# Sustainability in Luxury Textile Applications: A Contradiction or a New Business Opportunity?

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**Abstract** The recycling of textiles is heavily based on the material type and treatment of the fibre material. Especially materials that do not allow a recovery of the raw material in virgin material quality limit the possibilities of textile recycling significantly. This circumstance leads to great amounts of accumulating worldwide textile waste that is not yet processed into new valuable products. In this section, the authors will show two strategies for the re-use and recycling of high valuable fibre materials like polyamide and carbon used in luxury applications. Afterwards, two case studies are presented to validate the presented concepts.

**Keywords** Fibre recycling · Recycling concept · Carbon fibre · Polyamide carpet · Nonwoven

## 1 Introduction

In recent years, a growing demand for individualized products, which set the user off from the crowd could be noticed. Such products are only available to a certain group of people due to their innovative novelty, their availability or their price. Therefore, they are described as luxury goods [24]. Luxury goods are often perceived as personal pleasure, while sustainability and recycling are assigned to ethical motivations [1]. Achabou and Dekhili [1] highlights empirical studies in the French textile industry. These studies showed that the application of recycling materials in luxury clothing is affecting customer preferences negatively. This example illustrates, that recycling/sustainability and luxury goods are a perceived contradiction (Fig. 1).

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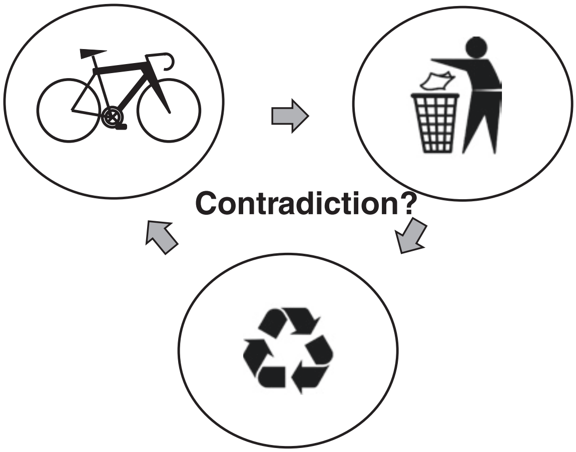


**Fig. 1** Sustainability in luxury goods—a contradiction? (*Source* ITA)

However, recent research projects like the EU Framework 7 funded project EcoMeTex (see Sect. 3.1) and the BMBF funded project CAMISMA (see Sect. 3.2) revealed that novel approaches allow the efficient recycling of luxury textile materials, adding new possibilities to the end of life options and increasing the sustainability of luxury textiles. Karus [23] mentions that companies from the field of luxury products started to use the aspect of sustainability to set themselves off from competitors in the market. This strategy upgraded the company's image in the perception of the customers [23] and links luxury to "excellence". By doing this, Karus shows the important role of luxury goods as a role model in the promotion of sustainable resource and product conception.

The following section will first give an insight on the necessary requirements to recycle textiles economically and which different procedures for recycling depending on the material exist. Finally two recycling methods are explained by using practical examples of carbon and carpet recycling.

## 2 Sustainable Resource Use—Conditions for Successful Recycling Concepts for Luxury Textile Goods

In recent years, a higher demand for individualized products, which set themselves off from the crowd could be noticed. Such products are only available to a certain group of people because of their innovative novelty, their availability or their price. Therefore, they are described as luxury goods [24]. One example from the world of fibres, such as the availability of material, which makes this a luxury good, is the carbon fibre. Therefore, the production capacity of carbon fibres came increasingly to its limits [9]. As a result, the price of these fibres remains high. This is the reason, why the use of luxury products—e.g. Limousines—is paid with a corresponding price, mainly as a distinguishing feature to other customers [38].

Despite the differentiation to other customers, there is also a sensitivity with respect to the price of luxury goods. Because of the customers' price acceptance (i.e. max. 5 € price increase per kg saved in lightweight applications [23]), the use of luxury materials is often limited on refining elements. For this reason—especially in the automobile sector—a mixed strategy has been employed: relatively inexpensive materials, such as steel or glass fibre reinforced composites, can provide the functionality of the product. Afterwards, the product is upgraded with individual modules by the use of luxury materials—e.g. carbon fibre reinforced plastic units [38].

Recent studies have shown that fibres, which are produced with high-priced materials, dispose of high mechanical properties (tensile strength, modulus of elasticity) even after the recovery of components by thermal or mechanical methods [4, 28]. Furthermore, it was shown in these studies that recycled materials—depending on the material—can be provided more cost effective than virgin materials, since the costs for recycling are lesser than the costs for producing new filaments.

It has furthermore to be considered, using the example of Carbon- fibre-reinforced plastics (CFRP), that litigation costs (machinery and labour costs) are responsible for about 30 % of the total cost and accounts 40 % of the costs for fibre material as shown in Fig. 2. This may result in a competitive advantage due to efficient recycling. Because of certain recycling approaches, the costs for the fibre—independent from material and product costs—can be reduced by up to 50 % [4, 7].

Based on these findings from the field of carbon recycling but also from projects with other fibre materials such as thermoplastics, four criteria have been determined at the Institut für Textiltechnik of RWTH Aachen University (ITA), which are necessary for a successful recycling of fibre materials to the new fibre products. However, there is no consideration of down-cycling but of the production of equivalent products.

These criteria are:

1. *Economic or legal pressure*: The price difference between virgin and recycled materials has to be higher than the costs of recycling and the treatment process, in order to make the process economical. Alternatively, there have to be legal regulations, which prescribe recycling.

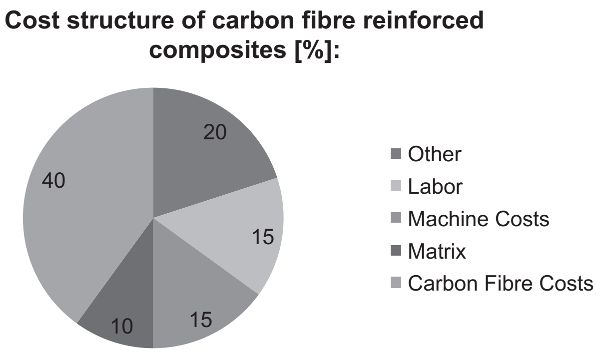


**Fig. 2** Cost structure in CFK (based on [9])

2. *Energy consumption*: The energy consumption (measured in the amount of ejected $CO_2/t_{\mathrm{material}}$) of the recycling process is lesser than the energy consumption of the production of virgin material.
3. *Material properties*: The material properties of the recycled product or raw material meet the requirements for using them in a new product.
4. *Amount available*: The material has to be available in sufficient quantity as a recyclate to pay off an industrial processing.

For an explanation of the criteria, these criteria are applied to two different fibre examples in the following. On the one hand, this is the recycling of carbon fibres and on the other hand, the recycling of BCF carpet yarns of polyamide.

## 2.1 Carbon-Fibres

Carbon-fibre waste generated by outtakes, production committees, destroyed components or at the end of the product life cycle of CFRP components, could not be recycled sufficiently [36]. Carbon fibres occur as waste at two different points:

- Primary waste due to cutting- and production errors
- Secondary waste due to errors in the production after applying the matrix, and after the end of the life cycle

Outtakes and production waste can be processed, usually without further treatment, since no matrix material was applied. RCF from end-of-life components and production errors (incl. matrix sheath) are currently acquired by undergoing a pyrolysis process (e.g. [29]) or the chemical dissolution of the matrix (e.g. [2]). The majority of the resulting carbon fibre waste is currently disposed of. This is induced by the fact that staple fibres can only be recycled insufficiently in typical fabrics like filament weavings due to their finite length [18, 34]. Nevertheless, the recycling of carbon fibres is lucrative due to the four criteria below.

### 2.1.1 Economic or Legal Pressure

With a price for virgin fibres of about 20 €/kg, the fibres are thus thirty to forty times more expensive than steel [35, 39]. According to Braun [4] and Cleff [6], the price may be reduced by up to 50 % through efficient recycling approaches. Additionally, the EU guideline 2000/53/EC demands a recycling ratio of 95 % of materials, which are used in transportation applications like automobiles and planes. This should start in 2015. Especially planes use a large amount of carbon fibres. Thus, this recycling criterion is fulfilled for carbon fibres.

**Table 1** Mechanical properties of recycled carbon fibres (rCF) [32, 42]

| Material value | Virgin carbon fibres | rCF (after pyrolysis) |
|---|---|---|
| Tensile strength (GPA/tex) | 2.5–7.0 | 2.5–3.2 |
| Elongation at fracture (%) | 0.5–2.1 | 1.3–1.6 |

### 2.1.2 Energy Consumption

The energy demand for the recovery of the carbon fibres based on Polyachrylnitril (PAN) can reach up to 700 MJ/kg$_{\text{C-fibre}}$. For the recycling of CFRP—waste by up to 50 % lesser energy is required due to currently used methods. Therefore, the price reduction results in the aspect of economy and the criterion of energy consumption is also fulfilled [4, 8].

### 2.1.3 Material Properties

The recycled fibres (rCF) still show nearly identical mechanical properties as virgin fibres after recycling [27] (Table 1).

Based on good mechanical properties, this criterion is also fulfilled.

### 2.1.4 Available Amount

For the year 2020, a worldwide demand of 130,000 t/a is predicted by the ‘Verein Deutscher Ingenieure’ (VDI), whereat already 4000 t/a of fibre waste occur [9]. However, the full amount of the fibres used will have to include recycled fibres [9], which is why a high value in the luxury sector can be achieved through intelligent recycling approaches. For this reason, the recycling of carbon fibres was the question of many research projects, of which one project is going to be presented as case study later in the section. Subsequently, this last criterion is also fulfilled for carbon fibres.

## *2.2 Polyamide BCF Fibres*

In the following section, the recycling of polyamide from carpets is used as an example. This application only meets the above four criteria partially to a small extent. This is revealed among other things by the fact that a large project on carpet recycling has failed in the past [21]. Thus, the Polyamide 2000 AG should sort old carpets from Germany and the EU and try to recover the polyamide [20]. Reasons for failure were, among others, the separation of the polyamide from the other materials of the carpet and the proportion of polyamide in the carpet [32]. This aspect has been considered in the EU project EcoMeTex, which will be described in the following section. With the ideas of this project, it is possible to improve the economy and the energy consumption during the recycling.

### 2.2.1 Economic or Legal Pressure

The recycling of carpet waste and the production of new carpets from raw materials are currently carried out only in limited scope due to the economy. Because of the new European regulation for construction products like carpeted floors, the BauPVO CPR, the aspect of the sustainable use of natural resources is emphasized [15, 46]. Thus, there is legal pressure for recycling. Moreover, there is also interest in environmentally-friendly carpets, which is reflected in the various environmental labels for carpets [6].

### 2.2.2 Energy Consumption

The energy consumption for reusing polyamide for new polymer fibres is less than the synthesizing of new polyamide from crude oil [14]. In the following, the exact reprocessing procedures are going to be presented. In order to keep the energy consumption for the separation of the polyamide from the other materials of the carpet low, the results of the project EcoMeTex are necessary.

### 2.2.3 Material Properties

For the recycling of polyamide two different ways are possible. On the one hand, the remelting and preparation of Polymer and on the other hand, the chemical breakdown of the polymer into his monomers and afterwards the new polymerisation. The material properties of the two different recycling concepts are different but both are good enough to use it for new products [40]. In the carpet section, a detailed description of the possibilities and requirements will follow.

### 2.2.4 Amount Available

Finally, the amount of waste of carpets is also interesting. Thus, about 1 million tons of carpet waste were available for disposal in 2005 in Europe. Of those 1 million tons, the proportion of polyamide was approximately 13 % [47].

# 3 Different Types of Recycling Strategies to Create Textiles Out of Textiles

## *3.1 Levels of Recycling*

Recycling can be processed in different ways and at different stations along the production- and product life cycle. These pathways are dependent on the material and the product, which should be recycled. A total of four recycling levels are distinguished, which are described briefly below to give an overview. A detailed description of the component stages can be found in source [44] (Fig. 3):

Stage 1: Recycling of raw materials and outtakes during the production.

During the first stage, occurring raw materials and outtakes from the production process are recycled back into the process. This recycling step can mainly be used for raw materials and product residues that can be dissolved by chemical or thermal influence. Material residues that occur in the appropriate structure for further processing can also be recycled at this stage. This is, for example, the case for fibre- based products such as cotton, if not processed slivers are again introduced into the fine opening process after the carding process.

Stage 2: Recycling by re-using the products.

At this stage, products are re-used after the end of the traditional life cycle. This happens rarely in the operational area of the existing life cycle but rather by the application in another scope. At this point, the use of waste textiles as cleaning rags may be mentioned as an example.

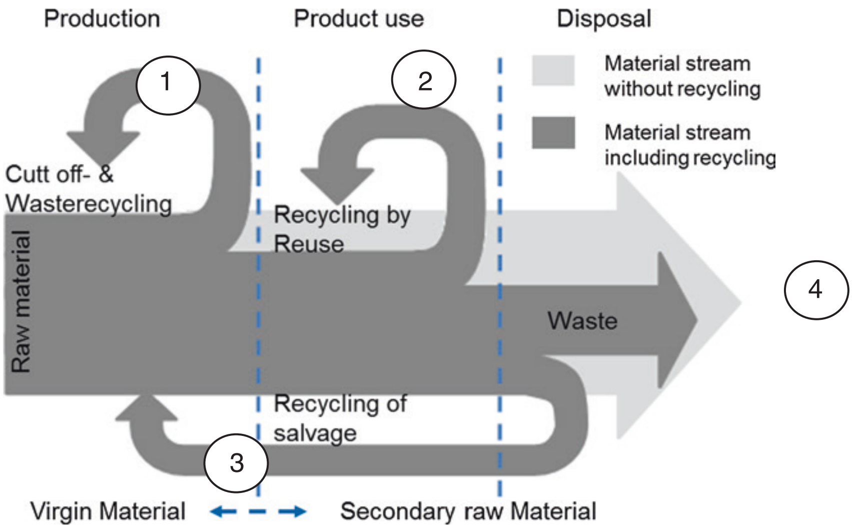


**Fig. 3** Levels of recycling according to [44]

Stage 3: Recycling of secondary raw materials.

At this stage, disused components and materials are decomposed and processed mechanically, chemically or thermally to recover as many of the used materials as possible. These materials are fed back into the first stage of the process to be processed into new products. Because of the environment and influences by usage during the product life, the raw materials that have been obtained during the third stage, are often of poor quality. This can result in poorer mechanical properties (e.g., shorter fibre length in carbon fibres), or the incorporation of impurities and unknown additives.

Stage 4: Recycling due to thermal utilisation.

In the last stage, raw materials and components are combusted to use the stored energy in them. This last step should be taken into consideration as late as possible due to the complete destruction of the material.

## 3.2 Recycling Strategies to Create Textiles Out of Textiles Depending from the Material

There are different ways to recycle textiles. One possibility is to continue to use clothes as second-hand textiles by selling them in developing countries [17]. The limitation on recycling processes, in which it is tried to restore old luxury textiles into new luxury textiles, shows that the recycling strategies are dependent on the raw materials. For two textile examples the possibilities are presented in Fig. 4. Afterwards it is explained with the help of case studies.

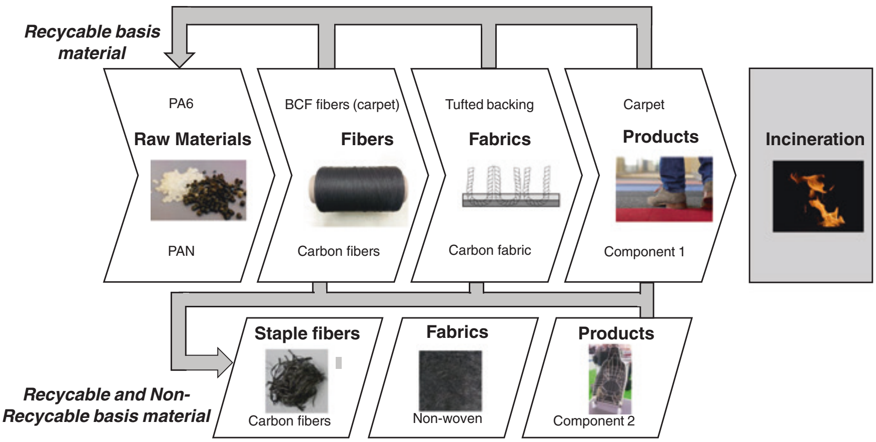


**Fig. 4** Possibilities for the recycling of high-quality textile products based on two examples (*Source* ITA, David Burri/pixelio.de.)

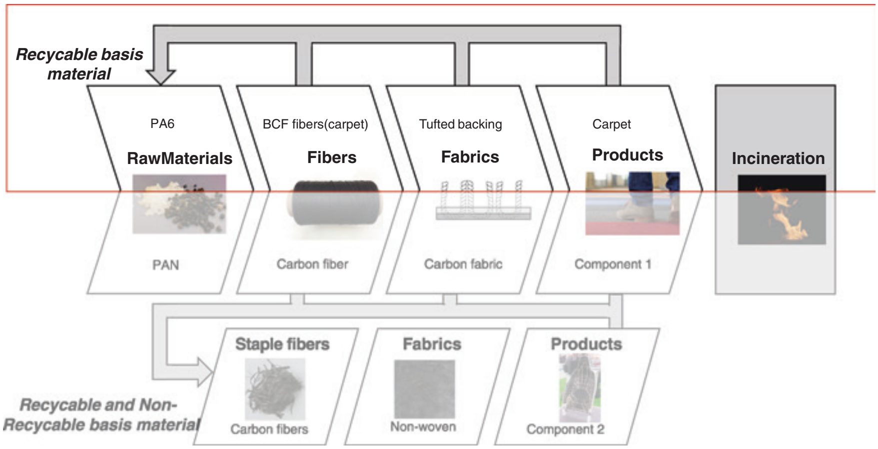


**Fig. 5** Recycling of recyclable raw material (*Source* ITA, David Burri/pixelio.de.)

Significant distinction for the use of the strategies is the question, whether the fibre material can be chemically or thermally dissolved and returned to the state of the raw material, or not. In the light of this distinction, either the top or the lower track can be chosen. In the top track the material can be transferred back to the state of the raw material from any state of the product life cycle. Consequently, the entire flow of material (100 %) can theoretically be transferred into the original product (Fig. 5).

This property of returning to the raw material is usually given for polymer fibres. Therefore, the upper way of recycling can be proceeded. In Sect. 3, this strategy is demonstrated by the recycling of high quality PA6 carpets, which are used in hotels or as doormats inside the vehicle.

The lower track in Fig. 4 must be selected when the fibres can no longer be transferred into the state of the raw material. This is, for example, the case for carbon fibres, which cannot be dissolved chemically or thermally into the original state and be reused to produce carbon filaments again.

In this case, after the upper path and after a mechanical treatment (e.g. cutting of fibre residues or tearing of textile structures), the only solution left is usually the thermal utilization. As a solution to the problem of the non-recyclable raw material, a recycling can thus be carried out via the detour of the usage in alternative products (second recycling stage, see Fig. 6).

This way forms the lower track of recycling possibilities. Later in this section, corresponding applications are illustrated in a case study, in which the carbon fibre mats are used as reinforcement for car seats. Due to the transfer to an alternative application level, the fibres can be used again in an area in which they meet the material requirements. In this alternative application level, different requirements of the material, that is to be processed and used, can be demanded. Depending on the application and the used material, a recycling on a small scale is possible according to the upper track within this detour. For example, non-woven

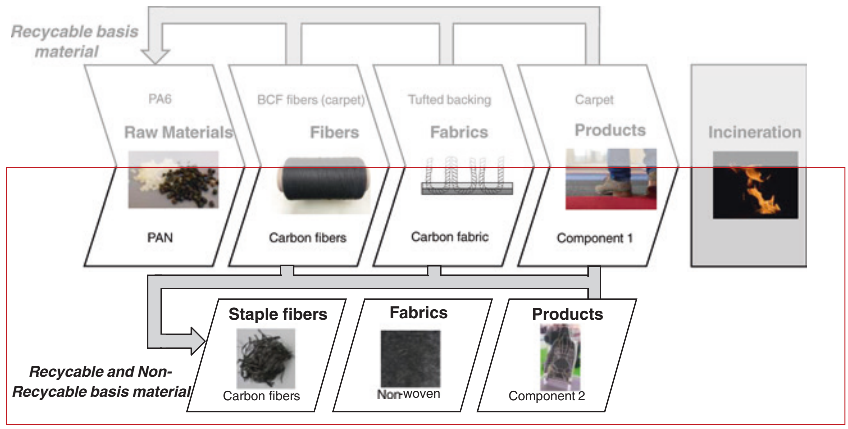


**Fig. 6** Recycling in non- recyclable raw material (*Source* ITA, David Burri/pixelio.de.)

residues—depending on the material—can be dissolved and supplied to the non-woven fabric plant once more.

# 4 Recycling of Polymers in the Process Chain Using the Example of Carpets

## *4.1 Carpet in General*

Most people know carpets from their everyday life. However, they are often perceived as regular commodity although they play an important role for a comfortable feeling. The luxury of carpets can be based on different aspects. One option is noble material such as animal hair or silk, which are usually processed by hand. These carpets are uninteresting for recycling processes because of their very small amounts. An alternative aspect to speak of a luxury good is the possibility of customizability. Thus, carpets can be produced from high-quality materials, such as polyamide, in industrial processes. These carpets are, for example, carpet tiles. With this type of carpet, the customer can freely combine carpet pieces with each other and thus create an individual interior design.

One way to make the carpet individually would be, for example, to use carpet tiles. It is mostly carpet pieces of 40 × 40, 50 × 50 cm or completely different forms which can be laid side by side without gluing. Therefore, these carpet tiles offer the advantage of a flexible use in a unique style [19].

Carpets can find application in various areas of our everyday life. The application area is divided into the private-, contract-, transport- and outdoor sector. Rooms such as the living room and bedroom, which are located in private homes, represent the private sector. This has to be differentiated from the contract sector. In addition to public buildings, such as offices, the contract sector includes hotel rooms. The transportation sector incorporates all carpets which are processed in cars, airplanes, trains or ships. Artificial grass surfaces usually represent carpets for the outdoor sector [11].

Depending on the application area, the requirements are very different. Thus, in the transportation sector, the requirements on the carpet in terms of weight are quite different from those in the contract sector. In the transportation sector, it is the aim to reduce weight by producing carpets, which are as light as possible, while in the contract sector, heavier carpets are preferred to fulfil requirements such as noise insulation. Based on these requirements, also the structure of the carpets is different.

Another aspect that affects the structure of a carpet is the manufacturing technique. The most common methods are tufted carpets, woven carpets and needle felt carpets. Here, the construction of a carpet is to be demonstrated with the help of a tufted carpet. The tufted carpets are the most common carpet construction in Western Europe with 480 million $m^2$ annually [48].

### 4.1.1 Construction of a Carpet

A tufted carpet is made up of several layers that are firmly connected. The top layer is the wearing surface, which consists of the pile yarn [11]. It is the only layer with which the end user comes into contact and is thus crucial for the design and pleasing haptics of the carpet. In 80 % of the carpets (in terms of the area), this layer consists of bulky continuous filaments which are referred to as BCF (bulk continuous filament) yarn [5]. For the application in the contract sector mainly PA6 is used because then the high requirements in terms of mechanical constraints can be withstood [15]. In the project EcoMeTex, carpets have been developed for the contract sector, which is why the choice of materials is limited on PA6 (Fig. 7).

In a tufted carpet, the pile yarn is embedded in a primary backing. Those tuft carriers usually consist of material combinations of PP, PES and PA. A coating is necessary to fix the pile threads in the carrier. This coating bonds the pile fibers to the carrier at the back. Usually, a latex dispersion with some filler material, such as chalk, is applied to reduce the price [12].

The last layer of a carpet is the backing. This carpet backing can be designed very differently depending on the application of the carpet. The tasks of a carpet backing are dimensional stability, elasticity, acoustics, heat insulation, and influencing the installation [45]. In the EcoMeTex project, carpet tiles by Interface, Inc. are taken as a reference. Such carpet tiles are special carpet square pieces of 50 × 50 cm [19].

Due to their small size, carpet tiles have to be relatively heavy so that they do not shift during use or vacuuming. This weight of a carpet tile is set on the back. Another important feature, which must be set on the back is the dimension stability, which is particularly important in carpet tiles. Only with absolute dimensional accuracy, carpet tiles can be installed in large numbers without problems. As a

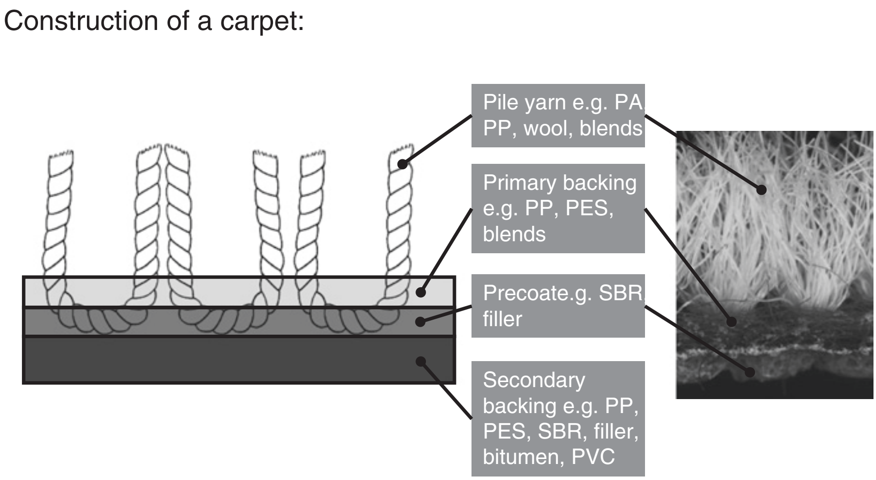


**Fig. 7** construction of a tufted carpet in total (*left*) (*Source* ITA) and cross section of a precoated tufted *grey* cloth (*right*) (*Source* TFI)

reference in the project EcoMeTex, backings of bitumen and glass nonwovens of the company Interface are prepared.

### 4.2 *Requirements for the Reuse of Polymers in Carpets and Carpet Tiles*

Dependent on where the recycled material should be used in a carpet, there are different demands on the material. In the following, this is illustrated by two examples.

1. Use of recycled polymer in the carpet backing

In addition to the heavy coatings such as those found in carpet tiles, there are textile backings, which are used for wall-to-wall carpets. These textiles are knitted, woven or non-woven fabrics [45]. When using the fibers in the carpet backing, there are no requirements for the color, because after laying the carpet, the back is no longer visible. Thus, also mechanically recycled fibers can be used in fleece backings without prior modifying of the polymer.

2. Use of recycled polymer in the pile yarn

To be used in the pile yarn, it is necessary that the recycled material can be processed to BCF yarn in the chemical fiber spinning process, because a productive application in the carpet is only possible with BCF yarn. The minimum requirement for the polymer is the fact that no major impurities, due to foreign particles or other polymers, are existent in the polymer when they threaten the

**Fig. 8** BCF bobbin with 100 % physical recycled material (*Source* Gneuss GmbH)

stability of the spinning process. In the EcoMeTex project, it could be shown that the waste material from the fiber production company AQUAFIL SpAItaly (Arco) can be mechanically processed with a melt filter by the company Gneuss Kunststofftechnik GmbH (Bad Oeynhausen) and then spun into new BCF filaments (Fig. 8).

At the same time, this experiment showed the limitations which exist due to the preparation of the polymer melts. Since the fundamental colour is already dark grey because of producing waste, it is not possible to selectively adjust the colour of the polymer. The requirements for a pile yarn are, however, that the colour can be set exactly and that there are no variations in the colour during production. Thus, it is necessary to recycle the polymer chemically in order to obtain new material for the pile yarn production.

## *4.3 Chemical Recycling of PA6*

The chemical recycling of PA6 is processed by the company AQUAFIL SpAItaly (Arco). Figure 9 shows the different steps during the chemical recycling. The first step is the production of the monomer. For this, a splitting of the PA6 into the monomer, the caprolactam, is processed with the help of chemical processes. As soon as the long polymer chains have been split into short monomer pieces, it is possible to separate the caprolactam from impurities like dyes or other polymers. At the end of this cleaning process, caprolactam, which has the same purity as something comparable to crude oil, is available [10].

After the depolymerization, the re-polymerization is carried out exactly like the process with PA6-based crude oil. Part of this process is, on the one hand, the extraction of the monomer and, on the other hand, the drying of PA6. Both steps are processed to increase the purity and quality of the polymer. Subsequently, the

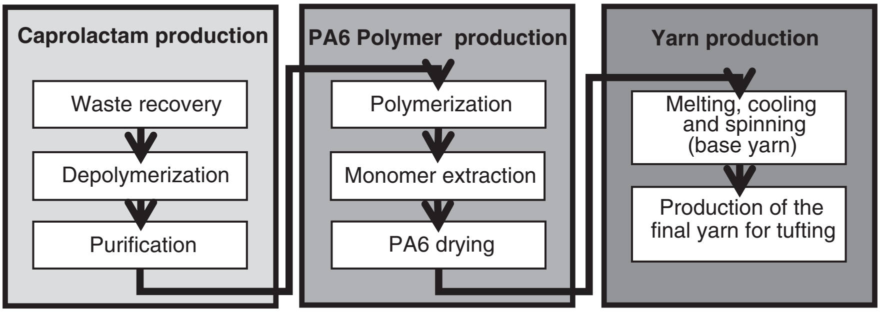


**Fig. 9** sequence of process steps during the chemical recycling at Aquafil (*Source* Aquafil SpAItaly (Arco))

material can be spun into yarns again. The result of this process is a yarn which is sold under the trade name Econyl [10].

Although many impurities can be removed during the depolymerization, and thus a final product originates that is virtually indistinguishable from a new material, there are requirements on the polymer waste to perform this type of recycling. The two main requirements are [33]:

1. A high content of PA6 (min. 70 %)
2. No or a very small proportion of PET, PA6.6 and SBR Latex

When comparing the requirements for chemical recycling and the current carpets, it becomes clear that they do not fit together. Carpets are made of many different materials and particularly include PET and SBR latex, which are especially cumbersome for depolymerization. The development of recycling concepts for separating the materials during the recycling process has failed in the industrial implementation. Projects which have considered these possibilities include, among others, the RECAM Project (Recycling of Carpet Materials 01.12.95–31.05.99) and the project Polyamide 2000 AG. Therefore, the polymer from current carpets can not be won again in that way that it can be used for the production of new carpets. One possibility to avoid this problem is to adapt the carpet to the recycling process beforehand. This has been done in the EcoMeTex project.

### *4.4 EcoDesign of Carpet Tiles*

An obvious solution would be to build a carpet with only one material, namely PA6. Consequently, there would be the possibility to recycle the entire carpet. However, when considering the requirements for the carpet tiles, such as weight and dimensional stability, it becomes clear that this mono-material solution is not possible or economical. Since PA6 is an expensive material, which cost at least

2 €/kg. To increase the weight of the carpet, it is easier and cheaper to use materials as bitumen.

Since the back is responsible for both the dimensional stability as well as the weight of the carpet tiles, the back of carpet tiles consists of bitumen and a fibreglass mat. With the assumption that this combination of materials must be retained, the only way out is a clean and simple separation of the components. The idea of the EcoMeTex project is to design the carpet in a way that the upper part of the carpet can be supplied to the chemical depolymerization and the lower part is provided for different recycling processes. Due to the fixed connection between pile yarn and tuft carrier, it makes no sense to separate them from each other. Thus, the separation layer must be below the tuft carrier. This in return has the result that also the tuft carrier has to consist for the most part of PA6 and must not contain PET.

The major challenge of the separation layer lies in the conflicting requirements that are placed on such a dividing point. Thus, the separation layer must not restrict the resistance of a carpet. These claims are very high as a carpet usually remains for 10 years in a building and is subjected to high mechanical stresses. However, other properties such as fire behavior or emission shall not be affected negatively. At the same time, it is important that the separation layer separates the layers easily and with a low energy consumption as soon as the carpet shall be re-fed into the recycling process.

## *4.5 Separation Layer*

One possible way how to realize such a separation layer was developed in the project EcoMeTex. This is based on the calendaring technology of the company Klieverik Heli BV (Oldenzaal) which is already applied in carpeting in the automotive sector. Here, the tufted nonwoven is not coated with latex but transported and heated between two calender rolls. The pile threads on the rear side of the tuft carrier are melted and thereby form a firm connection on the back side. In addition, the layer is enhanced by hot melts or thermoplastic powders.

An interesting feature of such hot melts or thermoplastic powders is that they melt at relatively low temperatures and thus are already liquid before the pile yarn or the tuft carrier soften. Thus, they form a weak spot in the carpet structure when heated up. Exactly this feature has been utilized by EcoMeTex. Because as soon as the carpet is heated up, for instance with a calender, the individual layers can be separated cleanly from each other with little effort.

To further increase the dimensional stability of the carpet and, furthermore, to prevent that the bitumen of the backing was mixed with the hot melt, a fiberglass mat has been introduced. For future products, this fiberglass mat shall replace the glass mat in the back. Figure 10 shows the different stages of production as well as the clean separation of the different layers by simply heating.

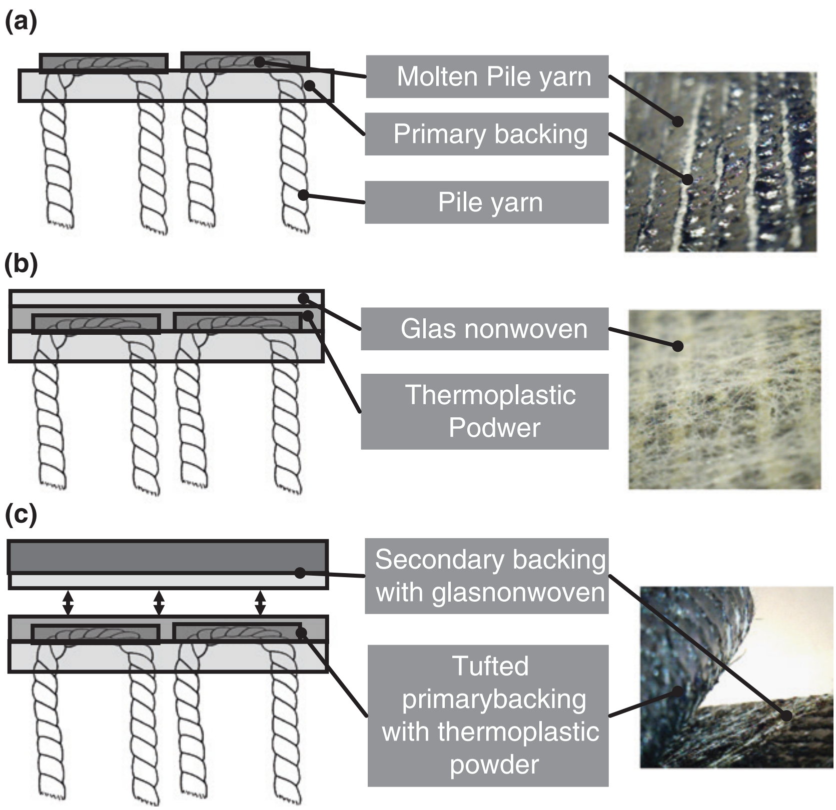


**Fig. 10** **a** The bottom of a tufted and calendered fleece, **b** combination with a glass mat, **c** separation of the layers

## 5 Utilization of Materials in a New Part Using the Example Carbon Fibers

As already mentioned, carbon fibres cannot be returned to their state of raw material. (1st or 3rd recycling step, cf. Fig. 3). That is why the fibres are currently mostly milled and used as filler material and additive in plastics [9]. Therefore, alternative solutions of application are needed to tap the full mechanical and economical potential.

The use as a non-woven fabric seems to be obvious because of the fibre characteristics. The manufacturing processes of non-woven fabrics were developed to produce sheet material from staple fibres and are very efficient [13]. According to the process, different fibre length fractions can be used and fibrous textures can be added into the textile material. Figure 11 gives an overview of the available processing procedures.

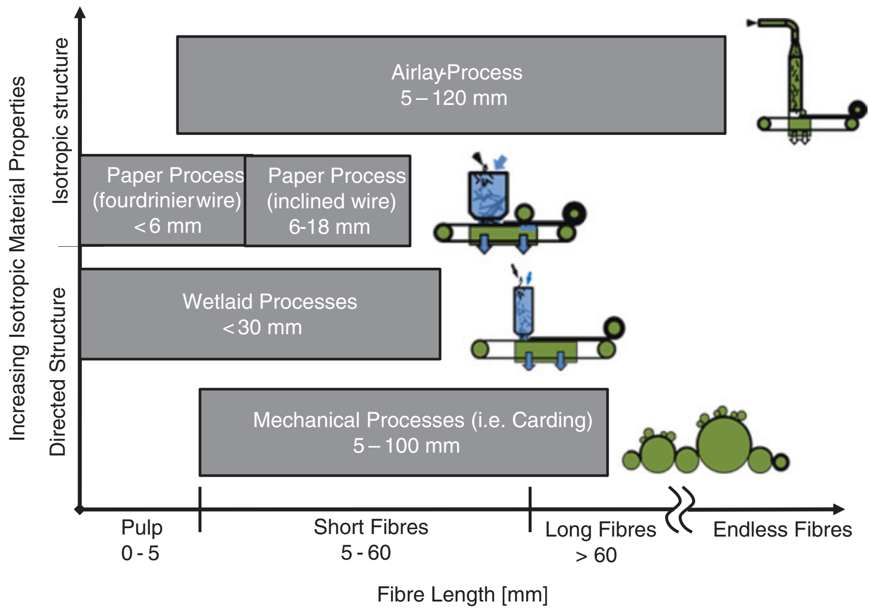


**Fig. 11** Depiction of the different manufacturing processes of non-woven fabrics [27] (*Source* ITA)

Staple nonwovens can be formed by mechanical, aerodynamic or hydrodynamic processes. Besides, nonwovens can be after-treated to fit their characteristics to the future field of application [40, 43].

At the dry manufacturing of non-woven fabrics (aerodynamic, mechanical), it is necessary to take precautionary measures to protect employees and machinery. Protective clothing for employees, safety glasses and respiratory masks for the protection against carbon dust must be intended to use during the processing. Furthermore, processing as well as near machinery needs to be encapsulated so that the carbon dust does not reach machine parts with electrical elements and causes a short-circuit [16, 41].

In many cases, companies can collect primary waste and reconvert it to other products. Especially the use as reinforcing material or functional additive in composite is favoured in practice [37] (Fig. 12).

The project CAMISMA (project name deduced from “Carbonfaser/Amid/Metall-basiertes Innenstruktur-Bauteil im Multimaterial-Ansatz”) serves as an example to demonstrate the added value of the use as reinforcing material. The consortium carrying it out from 2011 to 2015, consists of the RWTH Aachen [Institut für Textiltechnik (ITA), Institut für Kraftfahranwendungen (ika), Institut für Kunststoffverarbeitung (IKV), Institut für Aufbereitung und Recycling (IAR)], TohoTenax Europe GmbH, Johnson Controls INC. and HBW Gubesch Kunststoff-Engineering GmbH and is conducted by Evonik Degussa GmbH.

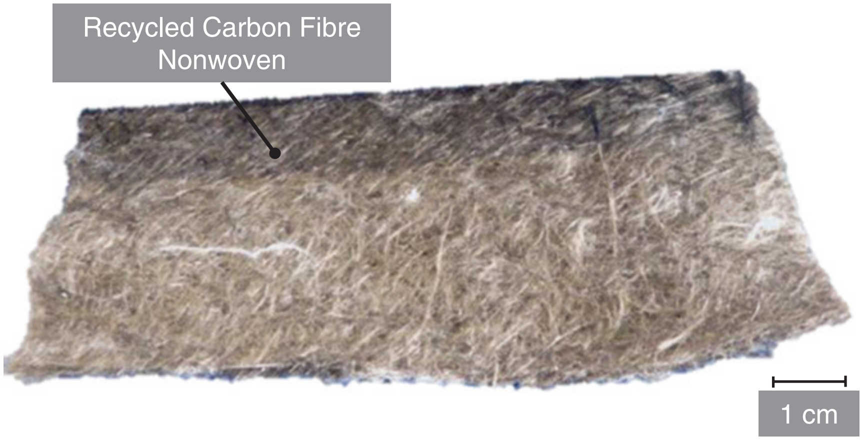


**Fig. 12** Coated recycled carbon fibre nonwoven [30] (*Source* ITA)

Project aim is the economical and environmentally friendly manufacturing of components in lightweight construction. In this context, the use of recycled carbon fibre non-woven fabrics plays a vital part in the success of the project. Within the context of the project, primary waste fibres are used [31]. The aim of reaching a weight reduction >40 % with concurrent restriction of the cost increase to < 5€/ $kg_{saved}$ was achieved by the new approach of lightweight design [23].

A fibre volume content of 32 % in the composite achieved a significant reinforcement effect of the construction element (seat back) during critical deformation testing. With this example, the project CAMISMA demonstrates well that recycling of high-quality and high-price materials does not only have to be a legally defined and economic necessity, but also a chance to solve technological problems. The exact project contents and results are presented in Fig. 13 [23, 26].

The CAMISMA-Design's idea is the intelligent combination of materials. A material is "used where it is needed". In this way, a combination of glass fibre reinforced (GRP), carbon filament reinforced (CRP) and carbon non-woven reinforced (CVK) composites with steel reinforcement in a polyamid-12-matrix is developed. In the process, the recycling carbon fibre non-woven fabrics serve as reinforcement of the injection moulding elements. They are only mechanically reinforced with tapes out of new filaments at process-related places with big material deformation. The mentioned component parts are most intensely subjected to the danger of material damage and thinning because of the high forming forces. That is why a specific reinforcement of these places is necessary. In Fig. 14, a finished CAMISMA-component with separate comments to the use of recycling material ("Non Woven CF-Tapes") is presented. The structure's biggest part was manufactured by large layers out of recycling material with reinforced injection moulding (Non Woven CF Tapes, cf. Fig. 14) [23].

Thus, by construction concepts like the CAMISMA-approach high-quality recycling materials can not only be technically and usefully integrated into new

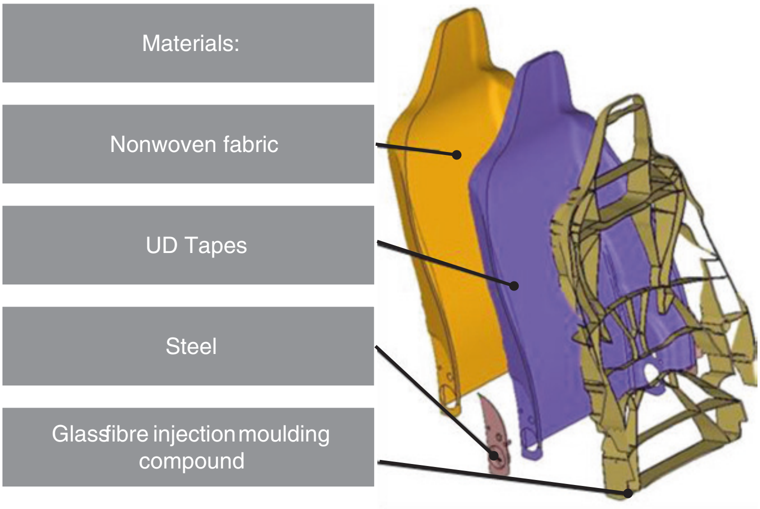


**Fig. 13** Concept CAMISMA-lightweight design [25] (*Source* Evonik)


**Fig. 14** Depiction of a seat back in CAMISMA's material mix approach with specific depiction of the recycling material [23] (*Source* JCI)

applications. Such approaches increase clearly the cost effectiveness as well as options after the product life cycle's end of high-quality products out of these materials. The saved costs for the disposal of carbon fibres, classified as hazardous waste, and the product costs, influenced by the material quantity, increase the cost effectiveness sustainably [29]. Besides, the construction elements can be sold to appropriate disposal companies for treatment after the product life cycle's end. Consequently, the material's economical potential can be exploited instead

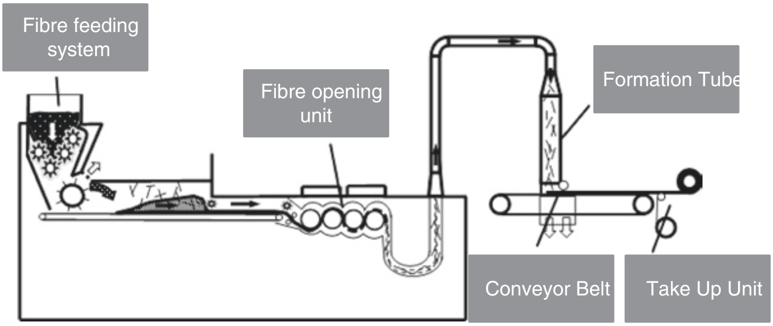


**Fig. 15** ITA Airlay process [26] (*Source* ITA)

of disposing it with high costs. Therefore, $CO_2$ emissions are produced delayed because of the thermal utilisation, which happens years later, and increase the construction element's energy balance.

To tap the mechanical and therefore the economical potential of the fibres, it is important that staple fibres received by recycling are not shortened too much during the processing. According to examinations of the Industrievereinigung Verstärkte Kunststoffe e.V. (AFK), fibres with a minimum length of 10 mm bear the highest possible load [3].

The lowest fibre damage occurs by using the airlay procedure because the fibres are only temporary mechanically loaded during the process steps fibre opening and non-woven formation. Over the period of transporting the fibres, no essential fibre loads occur. For this reason, a continuous airlay process has been developed within the scope of the project with which economical as well as mechanical project aims shall be supported. This process is presented in Fig. 15.

By the fibre opening unit with four rolls, the carbon staple fibre flakes are opened gently to minimize fibre damage by fibre fracture. Afterwards, an aerodynamic transport of the fibres to the formation area takes place where the fibres are laid down as an isotropic non-woven. Then, the non-woven fabric is pulled off by a conveyor belt, which makes a continuous production possible. By this concept, the predetermined cost limits for the fabrication of the materials could be kept within the scope of the project [23].

The fibre orientation within the non-woven fabric is influenced by the set flow conditions in the formation area and can be modified by adapting the geometry of this area. According to the future field of application for the non-woven fabric, this variation of geometry can be interesting. Within the scope of the CAMISMA project, a geometry was chosen that generates a constant flow in the formation area. This guarantees a constant isotropic non-woven formation across the width of the conveyor belt. In Fig. 16, the flow conditions are depicted on the basis of simulation results [28].

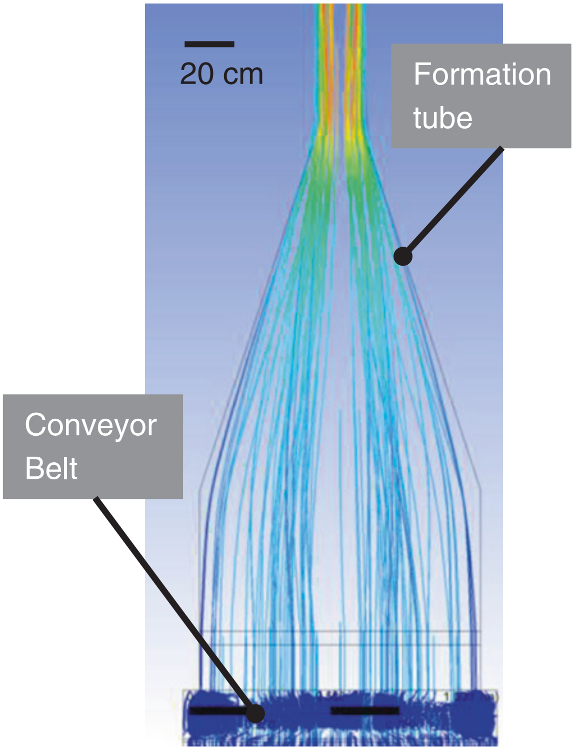


**Fig. 16** Airflow in the formation tube (*Source* ITA)

## 6 Conclusion

The presented work showed that novel approaches in fibre recycling increase the number of available options at the product's end of life. By following the author's model of two recycling ways, product designers and users of luxury textile goods can lead the valuable materials back into the production chain of the same of alternate products. Two examples were given for high valuable carbon and PA6-fibre products from the automotive and building sectors that can serve as an example for practical application of the presented strategic approaches.

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