	14.4	15.8	20.9	15.8	16.8
4	19.5	24.3	22.1	24.3	19.3
5	22.3	14.3	24.3	14.3	13.3
6	21.4	27.1	24.6	27.1	27.1
7	22.3	27.2	25.3	27.2	25.2
8	23.1	24.5	22.1	24.5	24.5
9	20.4	23.3	25.1	23.3	22.7
10	18.6	21.4	23.4	21.4	24.3

Fig. 3. Fibre before sifting (left), clean fibre (centre), and recovered rubber powder (right).

Table 4
Amount of separated rubber.

Lot no	Dirty fibre load [g]	Clean fibre load [g]	Residual rubber load [g]
1	250	99	151
2	250	102	148
3	250	101	149
4	250	105	145
5	250	118	132

design adopted by bituminous conglomerate producers. Moreover, different amounts of fibres were tested in order to finally produce a bituminous conglomerate compliant to the standard technical specifications. The volumetric and mechanical properties of each mixture were evaluated using the following procedure:

- The air void content at three different compaction levels were determined on shear gyratory compacted specimens;

Table 5
Comparison between two different types of asphalt with cellulose fibres and with ELT fibres.

	Asphalt with cellulose fibres	Asphalt with ELT fibres
Bitumen [%]	5.4	5.4
Filler [%]	6	6
Indirect tensile module [MPa]	4482	5212
Indirect Tensile Strength [MPa]	1.37	1.38
Number of cycles to failure	3085	4785

- The same specimens were tested through the indirect tension test to obtain two mechanical characteristics: the indirect tensile strength (ITS) and indirect tensile coefficient (ITC).

Table 6 presents the results of the tests performed. Depending on the amount of ELT fibres, filler, and bitumen, the air void content (drainage properties of asphalt) and drain-down loads were

Fig. 4. Comparison between cellulose fibres (left) and ELT fibres (right).

Table 6
Volumetric and mechanical properties of mix for porous wearing course.

Fibre content [%]	Filler content [% by agg.]	Total bitumen content [% by mix.]	Air void content [%]			ITS [MPa]	ITC [MPa]
			10 gyrations	120 gyrations	200 gyrations		
0	4	5.3	30.1	25.2	22.5	0.44	40
0.1	4	5.0	33.5	28.5	25.6	0.39	29
0.2	4	5.0	31.9	27.4	24.1	0.41	32
0.3	4	5.0	30.4	25.2	22.3	0.49	37
0.3	6	5.2	29.7	24.8	21.9	0.47	35
0.5	4	5.0	39.4	23.9	21.7	0.45	34
0.5	6	5.2	28.1	23.2	20.4	0.42	32
Specification limits		4.8–5.8	>28	>22	>20	0.34–0.58	>18

assessed. Comparing the second and the third mixes (respectively 0.1% and 0.2% of fibre content), it can be observed that the fibres cause an increase in air void content and a significant increase in ITS and ITC. In summary, the best performing mixture is that one containing 0.3% of fibres, 5.2% of bitumen (4.2% of virgin bitumen), and 2% of filler.

3. ELT fibre cleaning and preparation before reuse

Currently, the most widespread ELT disposal process consists of three main steps which results in the complete grinding of the tyres (Fig. 5):

- The first step is the production of ground particles of approximately 7–10 cm accompanied by the removal of the metallic fraction. The equipment is a double shaft grinder using single knife elements. Other inputs to the sub-system are electricity, water, and oil.
- The second step is further grinding to a size of approximately 2 cm. The equipment is made of a fixed external cylinder equipped with blades, and a rotating internal cylinder also equipped with blades. These components allow crunching of the inlet material. Electrical power is required to drive the equipment. A suction system equipped with fabric filters is also provided to remove the dust produced during the grinding phases. In order to move the materials from one step to the other, conveyor belts are provided and magnetic belts are used for scrap iron separation.
- The third step is the pulverization and separation of the tyre material to a size smaller than 1 mm, which takes place in a machinery with a fixed and a rotating disk equipped with blades. A pneumatic transport system, equipped with a fan and cyclone, is also used for material movement.

The textile fibre commonly extracted from the existing process (not clean textile fibres) has approximately 60% by weight of rubber residuals (see Table 4 in Section 2). The innovation proposed in

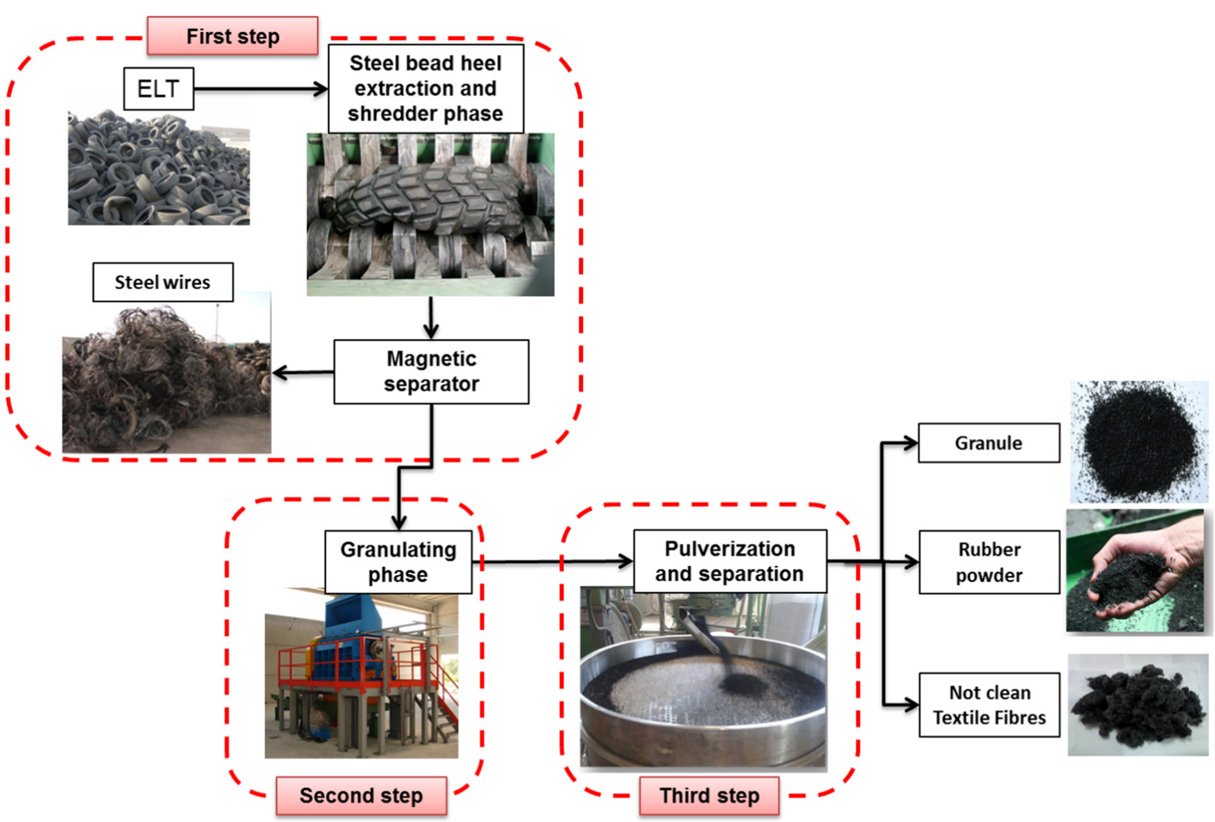

Fig. 5. Existing ELT disposal process.

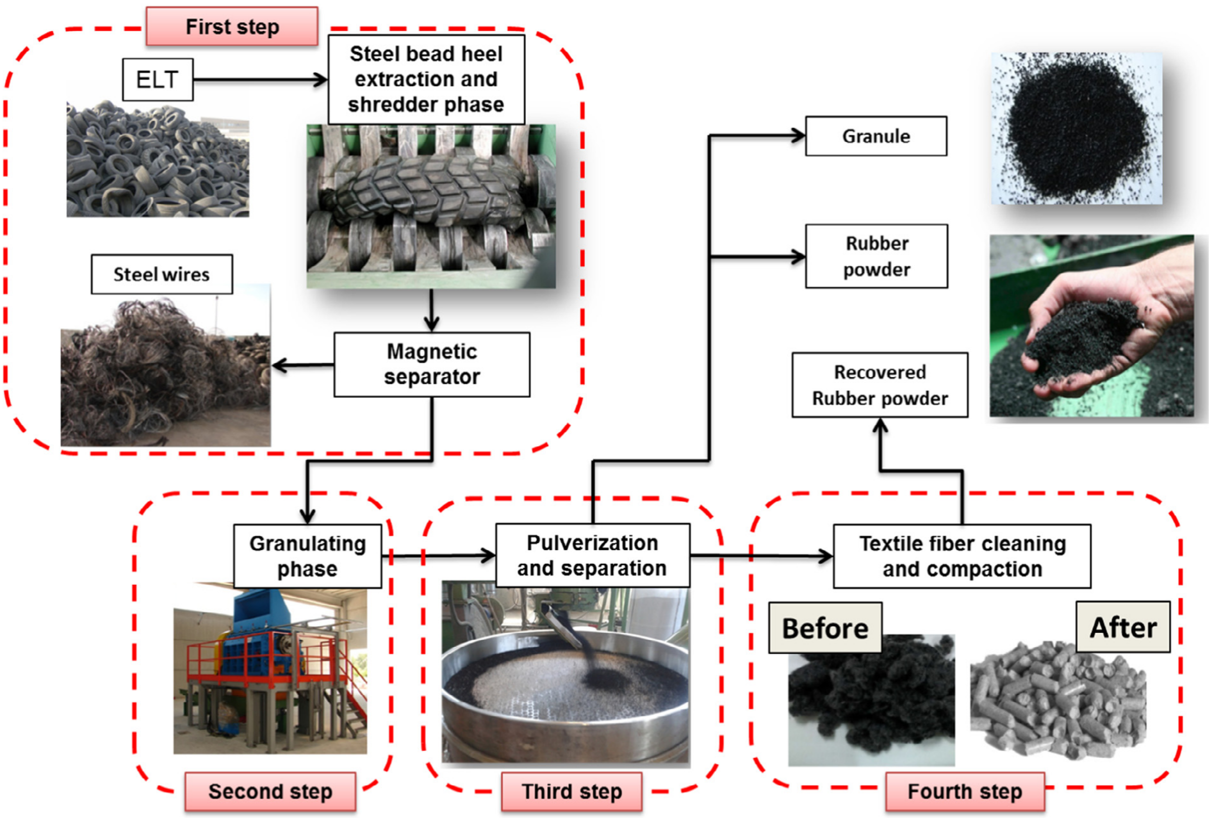

Fig. 6. Proposed ELT disposal process.

this study involves cleaning the fibrous material and its subsequent reuse in the asphalt industry. A fibre cleaning and compaction process has been developed and integrated into the ELT disposal process. In addition to the cleaning phase, a fibre compacting process (Fourth step) is required to facilitate transport and dosage during the standard bitumen production. Fig. 6 shows the proposed process.

The cleaning phase is performed using a 'dry washing machine'. It is made up of a drum of 1000 mm diameter and length of 4000 mm on which is inserted a reel (helicoid) that allows forward movement through its rotational motion. The rotational motion is generated by a moto-variator, which, applied on one of the four drive wheels, generates swirling motion within the drum. The principle of operation is to whip the textile fibres by means of fixed pockets set within the drum. This generates a gravitational drop during rotational motion.

During this phase within the drum, the separation of the granular rubber parts is obtained through a double stacking net positioned outside of the drum. The double sliding net is composed of two different nets: the first one with 6 mm hole diameter and the second one with 10 mm hole diameter. This double filter prevents mixing of the fibre with the residual rubber powder.

The developed fibre cleaning machine (see the 3D model in Fig. 7) has a production rate of 600–1200 tonnes/year and an hourly working rate of approximately 165 kg/h.

The subsequent fibre compaction phase is performed through another dedicated machine and additives are required to maintain the process temperature below the melting temperature of Nylon 6.6 (259 °C). The designed and manufactured pellet production machine (Fig. 8) has a nominal power of approximately 100 kW and it is able to guarantee a compaction ratio of approximately 1:10. The machine operates with a vertical system where the pressure is applied vertically on a grid through the rotation of two cylinders around the main axis.

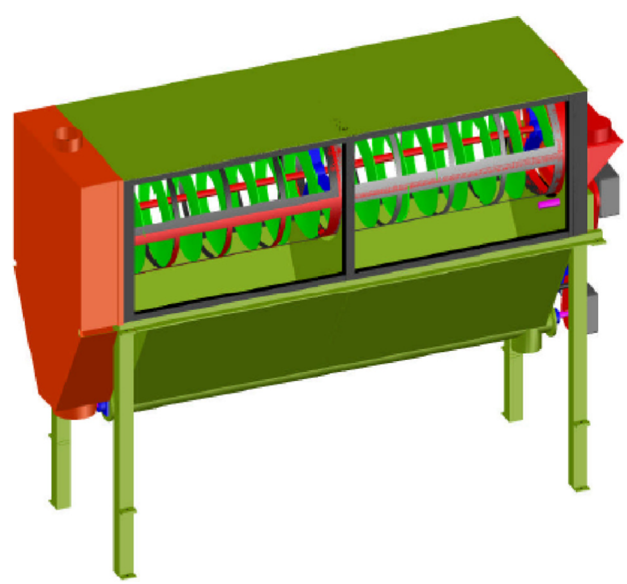

Fig. 7. Fibre cleaning machine.

Different tests on the pellet production machine were carried out in order to determine the correct working parameters, speeds, operating pressures, and amount of paraffin wax. The results obtained are as follows:

- The operating temperature, regardless of grid height, remains limited within 100 °C; thus, it does not deteriorate the material, which is always 'flaky'.
- The quality of the pellet, measured as its compaction and confinement, is better when the loading speeds, and therefore, the grid height, are lower.

Fig. 8. Machine for pellet production.

- The fibre, without the paraffin wax, is difficult to reuse in asphalts because its compaction is poor.
- The addition of fillers and/or oils does not improve the pellet quality.

Fig. 9 shows the differences between the fibre pellet obtained with and without paraffin wax. It is noted that the use of paraffin wax allows a better fibre compaction (the density is increased by approximately 10 times) that makes the product usable in the current asphalt production process. The optimal amount of paraffin wax, identified through experimental tests, is equal to 10% by weight of fibres.

The pellets are subsequently stored in large bags and sent to the bituminous conglomerate producer. The fibre can be used in the production process of bituminous conglomerates by loading it into the mixing chambers through the standard hoppers.

As for the production of bituminous conglomerates, much of the work is carried out by means of a fully automated closed-loop system and governed by a control unit. The process of producing bituminous conglomerate comprises several stages of work mentioned below:

- Inert treatment
- Filler process
- Bitumen storage
- Mixing inert with bitumen
- Bituminous conglomerate production

The use of the ELT fibre (compacted in pellets) does not require significant modification of the production cycle of bituminous conglomerates. Only one additional machine, equipped with a rotating knife, is required to prepare the pellets for mixing with other ingredients of the bituminous conglomerates.

4. Life cycle assessment

The first analysis performed to evaluate the feasibility and convenience of the proposed treatment and recycling process for tyre textile fibres is the environmental assessment. This analysis, based on the standardized LCA methodology (ISO, 2006a,b), quantitatively evaluates the environmental impacts caused by all the process-related activities through the entire lifetime. The results obtained through this analysis, first, provide a clear indication on the environmental sustainability of the new treatment process in comparison with the baseline scenario. Second, they will be used for the CBA to evaluate the economic feasibility of the proposed process (see Section 5). The next sub-sections illustrate the first three steps of the LCA analysis: (i) goal and scope definition, to establish the objectives and the assumptions; (ii) life cycle inventory (LCI), to collect relevant data; and (iii) LCI assessment, to quantify the impacts. The last step, results interpretation, is discussed in Section 5.

4.1. Goal and scope definition

The goal of this study is to determine and compare the environmental load of the two end-of-life scenarios considered for the ELT fibrous material (see Section 3) in order to identify the best option based on quantitative indicators.

The chosen functional unit is "the amount of clean fibres produced by the involved ELT disposal company in a year which is equal to 787.5 tonnes (3.150 kg produced per day multiplied by 250 working days in a year)". This quantity has been calculated from the measured 1968 tonnes of dirty fibres produced by the company in a year and in consideration of a content of clean fibres of approximately 40% which has been estimated through the above-mentioned tests (see Table 4).

The analysis is a 'gate-to-gate' study; thus, the considered system boundaries include all the activities related to a specific life cycle phase of the textile fibre. In particular, all the processes from the cleaning of the textile fibre to its end-of-life (energy recovery for the existing scenario or reuse in bituminous conglomerates for the proposed scenario) are considered which include all the transport phases. The excluded phases are (i) secondary processing (e.g. the movements within a plant), (ii) manufacturing of the transportation vehicles, (iii) transportation losses and inefficien-

Fig. 9. Fibre pellet obtained with (left) and without (right) paraffin wax.

cies, and (iv) manufacturing of the plant and equipment for the fibre treatment. The latter assumption is justified by the fact that the entire lifetime of the plant is much longer than the period considered for the chosen functional unit (i.e. one year). Therefore, the impact of the machine construction on the global LCA analysis can be considered negligible as demonstrated in other studies on LCA of production processes and plants (Favi et al., 2016).

The following assumptions have been made for the data collection and analysis:

- Based on the Italian average scenario (Giannouli et al., 2007), Euro 5 diesel vehicles have been chosen for all the transportation phases;
- A fully loaded vehicle of 23 tonnes has been considered for the transport of the ELT fibre to the incineration plant in Switzerland (existing scenario);
- A fully loaded vehicle of 15 tonnes has been considered for the transportation of the fibre pellets to the bituminous conglomerate producer (proposed scenario). These transportations are local; thus, a smaller vehicle has been considered;
- The 2012 Italian energy mix included in the software database used (i.e. SimaPro) has been used. According to a recent academic paper, this energy mix can still be considered valid (Cucchiella et al., 2017);
- The volume reduction ratio of the compaction phase is equal to 10;
- An annual operation of 2000 h has been considered for the compaction machine;
- A consumption of 50 kg of pellets for a production cycle of bituminous conglomerate (10 s) has been assumed.

Regarding the cut-off, all processes with an impact on the total energy consumption that is lower than 1% have been neglected.

4.2. Life cycle inventory

The LCI mainly consists of decomposing the full life cycle into elementary steps and carrying out an input–output analysis (i.e. identification of input and output flows). Data can be primary if they are directly collected through measurements, interviews, etc., or secondary, if they are retrieved from studies, standard databases, etc. In this study, the primary data include:

- Data related to the fibre treatment, and pellet production and transport which have been collected by measuring the parameters of the equipment.
- Data related to the bituminous conglomerate production, which have been collected by interviewing the key managers of the involved company.

Secondary data comprise the following items:

- Electricity supply and generation: a customized electricity production mix has been developed using the data on different sources given by the Energy Market Regulatory Authorities (AEEG, 2015) and considering the electricity transportation efficiency included in the Ecoinvent 3.1 database (Ecoinvent, 2014).
- Incineration: this phase has been essentially modelled based on the incineration processes included in the Ecoinvent 3.1 database. Considering that a specific dataset for Nylon 6.6 incineration process was not available, the dataset relative to plastic mixture incineration in Switzerland has been considered and suitably customized. This dataset includes waste-specific air and water emissions from incineration, auxiliary material consumption for flue gas cleaning, short-term emissions to river water, long-term emissions to ground water from slag compartment (from bottom slag), and residual material landfill (from solidified fly ashes and scrubber sludge). A lower (net) heating value of 31.6 MJ/kg (Walters et al., 2000) has been considered, instead of the original 30.79 MJ/kg, to correct the net electric and thermal energy production (considered as avoided impacts in the present LCA study, according to the system expansion allocation procedure). The other parameters (e.g. emissions) have been maintained unchanged, owing to the unavailability of more specific primary data.
- Wax paraffin: the impact related to wax paraffin production has been taken from the Ecoinvent 3.1 database.
- "Big bag": the impact related to the polypropylene (PP) used to produce the "big bag" has been taken from the Ecoinvent 3.1 database

Table 7 lists the data used for the LCA including their sources.

4.3. Life cycle impact assessment

The third stage involves quantification of the environmental impacts related to each process and flow considered through the use of characterization factors that 'transform' the inventory data to environmental indicators. In this study, the CML 2001 (updated in April 2015) impact assessment method has been chosen (Guinée et al., 2002). This methodology includes several impact categories, consistent with the objectives of this study, which enable

Table 7
Inventory data.

Scenario	Description	Value	Source
All	Clean fibre	787.5 tonnes	Primary
Existing scenario (Energy recovery)	Transport from fibre producer to incinerator (25 tonnes truck)	900 km	Primary (distance) Secondary (impact of operation)
Proposed scenario (Reuse)	Transport from fibre producer to bituminous conglomerate producer (15 tonnes truck)	300 km	Primary (distance) Secondary (impact of operation)
	Energy consumption of pellet processing machine	20,000 kWh	Primary (quantity) Literature (energy mix)
	Energy consumption of hopper	10 kWh	Primary (quantity) Literature (energy mix)
	Energy consumption of shredder	42 kWh	Primary (quantity) Literature (energy mix)
	PP for "big bag" production	340 kg	Primary (quantity) Secondary (impact of material)
	Wax paraffin (10% clean fibre)	78.75 tonnes	Primary (quantity) Secondary (impact of material)
	Avoided cellulose consumption	787.5 tonnes	Primary (quantity)

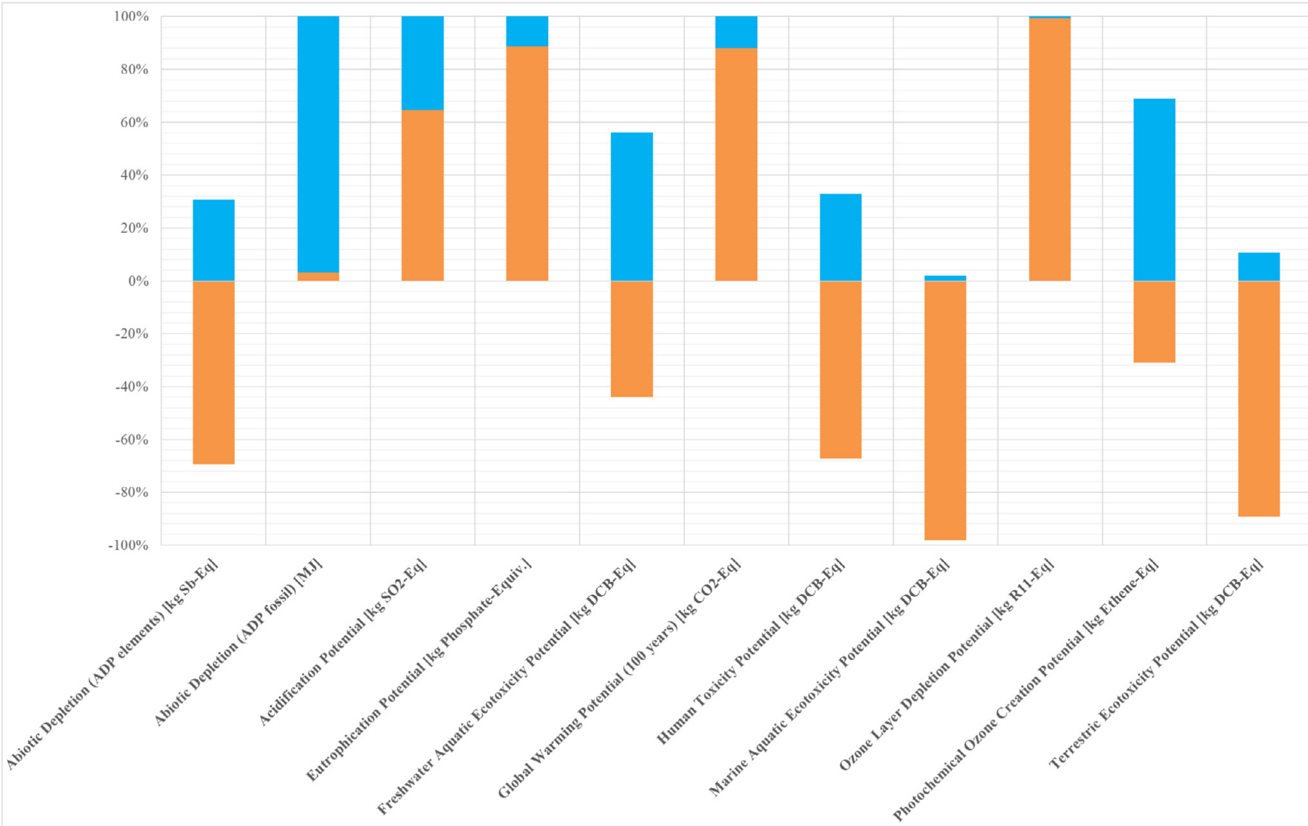

Fig. 10. Characterized environmental impacts (CML 2001 method).

Table 8
Characterized environmental impacts (CML 2001 method).

Indicator	Scenario	
	Existing	Proposed
Abiotic depletion (ADP elements) [kg Sb-Eq]	−1.56E − 01	6.86E−02
Abiotic depletion (ADP fossil) [MJ]	2.45E + 05	7.58E + 06
Acidification potential [kg SO_2-Eq]	1.67E + 03	9.15E + 02
Eutrophication potential [kg Phosphate-Equiv.]	5.52E + 02	7.11E + 01
Freshwater aquatic ecotoxicity potential [kg DCB-Eq]	−1.92E + 03	2.46E + 03
Global warming potential (100 years) [kg CO_2-Eq]	1.76E + 06	2.40E + 05
Human toxicity potential [kg DCB-Eq]	−4.75E + 04	2.31E + 04
Marine aquatic ecotoxicity potential [kg DCB-Eq]	−6.83E + 08	1.34E + 07
Ozone layer depletion potential [kg R11-Eq]	3.33E − 03	2.60E−05
Photochemical ozone creation potential [kg Ethene-Eq]	−4.34E + 01	9.67E + 01
Terrestric ecotoxicity potential [kg DCB-Eq]	−2.25E + 03	2.72E + 02

assessment of the environmental impacts in terms of air and water pollution, resource depletion, soil occupation, toxicity, etc.

Fig. 10 and Table 8 show the results calculated for both scenarios, considering all the impact categories included in the CML methodology. As expected, depending on the impact category considered, the end-of-life option with lesser impact can vary. As in most LCA studies, it is difficult to univocally establish the best scenario. Further considerations on the LCA results interpretation are included in the dedicated Section 6.1.

Table 9
Costs associated to fibre cleaning, compaction, and packaging and production of bituminous conglomerate.

Costs for fibre cleaning process	
Machinery (initial investment)	€200,000
Building	Negligible
Energy	Machine consumption: 160 kWh (18 cent/kWh)
Personnel	0.1 person/h (€14/h)
Maintenance (average)	€1000/year
Transport and disposal of the fibre	€80/tonne
Direct tax rate	44.5%
Costs for compaction and packing process of textile fibre	
Machinery (initial investment)	€600,000
Building	Negligible
Energy	Machine consumption: 100 kW/h (18 cent/kWh),2000 h /year
Personnel	0.1 person/h (€14/h)
Maintenance (average)	€31,500/year
Paraffin wax	€500/tonne (quantity: 10% of the fibre)
Pellets	906 tonnes/year
"Big bag"	€8 each (capacity: 1 m^3; a large bag contains 1.5 tonnes of pellets)
Costs for production of bituminous conglomerate	
Machineries (initial investment)	€2000
Building	Negligible
Energy	5000 kW/year (18 cent/kWh)
Personnel	3 h/day (€14/h)
Maintenance	Negligible
Cost for transport	
Journey cost (25 tonnes load capacity)	€48,100 (€1300 per journey)

5. Cost–benefit analysis

The second analysis performed to evaluate the economic feasibility of the proposed treatment and recycling process for tyre textile fibres is the cost–benefit analysis (CBA), defined by Kelman (1981) as simply the systematic thinking about decision-making. The present study is based on the standardized CBA methodology according to the European Commission guidelines (European Commission, 2014).

The primary objective of a CBA is to determine whether the benefits of a project, policy, or decision outweigh its costs and by how much relative to other alternatives. The CBA process requires the decision-maker to consider or identify all the related costs and benefits of a project, policy, or decision, including potential impacts on human lives and the environment (Pearce et al., 2006).

In order to perform the CBA, preliminary choices have been made. The reference period considered in the analysis is 30 years in order to evaluate the environmental and economic effects during the system implementation as well as its outcomes after the implementation. In accordance with the case study on waste management presented by the European Commission in its 'Guide to Cost–Benefit Analysis of Investment Projects', the residual value is set as zero because it is assumed that at the end of the reference period, the plant and machines will have provided nearly all their potential, and hence, the market value will be negligible (European Commission, 2014). The choice of a correct social discount rate (SDR) is very important. Percoco (2007) estimated a social discount rate for Italy and found that a 3.7–3.8% rate would be appropriate. For the programming period 2014–2020, the European Commission recommends that 'for the social discount rate, 5% is used for major projects in cohesion countries and 3% for the other member states' (European Commission, 2014). Owing to the lack of an updated value, two alternative discount rates, i.e. 4% and 3%, have been used to discount costs and benefits.

5.1. Financial analysis

Tables 9 and 10 present the cost and revenue items related to the introduction of the proposed process.

Because the ELT fibre is no longer incinerated, the cost for disposal becomes nil, while 337.5 tonnes of recovered rubber powder is sold. In particular, the amount saved is equal to 787.5 tonnes × €80 = €63,000 while the revenue is 337.5 tonnes × €350 = €118,125. The building, which was already owned by the involved ELT disposal company, covers a total area of 2200 m^2; the machinery for cleaning occupies approximately 5 m^2, or only 0.23% of the total. The opportunity cost of the building is set as zero.

As with the cleaning of the fibres, the cost of the building is neglected even for the compaction and packing phase. The machinery for cleaning occupies approximately 16 m^2, or 0.72% of the total. The opportunity cost of the building is set as zero.

Table 10
Benefits associated to fibre cleaning, compaction, and packing and production of bituminous conglomerate.

Benefits of fibre cleaning process	
Savings (due to non-disposal of fibre)	787.5 tonnes/year (€80/tonne)
Sale of rubber powder	337.5 tonnes/year (€350/tonne)
Benefit of production of bituminous conglomerate	
Savings (due to the reduced price for the acquisition of the fibre)	€300/tonne
Benefit for transport	
Savings (due to non-disposal of the fibre)	787 tonnes/year (€80/tonne)

As described in Section 2, the fibres from ELT can replace cellulose fibres. It is necessary to add 3 kg of fibre for each tonne of bitumen; thus, each year 906 tonnes of pellets are produced and each year an amount of 250,732 tonnes of bitumen is realized which can be used to asphalt approximately 300 km of a motorway.

According to the EC Guidelines, 'operating cost savings generated by the operation shall be treated as net revenue'. Because ELT fibres are less costly than cellulous fibres (€600 rather than €900), such price difference has been considered as an operating cost saving.

It is noteworthy to mention that after the performance of these activities, bitumen is sold as usual; therefore, this revenue is not considered in the CBA.

As with the previous activities, the building cost was considered negligible because the machinery for shredding occupies approximately 8 m^2, or only 0.12% of the total. Considering the simplicity of the machine (a rotating knife), the maintenance cost has been neglected because the machine does not provide for programmed maintenance.

Regarding the replacement costs, both in the financial and economic analyses, the following replacements have been considered:

- Cleaning machinery (lifetime: 10 years): replacements will occur in the 10th and 20th year.
- Machines for the production of pellets and conglomerates (lifetime: 15 years): replacement occurs in the 15th year and the residual value is estimated as almost zero.

Replacements costs are equal to the value of the initial investments, however, it is assumed that the new machines will consume 10% less energy than the former ones. Because one of EU's 2020 target is to achieve a 20% increase in energy efficiency and the first machine replacement will occur in 2028, it is considered that energy consumption will decrease by 10%, owing to the increased efficiency (10% is a conservative estimate).

Regarding the energy costs, the same value for all the years is considered, avoiding any estimation on possible modifications as 'the financial analysis should usually be carried out in constant (real) prices, i.e. with prices fixed at a base year. The use of current (nominal) prices (i.e. prices adjusted by the consumer price index or CPI) would involve a forecast of CPI that does not seem always necessary' (European Commission, 2014).

5.2. Economic analysis

The financial costs of the project are used as bases to estimate its economic costs. As the CBA methodology includes monetization of intangible items, it is intrinsically subject to assumptions and discretions. Nevertheless, it is essential to include these items to take into account the benefits that are derived from the project (Senaratne et al., 2015).

The economic and environmental benefits presented in Table 11 have been monetized in the economic analysis.

The benefits indicated in Table 11 are derived from both the cleaning of the fibrous material and from the reuse of the fibre as a secondary raw material. In particular, the economic value of

Table 11
Monetization of project benefits.

Cost savings	Value (€)
Economic value of recovered material	118,125.0
Avoided cost for fibre disposal	63,000.0
Avoided cost for acquisition of fibre	268,970.0
Avoided CO_2eq emissions through non-production of cellulose	10,200
Avoided CO_2eq emissions through fibre reuse	51,805.12
Avoided SO_2eq emissions through fibre reuse	7,408.8

the recovered material (rubber powder) is based on the price paid on the local market (given that the trade market for rubber powder is efficient in the Italian market). In addition, fibre reuse avoids disposal costs. By analysing the scenario of reinforced asphalt production, it is possible to observe a reduction in costs equal to the difference between the cost of natural cellulose (currently used) and the market cost of the ELT-based pellets.

Through the LCA analysis, the environmental performance was measured in terms of different indicators. However, for the economic analysis, only the environmental aspects that have been evaluated economically by the European Commission and the European Investment Bank have been included. From the LCA analysis, the avoided production of cellulose fibres is approximately 300 tonnes of CO_2eq per year in terms of global warming potential (GWP). The unitary economic value per tonne of the avoided CO_2eq emissions is based on the calculations illustrated by the European Investment Bank: 'it consists of a central estimate for the damage associated with an emission in 2010 of EU25 per tonne of CO_2eq. Reflecting a common finding that the marginal damage of emissions increases as a function of the atmospheric concentration of carbon, annual 'adders' are applied after 2010, i.e. an absolute increase in value per year (measured in constant 2006 prices)' (European Investment Bank, 2013).

Regarding acidification potential (AP), the reuse of ELT fibre avoids 0.759 tonnes of SO_2 emissions per year. According to the CAFÉ CBA report, the SO_2 damage per tonne of emission in 2010 is equal to €9800 (taking an approximate average across the EU15, i.e. excluding all the countries that acquired the EU membership after 1995 plus Luxembourg) (Holland et al., 2005). As it is generally considered that emissions in future years will have a greater impact than current emissions (European Commission, 2014), the cost of SO_2 emissions might be underestimated (as the above-mentioned value refers to 2010). However, this is the most recent estimate presented in an official EC study.

After performing the financial and the economic analysis, a crucial operation is the discount of costs and benefits, using the SDR. Once costs and benefits have been discounted, the project economic performance is measured by the economic net present value (ENPV), economic rate of return (ERR) and benefit/cost ratio (B/C ratio). ENPV is the difference between the discounted total social benefits and costs and is calculated through the following Eq. (1):

$$ENPV = PV(B) - PV(C) \tag{1}$$

where $PV(B)$ refers to the present value of economic benefits, $PV(C)$ refers to the present value of economic costs with present values calculated at the social discount rate (Pearce et al., 2006).

ERR is calculated solving the following Eq. (2):

$$B_0 - C_0 + \frac{B_1 - C_1}{(1+i)} + \frac{B_2 - C_2}{(1+i)^2} + \ldots + \frac{B_T - C_T}{(1+i)^T} = 0 \tag{2}$$

where i is the ERR, namely the discount rate that solves the equation.

Finally, B/C ratio is the ratio between discounted economic benefits and costs and is calculated according to the following Eq. (3):

$$B/C = \frac{PV(B)}{PV(C)} \tag{3}$$

6. Results discussion

This section presents the discussion and interpretation of the results obtained from the LCA and CBA. Here, we evaluate if the proposed treatment and recycling technology and scenario can improve the environmental performance of the involved companies and can be considered as good business opportunities. In particular, four main aspects are considered:

- Environmental sustainability measured in terms of GWP and AP which are the indicators that are also used in the CBA analysis;
- Financial sustainability which consists essentially of measuring the inflows against outflows in order to establish if 'the risk of running out of cash in the future is expected to be nil' (European Commission, 2014);
- Economic performance evaluated in terms of the expected ENPV and ERR;
- Risk analysis.

6.1. Environmental sustainability

The comparison between the considered scenarios (see Fig. 10 and Table 8) shows that the proposed reuse scenario is more environmentally sustainable according to only four impact categories: Acidification Potential, Eutrophication Potential, Global Warming Potential and Ozone Layer Depletion Potential. Considering the other seven impact categories (e.g. toxicity indicators), instead, an increase in the environmental impact is observed. Generally, the deterioration of the environmental performances of the proposed scenario is mainly due to the additional processes needed to prepare the fibre pellets. The high consumption of paraffin wax and electric energy during the compaction phase is certainly the main reason. Furthermore, it is necessary to take into account the avoided benefits related to the generation of electricity and heat, which are outputs of the incineration process.

However, according to the CBA methodology, the impact categories to be considered in the economic and financial analyses are the GWP and the AP. Considering the GWP impact category, the results show that a relevant saving can be obtained by choosing a closed-loop end-of-life for ELT fibres. The total impacts are reduced from 1.76E + 06 kg CO_2eq of the existing scenario to 2.40E + 05 kg CO_2eq of the proposed scenario (see Table 8). Going into more details of the different processes (Fig. 11), for the existing scenario, the most relevant contribution (approximately 90%) is from the fibre incineration. This negative impact is only partially compensated by the environmental benefits owing to the avoided consumption of fossil fuels for energy generation (system expansion modelling has been used). Regarding the proposed scenario, the global impact mainly depends on the pellet production. The paraffin wax, used to produce pellets from the fibrous materials and the energy consumed by the equipment represent the main contribution for the reuse scenario in terms of GWP.

The same considerations can be approximately derived from the results obtained considering the AP impact category (Fig. 12). In this case, the difference between the two scenarios is lower (1.67E + 03 kg SO_2eq versus 9.15E + 02 kg SO_2eq) and then a reduced environmental benefit can be attained with the implementation of the proposed scenario (−45%).

6.2. Financial sustainability

Analysing the costs of the project, the most significant ones are related to the installation of the necessary equipment (initial costs), bitumen and wax (purchase costs), and plant end-of-life (disposal cost). This leads to a negative net cash flow in the first year while this indicator becomes positive in all the succeeding years, except in the 15th year when important maintenance activities and replacement of equipment are required (Fig. 13). However, the initial investment costs are fully covered by the EU funds and private equity which are the sources of financing for this case study.

Considering the cumulative generated cash flow, which is expected to be positive or zero throughout all the reference periods, the results obtained are not fully satisfactory in the short term. This indicator becomes positive in the 5th year, which only guarantees medium and long-term financial sustainability (Fig. 14).

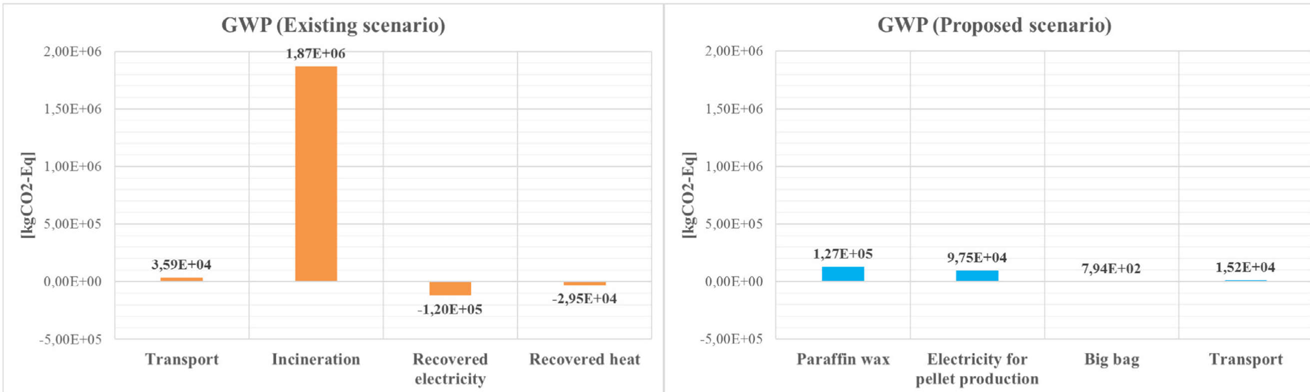

Fig. 11. Detailed comparison between the existing and proposed scenarios in terms of GWP.

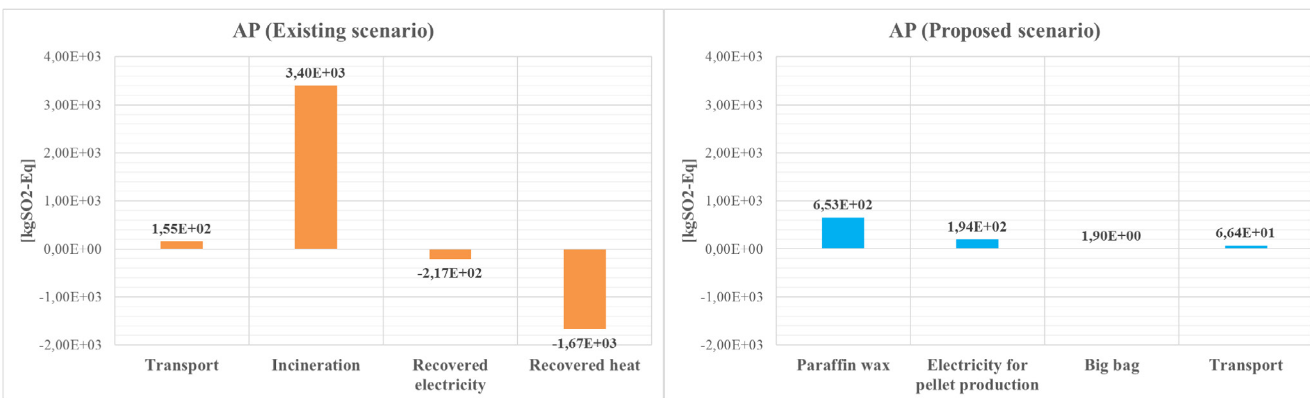

Fig. 12. Detailed comparison between the existing and proposed scenarios in terms of AP.

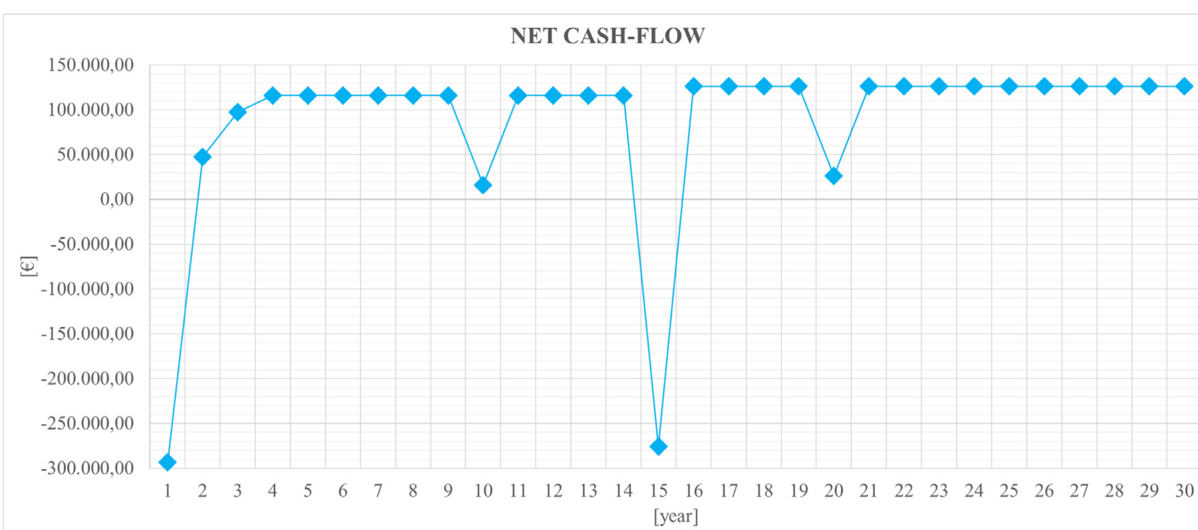

Fig. 13. Trend of the net cash flow over the considered period (30 years).

6.3. Economic performance

Regarding the economic annual benefits, the most important contributions are the following:

- Achieved valorisation of rubber powder recovered by cleaning the textile fibres which contributes €118,125;
- Avoided purchase of cellulose fibre owing to substitution with ELT textile fibre pellets which contributes €268,970;
- Avoided CO_2eq and SO_2eq emissions (respectively −1.52E + 06 kg CO_2eq and −7.59E + 02 kg SO_2eq as calculated with the LCA study) which contribute €51,805 in 2019 and increases every year.

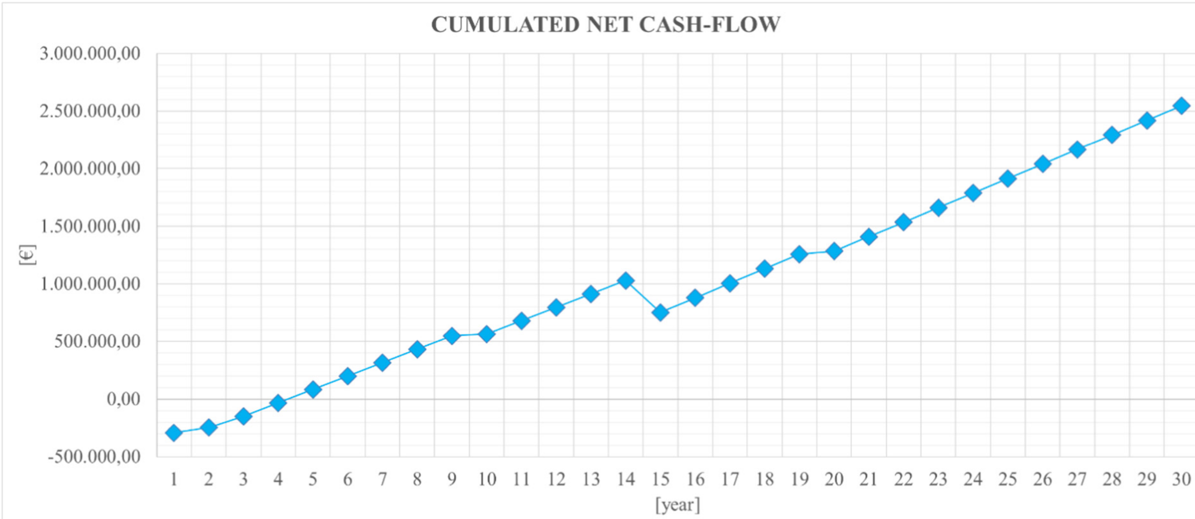

Fig. 14. Trend of the cumulative generated cash flow over the considered period (30 years).

Table 12
Economic performance indicators.

Discount rate [%]	ENPV [€]	B/C ratio [dimensionless]
3	3,330,902.02	1.52
4	3,892,842.92	1.55

As explained in Section 5, two different discount rates have been considered for the analyses: 3% and 4%. Table 12 presents the results related to the ENPV and B/C ratio obtained in both cases.

Considering that the ENPV is generally used as a single value indicator to evaluate benefits and costs this project should be considered as economically feasible, because the calculated value is largely positive in the period of observation. In addition, the B/C ratio results confirm that for both scenarios €1.00 of costs correspond to more than €1.50 of benefits.

Another significant economic indicator is the ERR, which in the present case study is equal to 30.21%. Even if it is controversial and some authors suggest using it with caution (Kelleher and Mac Cormack, 2004), the ERR is normally used to assess project profitability by comparing the obtained results with the social discount rate. In this case, the obtained value is significantly higher than the chosen discount rates which means that the project is economically viable and justified.

6.4. Risk analysis

A risk analysis has been conducted to identify the critical variables and their impact on the project performance as well as to list possible risks and mitigation strategies (European Commission, 2014).

6.4.1. Sensitivity analysis

The identification of critical project variables (i.e. parameters that significantly influence the economic performance) has been achieved by conducting a sensitivity analysis. First, the value of

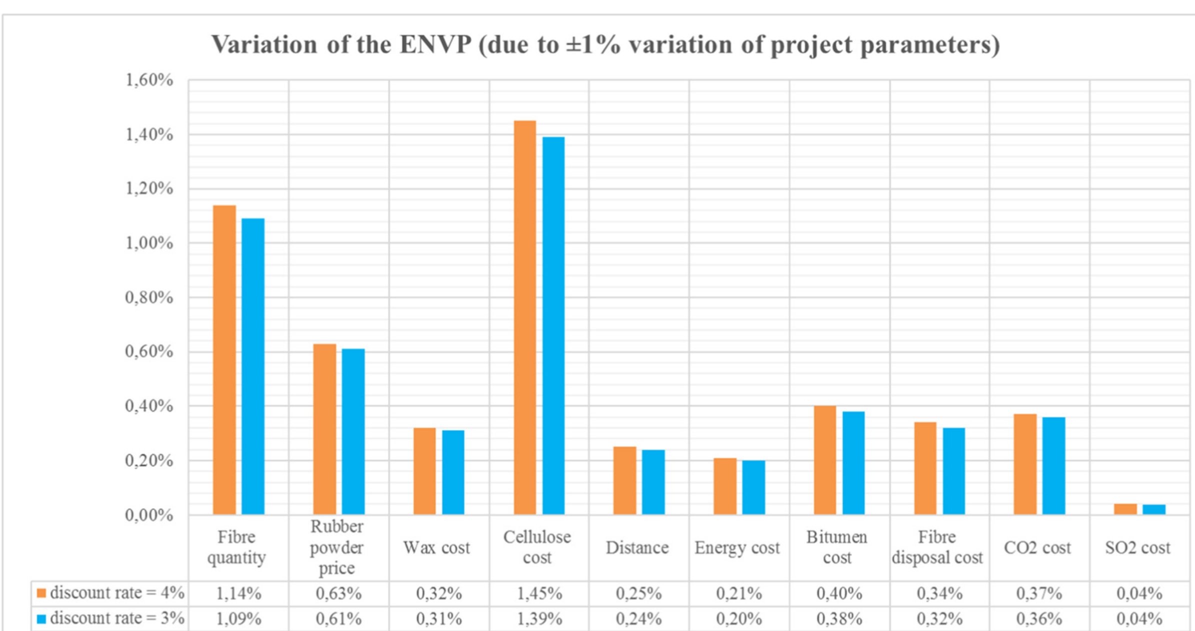

Fig. 15. Results of the sensitivity analysis in terms of ENPV variation [%].

Table 13
Switching values.

Variable	Switching value (4% discount rate)	Switching value (3% discount rate)
Fibre quantity	−87.7%	−91.2%
Wax cost	+314.6%	+328.1%
Cellulose cost	−68.8%	−71.7%
Distance from recycler to bituminous conglomerate producer	+393.6%	+409.6%
Energy cost	+465.1%	+488.8%
Bitumen cost	+246.6%	+256.6%

each relevant parameter has been varied in the range of ±1% while keeping the other parameter values fixed, in order to observe the effects on the ENPV. Second, the switching value (i.e. the value that causes ENPV zeroing) for each variable has been calculated. The results of these analyses are presented in Fig. 15 and Table 13.

Generally, a variable is considered critical if a variation of ±1% of its value leads to a variation of more than 1% of the ENPV. By considering this hypothesis, from the results shown in Fig. 15, it is possible to conclude that only the fibre quantity and the cellulose cost are the potential critical variables while the variations of the other parameters (e.g. CO_2 or SO_2 costs) have a very low impact on the economic performance. In particular, the availability of sufficient quantities of fibre from ELT is a critical factor to guarantee the return of investments required to implement the proposed recycling technology.

Another relevant outcome is the limited influence of the discount rate used to calculate the ENPV. The differences between the results obtained with 3% and 4% discount rates are very similar which means that the social discount rate does not constitute a critical variable for this analysis.

Concerning the switching values, they are the key indicators to evaluate if the project should be considered highly risky. The obtained results, calculated for all the considered variables (the switching values have not been calculated for variables that become 0 before the ENPV zeroing), confirm that the implementation of the proposed technology and end-of-life scenario is a low risk project because the variable values have to be varied considerably to make the ENPV null or negative (Table 13). Considering the two identified critical variables, a decrease of more than 68% of the cellulose cost and a decrease of approximately 90% of the fibre quantity are required to zero the ENPV. For the other non-critical project parameters, the required variations are obviously even greater.

In order to further investigate the sensitivity, a scenario analysis has been carried out to evaluate the joint effects of the different variables. An acceptable and realistic range of values in which each parameter can vary has been established based on literature data (see details in Table 14). By successively choosing the extreme values of each range, the following scenarios have been defined:

- Optimistic scenario which considers the extreme values (lower or upper) that represent the most favourable condition (e.g. maximum availability of material and maximum benefits);
- Pessimistic scenario which considers the extreme values (lower or upper) that represent the most disadvantageous condition (e.g. maximum costs).

The parameters used and results obtained with the scenario analysis are presented in Table 14.

Given that the social discount rate does not represent a critical variable that causes a relevant variation in the final economic performance, Table 14 only presents the results calculated by considering a value of 4% for the discount rate (results with 3% are very similar). Considering the pessimistic scenario, the maximum loss is only €467,631.22 which is much lower compared to the effective ENPV (€3,892,842.92) calculated for the real scenario. However, in the optimistic scenario, the calculated ENPV is more than €18,000,000 which means that the project is not very risky because only moderate losses are possible while the potential revenues are very high.

6.4.2. Risks

The last phase of the risk analysis concerns the classification of risks in order to identify and weigh the possible causes of failure and set mitigation measures to reduce the risk impacts. The risk matrix is based on the EC guidelines (European Commission, 2014) which suggest using the following classification rules:

- Risk category - to classify the risks based on the following typologies: (i) regulatory, (ii) demand side, (iii) administrative, (iv) construction, (v) operational, and (vi) others;
- Risk description - to explain the risk;
- Risk probability - to indicate the probability of occurrence of the risk. The following ranges are used: A for 0–10% probability, B for 10–33%, C for 33–66%, and D for 66–100%;

Table 14
Scenario analysis.

		Real scenario	Optimistic scenario	Pessimistic scenario	Source of data
Variable	**Fibre quantity [tonnes]**	787.50	4,000.00	0	Range calculated based on statistics of the Italian market of ELT and ELT recycling plants (Ecopneus, 2013)
	Rubber powder price [€/tonne]	350.00	450.00	250.00	Range provided by the involved companies
	Wax cost [€/tonne]	500.00	450.00	550.00	Range provided by the involved companies
	Cellulose cost [€/tonne]	900.00	850.00	950.00	Range provided by the involved companies
	Distance from recycler to bituminous conglomerate producer [km]	300	100	1000	Range fixed based on the actual distances between recycler and bituminous conglomerate producer (min. value) or incineration plant (max. value)
	Energy cost [€/kWh]	0.18	0.10	0.50	Range fixed based on Italian energy price statistics (Eurostat 2016)
	Bitumen cost [€/tonne]	0.30	0.20	0.40	Range fixed based on literature data (Global Natural Bitumen Industry Market Research, 2017)
	Fibre disposal cost [€/tonne]	80.00	60.00	100.00	Range fixed based on literature data (Waste and Resources Action Programme, 2015)
ENPV (4% discount rate) [€]		**3,892,842.92**	**18,071,793.58**	**−467,631.22**	

- Risk severity - to classify the extent of damage caused by the risk. The following categories are used: IV for very high severity, III for high severity, II for marginal, and I for negligible;
- Risk level which results from the combination of risk probability and risk severity;
- Risk prevention/mitigation measures - to describe the actions and strategies for preventing the risk occurrence or reducing the impacts related to the risk;
- Residual risk - to measure the risk level after the application of the listed prevention/mitigation measures.

Most of the identified risks for all the considered categories have a very low or low probability of occurrence (A or B categories) which confirms that the project is not highly risky as shown in the economic performance evaluation.

Generally, all the risks have a low level; thus, no specific issues are foreseen for the future implementation of the recycling technology. In addition, the prevention/mitigation strategies lead to significant reductions in the risk level. This is the reason that the probabilistic risk analysis, suggested by the EC guidelines in cases where the risk exposure is still significant after the implementation of mitigation strategies, has not been carried out. The only risk classified as high level is the possibility of lower available quantity of ELT fibre to be treated in the future (a critical variable already identified in the sensitivity analysis). However, the impacts of this potentially serious risk are reduced with the proposed mitigation strategy; thus, the residual risk is only moderate.

Further details of the risk analysis are presented in the table included in Appendix A.

7. Conclusions

Even though the management of used tyres has evolved considerably in Europe over the years, there is still room for improvement. Directive 2000/53/EC is aimed primarily at preventing the production of waste resulting from vehicles, including tyres (classified as CER160103), and to encourage the reuse, recycling, and other forms of recovery of components while reducing disposal and incineration. The textile fibre represents a limitation for the application of a recovery methodology because suitable technologies for fibre purification and densification as well as useful applications for its reuse, have not been identified yet.

The study aims to overcome such limitations by proposing a crucial technological add-on to existing installations as well as studying a series of solutions designed and tested to prepare the material for subsequent processing.

In this context, LCA and CBA analyses have been performed to assess the environmental and economic impacts related to two different scenarios. In particular, following the demonstration of the technical feasibility of the second life application for ELT fibres, the different processes have been analysed from an environmental point of view. The results show that there is an impact reduction, in terms of GWP and AP, in reusing ELT fibres as additive to bituminous conglomerates in comparison with the case of fibre disposal through incineration for energy recovery. The presented CBA demonstrated that in the medium and long term, the project is financially viable, while the high economic profitability (ENPV: €3,330,902.02, B/C ratio: 1.5) makes the project worthy of support from the EU and private funds. The greatest economic benefits are the economic valorisation of the rubber powder and the savings owing to non-use of cellulose fibre.

In conclusion, the proposed ELT treatment process and reuse scenario can be considered as a successful application of the circular economy principles.

Regarding further advances in ELT recycling, the next step could be to optimize the proposed reuse scenario, with particular attention on the reduction of the use of paraffin wax for fibre pellets preparation, which is the main cause of the degradation of environmental performances in several impact categories (e.g. toxicity). Another activity could be to investigate and evaluate alternative second life applications and to identify the optimal end-life-scenario for the ELT fibre to therefore ensure a lower environmental impact and the best economic performance. A more complete LCA study could be also conducted to better compare the environmental sustainability of the existing and proposed scenarios. Additional primary data should be considered in the LCI: (i) equipment and building construction, and (ii) incineration plant operation (e.g. emissions). Finally, the application of the proposed reuse scenario in different European countries could be evaluated by extending the CBA study.

Acknowledgements

This study is part of the activities carried out in the context of the ‘REFIBRE’ Project (LIFE14 ENV/IT/000160) funded by the European Union within the Life Framework Programme. Special thanks are expressed to Steca S.p.A (ELTs disposal company), Tires S.p.A (equipment producer), and Toto Costruzioni S.p.A (bituminous conglomerate producer) for the precious contribution.

Appendix A

Risk category	Risk description	Probability	Severity	Risk level	Risk prevention/mitigation measures	Residual risk
Regulatory	Changes of regulations regarding ELT treatment	A (0–10%)	IV	Low	• Advocacy activities • Dialogue with public authorities and associations incharge of elaborating directives and regulations on ELT (e.g. Ecopneus, ETRMA)	Low
	Introduction of a tax on ELT treatment	B (10–33%)	II	Low	• Consider stochastic values (i.e. probability distribution) instead of deterministic values for project parameters • Carry out stochastic analyses to identify a variation range of the economic instruments	Low
Demand side	Low ELT quantity to be treated	C (33–66%)	IV	High	• Maintain a high energy and environmental performance to be selected by trade associations in public tenders	Moderate

Appendix A (*continued*)

Risk category	Risk description	Probability	Severity	Risk level	Risk prevention/mitigation measures	Residual risk
					• Continuously monitor the environmental performance of the company	
Administrative	Missed permission for using fibre reinforced asphalts	A (0–10%)	IV	Low	• Verify authorization before the plant installation • Produce asphalts with higher mechanical and technological performance in comparison to commonly used asphalts	Low
Construction	Investment costs overrun (e.g. costs of equipment)	C (33–66%)	III	Moderate	• Compare estimated investment cost with costs of similar projects implemented in the EU • Check and update plant and equipment quotations by directly involving suppliers	Low
Operational	Operating costs overrun (e.g. energy costs and paraffin wax costs)	C (33–66%)	III	Moderate	• Compare estimated operating cost with costs of similar projects implemented in the EU • Check and update plant and equipment quotations by directly involving suppliers • Check and update waste disposal costs by directly involving waste treatment companies located in the same geographical region	Low
	Low product workability (e.g. temperature increase due to fibre composition change)	A (0–10%)	III	Low	• Increase the equipment cycle time	Low
	Poor technical performance of the modified asphalts (e.g. fatigue strengths, stress resistance, and lifetime)	B (10–33%)	IV	Moderate	• Continuously improve and refine the laying process • Carry out tests to optimize the asphalt formulation (e.g. change composition and quantities, add additives) and verify the compatibility of the ELT fibre with the asphalt	Low
Others	Low environmental impact reduction	A (0–10%)	II	Low	• Continuously monitor the environmental performance of the company • Implement technological innovation to reduce the energy consumption and increase the efficiency • Implement Industry 4.0 technologies to monitor and improve the production • Refine the LCA calculation model • Improve the quality of data collected to compose the LCI	Low
	Problems with citizen action groups against the plant construction	B (10–33%)	III	Moderate	• Promote advertising campaigns and public events to highlight the positive environmental (e.g. reduced CO_2 emissions), economic (e.g. recovery of value from end-of-life materials), and social (e.g. job creation) impacts	Low

References

AEEG – Autorità per l'energia elettrica il gas e il sistema idrico, 2015. Relazione annuale annuale sullo stato dei servizi e sull'attività svolta. Online: <https://www.autorita.energia.it/allegati/relaz_ann/15/RAVolumeI_2015.pdf> (accessed 03.02.2017).

Aliapur, 2010. Life Cycle Assessment of 9 Recovery Methods for End-of-Life Tyres. Online: <http://www.etrma.org/uploads/Modules/Documentsmanager/aliapur_lca-reference-document-june-2010.pdf> (accessed 30.10.207).

Aoudia, K., Azem, S., Hocine, N.A., Gratton, M., Pettarin, V., Seghar, S., 2017. Recycling of waste tire rubber: microwave devulcanization and incorporation in a thermoset resin. Waste Manage. 60, 471–481.

Blessen, S., Gupta, R., Panicker, V., 2016. Recycling of waste tire rubber as aggregate in concrete: durability-related performance. J. Cleaner Prod. 112, Part 1, 504–513.

Cucchiella, F., Gastaldi, M., Trosini, M., 2017. Investments and cleaner energy production: a portfolio analysis in the Italian electricity market. J. Cleaner Prod. 142, Part 1, 121–132.

Re Depaolini, A., Bianchi, G., Fornai, D., Cardelli, A., Cardelli, C., Badalassi, M., Cardelli, C., Davoli, E., 2017. Physical and chemical characterization of representative samples of recycled rubber from end-of-life tires. Chemosphere 184, 1320–1326.

Decreto Legislativo (DL) 3 aprile 2006 n.152 - Norme in materia ambientale.

Decreto Ministeriale (DM) 11 aprile 2011 n.82 - Regolamento per la gestione degli pneumatici fuori uso.

Decreto Ministeriale (DM) 7 marzo 2012 n.44 - Decreto di nomina del Tavolo Permanente di Consultazione sulla gestione degli pneumatici a fine vita.

Ecoinvent, 2014. Ecoinvent Database 3.1 Documentation. Online: <http://www.ecoinvent.org/login-databases.html> (accessed 30.10.2017).

Ecopneus, 2013. Sustainability Report 2013. Online: <http://www.ecopneus.it/_public-file/Ecopneus%20sustainability%20Report%202013.pdf> (accessed 03.02.2017).

European Commission, 2014. Guide to Cost-Benefit Analysis of Investment Projects. Online: <http://ec.europa.eu/regional_policy/sources/docgener/studies/pdf/cba_guide.pdf> (accessed 03.02.2017).

European Commission, 2015. COM(2015) 614 final – Closing the loop – An EU action plan for the Circular Economy. Online: <http://eur-lex.europa.eu/

resource.html?uri=cellar:8a8ef5e8-99a0-11e5-b3b7-01aa75ed71a1.0012.02/DOC_1&format=PDF> (accessed 30.10.2017).

European Commission – DG Environment, 2014. Development of Guidance on Extended Producer Responsibility (EPR) – Final Report. Online: <http://ec.europa.eu/environment/waste/pdf/target_review/Guidance%20on%20EPR%20-%20Final%20Report.pdf> (accessed 30.10.2017).

European Investment Bank, 2013. The Economic Appraisal of Investment Projects at the EIB. Online: <http://www.eib.org/attachments/thematic/economic_appraisal_of_investment_projects_en.pdf> (accessed 03.02.2017).

European Parliament and Council, 2000. European Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on End of Life Vehicle. Online: <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX: 32000 L0053: EN: HTML> (accessed 03.02.2017).

European Parliament and Council, 2013. Decision No 1386/2013/EU of the European Parliament and of the Council of 20 November 2013 on a General Union Environment Action Programme to 2020 'Living well, within the limits of our planet'. Online: <http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32013D1386&from=EN> (accessed 30.10.2017).

European Tyre Rubber Manufactures Association (ERTMA), 2015. The European Tyre Industry – Our Vision for 2030. Online: <http://www.etrma.org/uploads/Modules/Documentsmanager/20150706_etrma_trifold_05-15_final_print.pdf> (accessed 31.01.2017).

European Union Road Federation (ERF), 2017. Road Statistics 2017, <http://www.erf.be/images/2017/Statistics/Road_statistics_2017.pdf> (accessed 03.02.2017).

Eurostat, 2016. Energy Price Statistics. Online: <http://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_price_statistics> (accessed 06.06.2017).

EASME – Executive Agency for SMEs, 2015. Recycling Rubber to Reduce Noise. Online: <https://ec.europa.eu/easme/en/news/recycling-rubber-reduce-noise> (accessed 03.02.2017).

Favi, C., Germani, M., Mandolini, M., Marconi, M., 2016. PLANTLCA: a lifecycle approach to map and characterize resource consumptions and environmental impacts of manufacturing plants. Procedia CIRP 48, 146–151.

Favi, C., Germani, M., Luzi, A., Mandolini, M., Marconi, M., 2017. A design for EoL approach and metrics to favour closed-loop scenarios for products. Int. J. Sustainable Eng. 10 (3), 136–146.

Fazaeli, H., Samin, Y., Pirnoun, A., Sadate, Dabiri A., 2016. Laboratory and field evaluation of the warm fiber reinforced high performance asphalt mixtures (case study Karaj – Chaloos Road). Constr. Build. Mater. 122, 273–283.

Flores Medina, N., Flores Medina, D., Hernandez-Olivares, F., Navacerrada, M.A., 2017. Mechanical and thermal properties of concrete incorporating rubber and fibres from tyre recycling. Constr. Build. Mater. 144, 563–573.

Fornai D., Sangiorgi C., Mazzotta F., Bermejo J.M., Saiz L., 2016. A new era for rubber asphalt concretes for the green public procurement in road construction. In: Proceedings of the 1st European Road Infrastructure Congress, Leeds, United Kingdom.

Giannouli, M., De Haanb, P., Kellerb, M., Samarasa, Z., 2007. Waste from road transport: development of a model to predict waste from end-of-life and operation phases of road vehicles in Europe. J. Cleaner Prod. 15 (11–12), 1169–1182.

Global Natural Bitumen Industry Market Research, 2017. Online: <http://www.marketresearchstore.com/report/global-natural-bitumen-industry-market-research-2017-133086> (accessed 06.06.2017).

Gonzalez, V., Martínez-Boza, F.J., Gallegos, C., Perez-Lepe, A., Paez, A., 2012. A study into the processing of bitumen modified with tyre crumb rubber and polymeric additives. Fuel Process. Technol. 95, 137–143.

Guinée J.B., Gorrée M., Heijungs R., Huppes G., Kleijn R., de Koning A., van Oers L., Wegener Sleeswijk A., Suh S., Udo de Haes H.A., de Bruijn H., van Duin R., Huijbregts M.A.J., 2002. Handbook on life cycle assessment. Operational guide to the ISO standards. I: LCA in perspective. IIa: Guide. IIb: Operational annex. III: Scientific background. Kluwer Academic Publishers, Dordrecht.

Hanifzadeh, M., Nabati, Z., Longka, P., Malakul, P., Apul, D., Kim, D.-S., 2017. Life cycle assessment of superheated steam drying technology as a novel cow manure management method. J. Environ. Manage. 199, 83–90.

Holland M., Pye S., Watkiss P. Droste-Franke B., Bickel P., 2005. Damages per tonne emission of PM2.5, NH3, SO2, NOx and VOCs from each EU25 Member State (excluding Cyprus) and surrounding seas. Online: <http://ec.europa.eu/environment/archives/cafe/activities/pdf/cafe_cba_externalities.pdf> (accessed 03.02.2017).

ISO 14040, 2006a. Environmental Management – Lyfe Cycle Assessment – Priciples and Framework; July Geneva, Switzerland.

ISO 14044, 2006b. Environmental Management – Life Cycle Assessment – Requirements and Guidelines; July Geneva, Switzerland.

Kelleher J., Mac Cormack J., 2004. Internal Rate of Return: A Cautionary Tale, McKinsey Quarterly. Online: <http://www.mckinsey.com/business-functions/strategy-and-corporate-finance/our-insights/internal-rate-of-return-a-cautionary-tale> (accessed 07.04.2017).

Kelman, S., 1981. Cost-benefit analysis: an ethical critique. AEI J. Gov. Soc.

Landi, D., Vitali, S., Germani, M., 2016. Environmental analysis of different end of life scenarios of tires textile fibres. Procedia CIRP 48, 508–513.

Li, G., Garrick, G., Eggers, J., Abadie, C., Stubblefield, M.A., Pang, S.-S., 2004. Waste tire fiber modified concrete. Compos. B Eng. 35 (4), 305–312.

Liang, M., Xin, X., Fan, W., Sun, H., Yao, Y., Xing, B., 2015. Viscous properties, storage stability and their relationships with microstructure of tire scrap rubber modified asphalt. Constr. Build. Mater. 74, 124–131.

Nazzal, M.D., Iqbal, Md.T., Kim, S.S., Abbas, A., Quasema, Md.T., Mogawer, W., 2017. Evaluating the mechanical properties of terminal blend tire rubber mixtures incorporating RAP. Constr. Build. Mater. 138, 427–433.

Pacheco-Torgal, F., Ding, Y., Jalali, S., 2012. Properties and durability of concrete containing polymeric wastes (tyre rubber and polyethylene terephthalate bottles): an overview. Constr. Build. Mater. 30, 714–724.

Pearce, D., Atkinson, G., Mourato, S., 2006. Cost-Benefit Analysis and the Environment. OECD Publishing.

Percoco, M., 2007. A social discount rate for Italy. Appl. Econom. Lett. 15 (1), 73–77.

Ramarad, S., Khalid, M., Ratnam, C.T., Luqman Chuah, A., Rashmi, W., 2015. Waste tire rubber in polymer blends: a review on the evolution, properties and future. Prog. Mater Sci. 72, 100–140.

Senaratne, S., Gerace, D., Mirza, O., Tam, V., Kang, W., 2015. The costs and benefits of combining recycled aggregate with steel fibres as a sustainable, structural material. J. Cleaner Prod. 112, 2318–2327.

Sienkiewicz, M., Borzędowska-Labuda, K., Zalewski, S., Janik, H., 2017. The effect of tyre rubber grinding method on the rubber-asphalt binder properties. Constr. Build. Mater. 154, 144–154.

Sofi, A., 2017. Effect of waste tyre rubber on mechanical and durability properties of concrete – a review. Ain Shams Eng. J. (in press)

Sousa, S.P.B., Ribeiro, M.C.S., Cruz, E.M., Barrera, G.M., Ferreira, A.J.M., 2017. Mechanical behaviour analysis of polyester polymer mortars reinforced with tire rubber fibres. Ciência & Tecnologia dos Materiais 29 (1), 162–166.

Torretta, V., Rada, E.C., Ragazzi, M., Trulli, E., Istrate, I.A., Cioca, L.I., 2015. Treatment and disposal of tyres: two EU approaches. A review. Waste Manage. 45, 152–160.

Van de Lindt, J.W., Carraro, J.A.H., Heyliger, P.R., Choi, C., 2008. Application and feasibility of coal fly ash and scrap tire fiber as wood wall insulation supplements in residential buildings. Resources Conserv. Recy. 52 (10), 1235–1240.

Walters, R.N., Hackett, S.M., Lyon, R.E., 2000. Heats of combustion of high temperature polymers. Fire Mater. 24, 245–252.

Waste and Resources Action Programme, 2015. Comparing the cost of alternative waste treatment options Gate Fees report 2015. Online: <http://www.wrap.org.uk/content/comparing-cost-alternative-waste-treatment-options-gate-fees–report-2015#sthash.cd8sEMfk.dpuf> (accessed 06.06.2017).

Wei Y.T., Qiu E.C., Nasdala L., 2005. Analysis of tire shoulder endurance for a heavy-duty radial tire by FEA and material characterizations. In: Proceedings of the 4th European Conference for Constitutive Models for Rubber, Stockholm, Sweden, pp. 567–570.

Wong, S.C., Sui, G.X., Yue, C.Y., Mai, Y.-W., 2002. Characterization of microstructures and toughening behavior of fiber-containing toughened nylon 6,6. J. Mater. Sci. 37 (13), 2659–2667.

WBCSD – World Business Council for Sustainable Development, 2010. End-of-Life Tires: A Framework for Effective Management Systems. Online: <http://wbcsdpublications.org/project/end-of-life-tires-a-framework-for-effective-management-systems/> (accessed 07.04.2017).

Xiong, R., Fang, J., Xu, A., Guan, B., Liu, Z., 2015. Laboratory investigation on the brucite fiber reinforced asphalt binder and asphalt concrete. Constr. Build. Mater. 83, 44–52.

Yadaw, J.S., Tiwari, S.K., 2017. Effect of waste rubber fibres on the geotechnical properties of clay stabilized with cement. Appl. Clay Sci. 149, 97–110.

Yang, Y.Y., He, L.L., 2013. Measurement and evaluation of the wearing condition of the tire tread. Appl. Mech. Mater. 239–240, 816–820.