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LIFECYCLE OF NYLON

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ABSTRACT

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Lifecycle of Nylon

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The problem of a nylon carpet waste was addressed in the thesis. Main stages of nylon carpet lifecycle were defined. Conditions for closed-loop circular structure of nylon lifecycle were listed. The component structure of nylon carpet was studied. Four main nylon waste recycling categories were studied. Possible applications of recycled waste materials were addressed in the thesis. The study of nylon waste collection and identification processes was performed. An environmental study based on ISO 14015 standard called "Environmental Product Declaration" of three selected nylon carpets with different structure was carried out. The carpet with the best environmental performance was named.

Main stages of nylon lifecycle include nylon polymerization, product production, product use, waste disposal, waste collection, recycling. Nylon recycling includes depolymerization, extraction, melt-blending and incineration. Recycled nylon waste is used in carpet re-production, construction, textile and automotive industries as well as for production of melded polymers and thermoplastics. Based on the conducted study carpet with nylon 6 face fiber and polyester backing had the best environmental performance. It is proposed to be sold by the carpet retailer.

Key words: Nylon, Lifecycle, Closed-loop, Carpet, Recycling, Waste.

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ABBREVIATIONS AND TERMS

EPD	Environmental Product Declaration
CARE	Carpet America Recovery Effort
PP	Polypropylene
PVC	Polyvinyl Chloride
LCA	Life Cycle Assessment
SBR	Styrene-butadiene
PET	Polyethylene Terephthalate
HMD	Hexamethylene Diamine
CL	Caproactam
MSW	Municipal Solid Waste
CVAM	5-Cyanovaleramide
ADN	Adiponitrile
6-ACAM	6-Aminocaproamide
DINP	Diisononyl Phthalate

1 INTRODUCTION

Life cycle assessment (LCA) is an environmental management tool which enables evaluation of environmental burdens and impacts over a whole life cycle of a product, process or activity (Leonas 2017).

Environmental concerns and governmental regulations on a worldwide scale are putting effort for recycling of all synthetic polymers, of which carpet and carpet fibers constitute a large percent. Carpet is not biodegradable and is a petroleum-based product. According to the US Department of Energy more than 1 billion tons of waste carpets are generated every year in USA alone (Vaidyanathan et al., 2013). About 236 million tons of waste carpet was collected in 2015 by Carpet America Recovery Effort (CARE), an organization committed to carpet recycling in USA. Out of that amount of collected waste 32% was recycled and 28% was sent to landfills (CARE 2015 Annual Report 2016). The disposal of carpet waste to landfills is banned across the European Union. However, the amount of carpet waste on the worldwide scale is significant. The only real and sustainable solution for the problem of carpet waste lying in landfills and being discarded there is the recycling. It is estimated that recycling of carpets could save about 700,000 barrels of oil per year which amounts to 4,4 trillion BTUs of energy (Vaidyanathan et al., 2013).

Carpet waste can be considered as both environmental and economic problem. The cost of waste disposal includes not only hauling, transportation and other infrastructure costs but also discarding a valuable raw material in the form of high engineering value fibers like nylon 6, polyester, polyvinyl chloride (PVC), polypropylene (PP), etc. Energy consumed for polymerization, spinning and finishing of nylon is between 369 and 432MJ/kg. The calorific value of crude oil is between 38 and 46MJ/kg (Vaidyanathan et al., 2013). Thermal utilization of carpet waste uses only the calorific value which is the same or lower than of crude oil. That is why the development of sustainable carpet recycling solutions becomes highly desirable.

2 SCOPE

The purpose of this report was to define and describe the lifecycle of the subclass of synthetic polymers called polyamides or nylons. Another objective was to determine conditions, under which the lifecycle can have the circular closed-loop shape. The topic was rather extensive. The thesis focused on nylon carpets, since the main application of nylons is fiber production. Current recycling technologies were also primarily developed for the processing of used carpet waste due to the high amount of nylon fiber in carpets compared to other nylon products.

Within the thesis main steps of nylon lifecycle were defined. LCA tool was used to trace the step-by-step process of nylon carpet manufacturing starting from nylon polymerization and carpet production to its disposal, collection, identification and recycling back to the state of virgin nylon. Main types of nylon products and their monomers were studied. The process of waste carpet collection and techniques of nylon fiber identification were listed. Patent and literature reviews on current recycling technologies were carried out. Possible applications of the recycled nylon materials were revised.

The second part of the thesis included the environmental study of three nylon carpet products most sold at the carpet retailer store in Tampere, Finland. The study was based on ISO 14025 standard called “Environmental Labels and Declarations”. The purpose of that study was to distinguish the most environmentally friendly type of nylon carpets with the best environmental performance out of all listed. Results were prepared for the management of the store as a recommendation for consideration during the future procurement of nylon carpets.

3 METHODS

The primary environmental study of three most selling nylon carpets at a carpet dealer store was carried on the bases of ISO 14025 standard called "Environmental Labels and Declarations'. Various environmental characteristics found in Environmental Product Declarations (EPDs) are analyzed. The focus of the study was drawn on the production stage of the lifecycle. The general structure of all the carpet samples was compared, including the face fiber, primary backing material, fillers and backing materials. Normally, the production stage of the lifecycle include raw material acquisition, transportation to manufacturing and manufacturing stages. Transportation and installation stage, use stage and end of life stage were not a part of the study since these stages may have different environmental performance when applied to Finland.

Initially, the life cycle inventory analysis of each EPD for all the carpet samples was compared. Two most important characteristics were retrieved. They were: total non-renewable primary energy (including crude oil, hard coal, lignite, natural gas, uranium) and total renewable primary energy (including geothermal, hydro power, solar energy, and wind power).

The amount of waste generated by the production of each type of carpet samples were analyzed. EPD contains information on the three categories of waste, which are hazardous waste, non-hazardous waste, and radioactive waste. All three types of waste were included in the comparison of samples.

Environmental impacts for one lifecycle of each carpet samples were studied. Global warming potential was selected out of all the impact categories due to its importance. Other categories, including ozone layer depletion, acidification potential, eutrophication potential were left out of study. The result of the study were presented in the form of a comparison table.

4 LIFE STAGES OF NYLON CARPET

4.1 Life cycle of nylon carpet

Current global movement towards the circular economy is relevant for the carpet industry as well. Goals of the circular economy are to use the products, components and materials to their highest value. Resources are recovered and restored and later reused to reproduce the product. For many years carpet waste ended up in landfills or was incinerated. Today industry strives for the closed-loop cradle-to-cradle model of recycling as shown on figure 1. In this case waste is collected and reprocessed back to raw material.

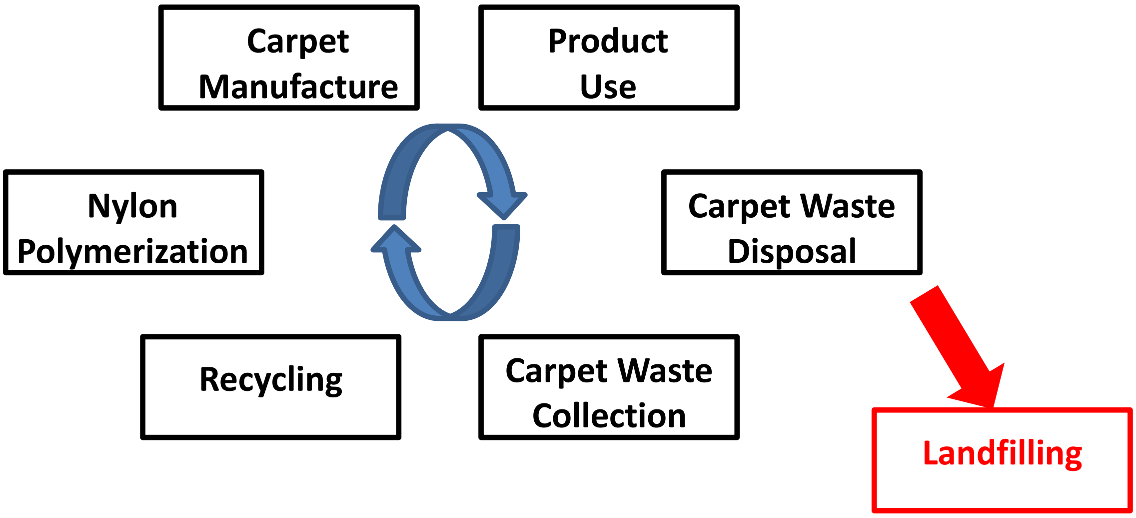

FIGURE 1. Closed-loop circular lifecycle of nylon.

4.2 Manufacturing of nylon

4.2.1 General information on Nylon

Nylon is generally used to refer to the class of polyamide polymers. Nylons or polyamides are the first engineering plastics and up to day are the most important type of these materials (Ibeh 2011). The word polymer means a large molecule composed of repeating structural units connected by covalent chemical bonds (Wilczura-Wachnik). Polymer does not necessarily mean plastics. It may refer to large class of natural and synthetic materials.

Polymers can be synthetic and biological. Synthetic polymers are the ones which do not exist in nature and are man-made. Biological polymers do exist in nature and can also be synthesized in laboratory. Polymerization is the reaction of combining monomers into covalently bonded chain bonds (Wilczura-Wachnik). Depolymerization is the reverse reaction of converting polymer into a monomer.

The creation of polyamide can be directed to the first developments of polycondensation back in 1929. That reaction is the basic principle for nylon synthesis. Nylon 6,6 was for the first time synthesized by Wallace H. Caruthers in a DuPont laboratory in 1935 (Ibeh 2011). Originally, he was searching for the possible replacement of the silk in parachute production. The first patent for the production of synthetic polyamides was issued in 1937. The first applications of nylon were production of stockings and toothbrushes. Other important polyamide named nylon 6 was produced by IG Farbenindustrie in Germany by Paul Schlack in 1938 and was patented in 1941 (Ibeh 2011). Even though it has been used in various commercial applications, the real development of the market of polyamides started in 1950s.

Polyamides include a wide range of materials depending on the monomer used. Most commonly used products are nylon 6; 6,6; 6,12; 11 and 12. The number indicates the number of carbon atoms that separate the repeating amide group. Among most types of polyamide, about 85-90% of nylon globally are nylon 6 or nylon 6,6 (Vaidyanathan et al., 2013). They find application in woven and non-woven industries.

Caprolactam (CL) is monomer for nylon 6 while the monomers for nylon 6,6 are adipic acid and hexamethylene diamine (HMD) (NPTEL 2013). Both adipic acid and caprolactam are sourced primarily from benzene. Today oil is the largest source of aromatics, especially benzene. That means that main ingredients of nylon 6 and 6,6 are derived from oil.

Nylons are strong, elastic, easy to wash, resistant to chemicals, low in moisture absorbency. They have good appearance and good processability. Nylon 6 and nylon 6,6 appear to be relatively similar, though nylon 6 has better toughness and processability (Ibeh 2011). Nylon 6,6 has a higher a better heat resistance and better mechanical properties. The general characteristics of nylon 6 and nylon 6,6 are given in table 1.

TABLE 1. Main characteristics of nylon 6 and nylon 6,6 fibers (NPTEL 2013).

Name of the fiber	Monomer	Basic chemicals	Properties of the synthetic fiber		Characteristics
			Density (g/cm^3)	Maelting point (ºC)	
Nylon 6	Caprolactam $C_6H_{11}NO$	Phenol, cyclohexane, toluene	1,014	213-221	Resistant to weak acids, decomposed by strong mineral acid. Good biological resistance to heat.
Nylon 6,6	Adipic Acid $C_6H_{10}O_4$ Hexamythelene Diamine $C_6H_{16}N_2$	Phenol, cyclohexane, butadiene, furfural	1,14	230	Resistant to weak acid, decomposed by strong mineral acid. Chemically stable.

Traditionally, the majority of the produces nylon is used in fiber production. Nylon fiber is also applied in the production of home furnishing, tire cords, hoses, conveyer, seat belts, parachutes, ropes, mono fishing line, dental floss, etc. A new trend has developed in the last decade. The big amount of nylon is now used in the engineering thermoplastics market. This trend has developed due to the fact, that nylons perform well those mechanical duties which were previously done by metal parts (Ibeh 2011). This is mainly visible in the automotive market. There the metal parts are being replaced with the plastics in order to reduce weight, costs and meet vehicle emission standards.

Currently, Nylon 6,6 is manufactured by Dupont, Solutia and other companies and is mainly sold as fibers. Nylon 6 is made by carpet manufactures like Aquafil, Shaw Industries or produced by chemical companies like Honeywell, BASF. The manufacturers of carpet most of the time have their own stand-alone nylon production. Several technology holders have similar features for commercially produced nylon. The basic production steps of nylon manufacturing have not changed through the time. The technology has improved in terms of costs and efficiency. The improvement of the technology has also been aiming the reduction of the need of raw materials, reduction in utility requirements and the improvement of the quality of the product (Ibeh 2011).

4.2.2 Manufacturing of Nylon 6

As it has been already mentioned, nylon 6 is the linear addition polymer of caprolactam (6-amino-caproic acid). Nylon 6 is formed by the ring-opening polymerization of caprolactam as shown in equation (1) (Yong 2007).

$nC_6H_{11}NO + H_2O \rightarrow H(NH(CH_2)_5CO)_nOH$ (1)

Caprolactam Water Nylon 6

Main process steps include:

- Polymerization: batch or continuous and chip production;
- Washing and drying of chips;
- Spinning of nylon;
- Recovery section.

The ring opening polymerization of caprolactam takes place at 240-270ºC. In order to initiate polymerization water is needed. Caprolactam does polymerize alone when heated in a closed vessel. Water opens the ring structure to create aminocaproic acid. Sulfur dioxide reacts with ammonium nitrate and ammonium carbonate. That leads to the production of hydroxylamine disulfonate. Later the hydrolysis of hydroxylamine disulfonate takes place at the temperature of 95ºC (NPTEL 2013).

4.2.3 Manufacturing of Nylon 6,6

Nylon 6,6 is produced by the polymerization of hexamethylene diamine and adipic acid as shown on equation (2) (Yong 2007).

$nHOOC(CH_2)_4COOH + nH_2N(CH_2)_6NH_2 \rightarrow (C_{12}H_{12}O_2N_2)n + 2NH_2O$ (2)

Adipic acid Hexamethylene diamine Nylon 6,6 Water

Main process steps include:

- Preparation of nylon salt by reaction of adipic acid and hexamethylene diamine. Both of them are mixed together in a 1:1 molar ratio. The demineralized water is added at this point;
- Concentration of molar salt;
- Polymerization of the nylon salt in a vessel with internal coils;
- Cooling down the mixture;
- Chips production;
- Spinning of nylon 6,6 chips;
- Recovery.

4.3 Nylon carpet production

4.3.1 Carpet construction

A typical carpet consists of four layers as shown on figure 2: face fibers, primary backing, binder and secondary backing.

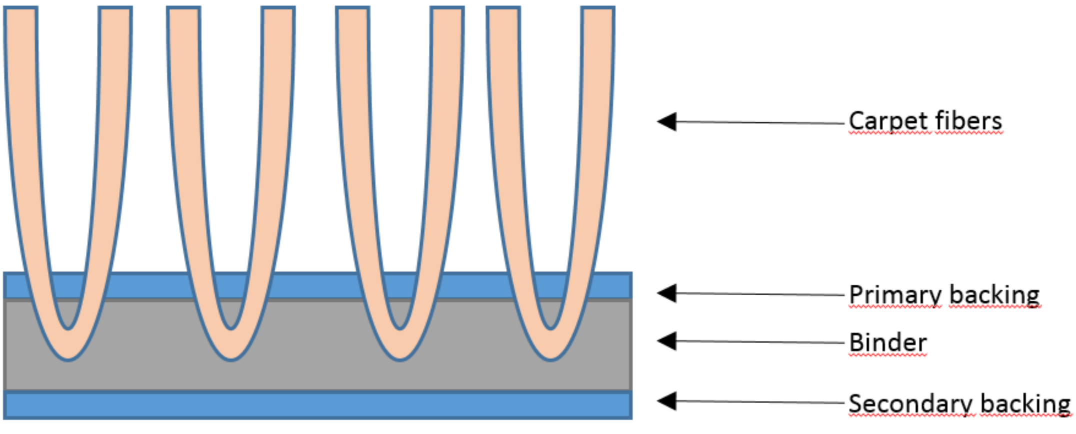

FIGURE 2. The typical layout of the carpet layers.

The top layer consists of the face fibers that are normally tufted through the primary backing made of polypropylene (PP). Some other materials like polyesters, polyethylene and rayon may be used as backing materials as well. In order to secure the face fiber a latex adhesive made of butadiene rubber co-polymer (SBR) is laid under the primary backing. The SBR adhesive is combined with inorganic filler material like calcium carbonate or barium sulphate in order to form a binder and bond the secondary and primary backing (Vaidyanathan et al., 2013). Usually, the primary and secondary backings are made of the same material. The face fiber might contain dyes, soil repellents, fire retardants and other additives in order to improve the quality of the carpet.

Table 2 provides information on the components of a typical carpet with PP/SBR construction . This type of carpets accounts for 95 percent of all the residential and commercial carpets in the United States (Vaidyanathan et al., 2013). One of the reasons why the process of carpet recycling is complicated is the presence of multi-component structure, backing materials as well as dyes and coatings.

TABLE 2. Layout of a typical carpet with a PP/SBR construction

	Constituent	**Composition (in percentage wt.)**
1	Face Fiber (Nylon 6/Nylon 6,6)	45,80
2	PP (Primary backing)	6,11
3	Latex Adhesive	44,27
4	PP (Secondary backing)	3,82
5	**TOTAL**	100

4.3.2 Carpet classification

There are three main carpet classifications: based on its consumption, based on its construction and based on the face fiber used in it.

Based on the consumption carpets may be classified as virgin carpets, pre-consumer carpet waste and post-consumer carpet waste. A virgin carpet is considered to be unused without any history of foot traffic. It is clean and mainly consists of the fiber, backing and various chemical adhesives, fire retardants, dirt resistant, stain resistant dyes, colour dyes, etc. The pre-consumer carpet waste is the waste disposed to landfills from different manufacturing processes. The main sources of such waste are carpet manufacturing and carpet fitting processes. During the production of a carpet the edges of the product are trimmed. These edge trims and off-cuts amount to 12% of the total carpet production. The process of cutting of automotive carpets into various irregular shapes and sizes is called fitting. The leftover waste contributes to the pre-consumer carpet waste. Post-consumer carpet waste includes the old carpets disposed after the use from residential and industrial areas. The average age of the carpet is between 8 and 10 years. The post-consumer carpet weighs more than the virgin one due to the presence of the dogs' hair, metal fragments, bacteria, food, etc (Vaidyanathan et al., 2013).

Based on its construction carpets may be defined as: cut-pile, loop-pile, patterned loop and cut &loop styles. These types of carpet may be produced by weaving, tufting or needle felt type of manufacturing. Weaving includes production of a highest grade carpet in a loom by a process similar to woven cloth. Tufting involves sewing strands of yarn to the backing material. In this way a big amount of yarn loops are created. Cut-pile type of carpet as shown on figure 3 is created by cutting the loops on the top. Loop-pile type of carpet as shown on figure 4 is made in such a way, that the face fiber remains uncut. Patterned loop carpets as shown on figure 5 are made so that the loops are uncut and have multiple heights. Cut & loop type of carpets as shown on figure 6 are made so that the cuts and loops are combined in order to gate wide range of patterns (Vaidyanathan et al., 2013).

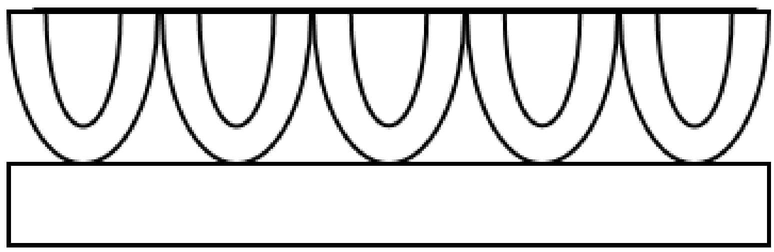

FIGURE 3. Cut-pile type of carpet.

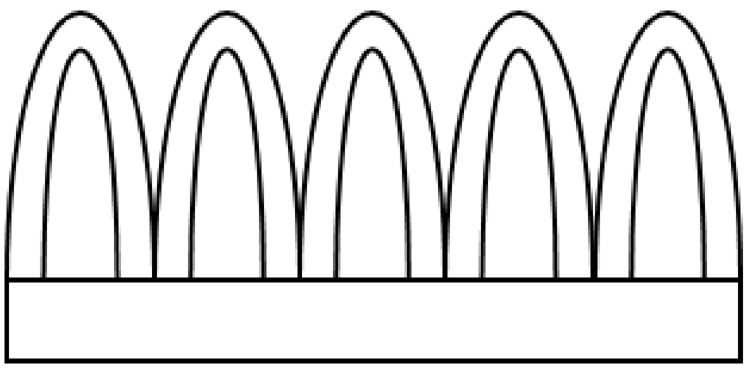

FIGURE 4. Loop-pile type carpet.

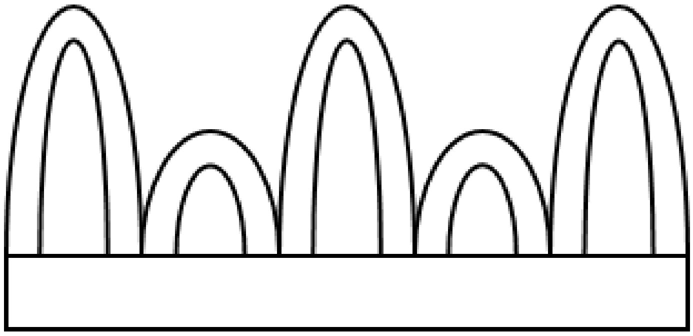

FIGURE 5. Patterned loop type carpet.

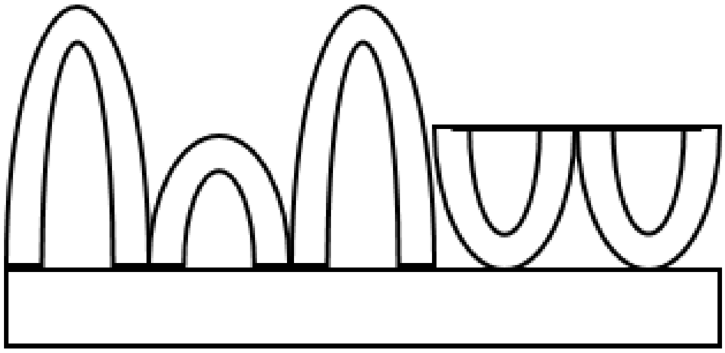

FIGURE 6. Cut & loop type carpet.

Based on the type of material used for the face fiber carpets can be classified as follows: Nylon (made from Nylon 6 or Nylon 6,6), Polyester, Polypropylene (PP), Polyethylene Terephthalate (PET), polyvinylchloride (PVC). Other olefins, jute, rayon, wool, cotton and other materials could be used for the face fiber production as well. Most of the carpets manufactured in the world are made from synthetic fibers. This is explained by the fact that this type of fiber is more resistant to stains while being less expensive. About 90% of all residential carpets and 65% of all carpets are made from nylon. Nylon 6 and Nylon 6,6 account for 45% and 55% of the nylon carpet market (Vaidyanathan et al., 2013).

4.3.3 Postconsumer carpet collection

Collection of postconsumer carpets is an important step prior to the actual recycling. The primary focus is often on buildings with large amounts of discarded carpets, such as large commercial offices (Lave et al., 1998). The availability of big amount of carpet waste reduces hauling costs. The waste owner would most of the time know the type of the face fiber. It is also reasonable to conduct a test to determine the type of carpet fiber prior to removal due to the large amount of collected carpets. In this way the business collecting the carpet which is the first level of processing can collect the desired type of fiber.

Household carpets are also attractive for recyclers since they contain larger amount of face fiber compared to commercial ones. However, the amount of the carpet waste is smaller and the type of fiber is most of the time unknown. The recycler is most likely to collect different types of face fiber. There is a number of available equipment which can be used to identify fiber types. The brief description of that equipment will be provided further on. The collection of carpet waste from the dumpsters is rather challenging. Most of the time large dumpsters are not covered, and thus the waste gets wet and mixes with other trash. In this has the only reasonable solution is to collect the waste which is sorted and kept in a dry place.

Nowadays large-scale carpet producers, such as Shaw Floors or Aquafil, have their own reclamation programs. Within those programs collection network is established in major market location where people can bring their used carpets. Most of these carpet manufacturers also join various programs and initiatives which are aimed to recover carpet waste. A good example of such initiative is Carpet America Recovery Effort (CARE). It is a nonprofit organization which focuses on developing the infrastructure for collection of post-consumer carpets. Through the extensive network of carpet dealers, enterprises and installation companies it was able to recover 520 million pounds of carpet waste in the USA in 2015. Since the launch of CARE in 2002 the total 4,2 billion pounds of carpet waste was diverted from landfills (CARE 2015 Annual Report 2016). People can bring their used carpets to collection sites. The fee is between 5 to 25 cents pound of old carpet. Carpets normally weigh about 4-5 pounds per square yard. This money covers the transportation and recycling costs.

Carpets have been banned from landfill across the European Union. There are currently few operation recycling plants. Most of the waste is incinerated or burned in cement kilns. Some plants closed due to the lack of raw materials. Unfortunately, there is no centralized system of carpet waste collection as compared to the US. This is the worldwide problem. The shortage of collected carpet waste prevents the whole recycling industry from developing.

4.3.4 Postconsumer carpet identification

Many manufacturers today provide brand name on the back of their products making it easier to identify the face fiber. There are a number of codes which might be applied on the back of the carpet. One of the examples is Carpet Component Identification Code (CCIC), which was developed in 1996 by US Carpet and Rug institute and is used in the USA on all the carpets. The code is either printed on the back of the carpet or on an attached bar code (Warmer Bulletin 2000).

The melting point identification is a cheap technique to distinguish between different face fibers based on their melting point. Typically, two heated probes are used. One is heated just above 180ºC and the second one just above 220ºC. Aluminum foil is placed on carpet and probes applied. After ten seconds the foil with probes is removed. Face fiber is determined as nylon 6 if only one dot is melted with the device. If there are two dots, then the fiber is polypropylene. If no dots appear, then the fiber is nylon 6,6, wool, cotton or acryl (Warmer Bulletin 2000). Additional probe can be used in this case to distinguish between the materials.

Near infrared (NIR) spectroscopy is the most reliable way of carpet identification. The face fiber is illuminated. The reflection of the light tells about the type of carpet face material. The example of such equipment is CarPID (Warmer Bulletin 2000). It is a portable device for fast identification of fibers. Large waste carpet handling facilities would normally have automated NIR systems which determine the face fiber within hundreds of the second. Carpets are transported and automatically sorted by stationary device.

4.4 Nylon recycling technology

4.4.1 Classification

Recycling is the breakdown of the product into its raw materials (Leonas 2017). Nylon recycling has developed substantially in the last few years. Most efforts have been focused on recycling of carpets due to the higher value of nylons in comparison with other polymers used in carpet production. According to the US Department of Energy, every year more than 3 billion lb of waste carpets are disposed in the United States alone. About 30% of them are made from nylon 6 (Vaidyanathan et al., 2013).

Typically, carpet consists of layers and various materials are present. Carpets contain not only nylon fiber but also backing material, dyes and coatings. That makes it more difficult for recycling, since the contaminants may affect the overall process.

The technology of recycling of nylon can be divided into four main general categories:

- **Primary recycling or depolymerization**. This method can break down the long polymer chains into their monomeric components. In the case of nylon 6 the monomer is caprolactam. In the case of nylon 6,6 the monomers are hexamethylene diamine and adipic acid.
- **Secondary recycling**. Includes the extraction individual components of polymers without breaking them. Is carried out by extraction or separation.
- **Tertiary recycling**. Preparing thermoplastic mixture by melt blending of carpet waste. No prior separation of carpet waste is required in this case. The product of such recycling is of a lower quality than the original polymer material.
- **Quaternary recycling**. Means energy recovery by incineration of polymer waste (Mihut et al., 2001).

The summary of all the nylon recycling methods is shown on figure 7.

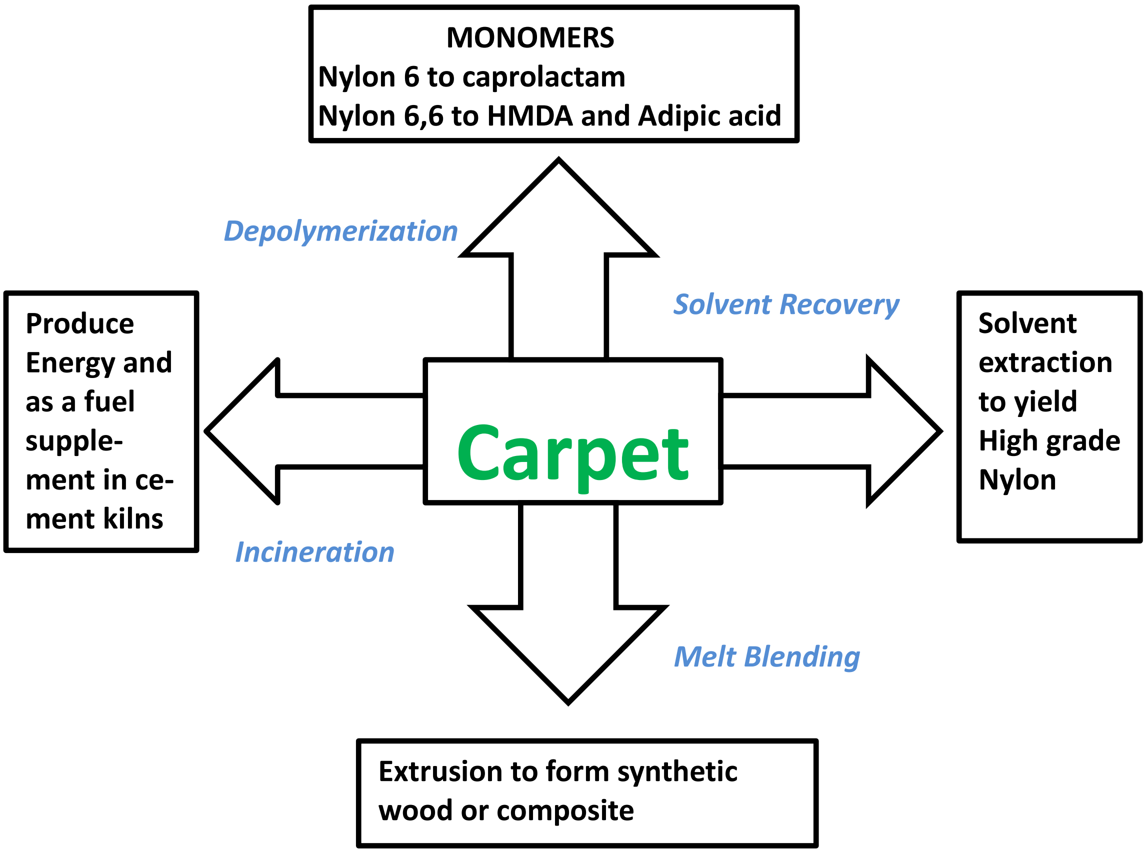

FIGURE 7. A diagram of products obtained by various recycling processes

TABLE 3. Description of primary recycling process of nylon (Mihut et al., 2001).

Purpose of recycling	**Process Description**	**Conditions of the reaction**
Primary recycling or depolymerization		
Full recycling of the nylon component of the carpet into the recycled nylon material. Obtained recycled nylon has the same qualities as the original one.	Polymeric chains are broken down into their monomeric components. Water serves the role of the initiator of the Process. Liquid polymer melt and a gas-phase caprolactam product is formed. The caprolactam monomer and the steam is removed from the reactor resulting in the further monomer formation. Various catalysts may be added during the reaction in order to accelerate the process.	Temperatures above the boiling point of nylon monomers (above 250ºC). Superheated steam is fed to the reactor at a temperature between 100ºC and 450ºC.

TABLE 4. Description of secondary recycling process of nylon (Mihut et al., 2001).

Purpose of recycling	Process Description	Conditions of the reaction
Secondary recycling or extraction of polyamides		
To extract polyamide components from the rest of the carpet. Polyamides are not converted into their monomers. The extracted nylon is then injection molded into other products	The mixture containing nylon is first dissolved in organic solvent which is able to separate nylon from other carpet components. The insolubles are separated from the mixture. The nylon is precipitated by cooling down the mixture.	Temperatures above 200ºC

TABLE 5. Description of tertiary recycling process of nylon (Mihut et al., 2001).

Purpose of recycling	Process Description	Conditions of the reaction
Tertiary recycling or meld blending		
Usage of the carpet material by melting it to a form of a blended mixture. In this way it can be further used in the production of molded polymers or thermoplastics	The original waste melted to obtain the thermoplastic material. The waste without excess dirt is added to the twin screw extruder. Rapid mixing and pressure convert the carpet to a homogneous mixture. The blending of all carpet materials takes place. After cooling the blend it is cut into pellets or chips. The obtained thermoplastic material can be used to produce injection-molded products	Normally at temperature 250-350ºC and pressure of 350-450 psi.

TABLE 6. Description of quaternary recycling process of nylon (Mihut et al., 2001).

Purpose of recycling	Process Description	Conditions of the reaction
Quaternary recycling or incineration		
To recover the energy content of the carpet waste by inceniration.	Two types of ash are produced: fly ash located in the incinerator's exhaust gases and bottom ash consisting of heavy and large particles removed from the bed of the incinerator. The recent municipal solid waste (MSW) combustion technologies involve the recovery of the energy product (steam used for district heating or electricity).	The development of the incineration technologies has lead to a merely complete absence of toxic fumes throughout the whole process.

4.5 Application of recycled nylon

4.5.1 Nylon recycling today

There are a number of examples of a successful implementation of nylon recycling technologies. One of them is the recycling facility of Shaw Industries Inc. The process of recycling was developed by Honeywell International Inc. and DSM Chemicals North America Inc. That is the largest nylon recycling facility in the USA. The end-product of the recycling is caprolactam which could be re-used in the production of the carpet fiber in the future.

Introduction of the closed-loop depolymerization and purification processes led to the recovery of a significant amount of raw material while using less energy. The calcium carbonate used in carpet backing and other polymers can also be recovered. Shaw Industries Evergreen Nylon Recycling facility is able to recover about 25 million pounds of caprolactam and 35 million pounds of calcium carbonate every year (Nylon Carpet Recycing 2012).

TABLE 7. Impact of the implemented technology by Shaw Industries (Nylon Carpet Recycing 2012).

		2007	2008	2009	2010	2011
Energy Saving (Trillion Btu)		0,438	0,455	0,428	0,398	0,516
Emission reduction (Thousand tons)	Carbon	6,953	7,222	6,794	6,318	8,191
	NO_x	0,051	0,053	0,050	0,047	0,060

4.5.2 Recycled nylon fiber as reinforcement

Recycled nylon fiber has a great potential as reinforcement for sustainable construction materials. A recent study performed by Ozger et al. focused on the production of concrete using polyamide fibers from post-consumer textile carpet waste. Various types of nylon 6,6 fibers derived from recycled carpet waste of different colours and of mean length of 8±3 mm were used. A fiber reinforced concrete mix was prepared by mixing limestone cement with recycled nylon 6,6 fibers in a proportion of 5kg/m^3. A number of thermo-mechanical properties, such as compressive and tensile strengths, toughness, specific heat capacity, thermal conductivity, thermal expansion and hydrometric shrinkage were examined. The results indicate that fiber-reinforced concrete suffered less drying shrinkage than the plain concrete (Ozger et al., 2013). That means that less microcracks will appear, thus making the material more durable.

A similar study was performed by Spadea et al. where the concrete was mixed with recycled nylon fibers obtained from waste fishing nets. Abandoned fishing nets were recovered and cut to obtain reinforced fibers at convenient length. Various tests, including bending and compression tests were conducted. The results of the study confirmed that reinforced concrete mix has significantly improved fracture properties. An increase in tensile strength up to 35% was observed (Spadea et al., 2015).

The application of recycled fiber as reinforcement material not only reduces the need for landfilling, but also could lead to improved infrastructure with better durability and reliability. Reinforced concrete could also be applied in pavements, columns, bridge decks, barriers, airport runways and taxiways. Additionally, different studies indicate that recycled nylon fiber could be used in reinforcement of the soil (Wang 2003). That could be practically applied for construction of roadway slopes, sport surfaces, levees, etc. The increasing implementation of green building standards all over the world such as LEED adds up to the development of construction materials with a recycled content. Using the nylon as reinforcement for sustainable construction materials may provide additional points according to LEED rating system in order for the building to be considered as environmentally responsible structure and be certified.

4.5.3 Application in textile and apparel industry

The global movement towards circular economy and closed-loop production is valid for the textile and apparel industry. Main goals of that movement are seen as diverting the waste from the landfills, improving current production processes and waste management behaviours (Leonas et al., 2017). The introduction of synthetic fibers in the twentieth century has slowed down the recycling of textile products. For a long time textile industry has been slow in adopting the practice of recycling.

Recently, there has been great effort and interest in recycling thermoplastic polymer-based fibers like nylon. Most of the time nylon in textile industry is used together with spandex as a blend for high-performance sportswear and active wear (Leonas et al., 2017). The percentage of nylon is much greater than spandex. Spandex can be removed from the blend by dissolving it in solvents like N-dimethylformamide. However, the cost of the solvent is high. There has been another way to remove spandex. It is by treating the blended mixture with heat and applying washing with ethanol. That procedure leaves pure nylon at the end of the recycling process (Leonas et al., 2017).

There are several programs throughout the industry that focus on collecting and processing of the textile waste. A big number of companies have been using recycled nylon fiber. Among them are Levi’s, Milliken, Speedo and others (Leonas et al., 2017). A Powerflex Eco was launched by Speedo in August 2015 in cooperation with Aquafil and Italian yarn maker. The scrap and waste generated during textile manufacturing process is collected and recycled into Econyl fiber. Powerflex Eco is a combination of Econyl (78%) and extra-life nylon fabric (22%) (Leonas et al.,2017). It is chlorine-resistant and retains its shape up to 10 times longer than traditional swimwear. As an additional example, on its website Adidas claims that in 2015 more than 30% of its swimmer collection will be made of recycled nylon (Materials 2017).

4.5.4 Recovery of fishing nets

Abandoned fishermen nets called the "ghost nets" are a great source of used nylon. An average of 640,000 tonnes of fishing nets is left in the oceans every year. That is 1/10 of all the marine litter. The "ghost nets" remain in the seas for years. The marine fauna gets entangled in them and eventually ends up dying. The Healthy Seas Initiative by Aquafil Corporation is an example of recycling of such waste. The rescued fishing nets are transformed into the ECONYL yarn (The Econyl Regeneration System 2017). It is nylon 6 polyamide fibre used as a raw material for further production of carpets, socks, swimwear, underwear, etc.

The Econyl Regeneration System was first introduced in 2011. In the system nylon 6 polymers are manufactured using both post-consumer and pre-consumer types of waste. Aquafil started developing the process in 1998 and continue to expand it by increasing the post-consumer waste collection sites. The company continues to increase the waste-collecting network of sites throughout the world. Currently, the collection sites are located in USA, Egypt, Pakistan, Thailand, Norway and Turkey (The Econyl Regeneration System 2017). Aquafil has partnership with institutions, customers and consortia like Carpet America Recovery Effort (CARE).

4.5.5 Automotive production

Some of the properties of nylon allow its successful usage in automotive industry. Nylon has relatively light weight. It has good chemical resistance, high impact resistance, vibration resistance and low coefficient of friction. Most of the time nylon is used to replace the parts previously made my metal (Ibeh 2011). It is done to reduce the weight of the car and thus improve fuel consumption. Another reason is to lower the costs of the manufacturing and to meet vehicle emission standards.

Many worldwide automotive manufacturers have launched their programs of sustainability development. They strive for the reduction of CO_2 emission levels as well as lowering the consumption of raw materials such as petroleum. Most of the implemented initiatives include the usage of natural fibers and bioplastics made from organic biomass sources in interior lines and surfaces, such as soy-foam seat cushions, sugar-cane based PET, etc.

DuPont has taken it to one step further. It has started a separate Zytel RS line of bioplastics, which contain 60-100% renewable material. It is a collection of nylon products for automotive suppliers (Ibeh 2011). Products can be adapted for different temperature resistance. Ford Motor Co. is using post-consumer recycled nylon in many underhood parts (Recycled Materials 2017).

Many other auto parts are already made from nylon and can possible be made of recyclable nylon. They are: fuel connectors, bumpers, hydraulic clutch lines, engine cooling fans, odometer frames, windshield wiper bearing, mirror housing etc (Ibeh 2011).

4.5.6 Suggested improvements

There are a number of examples of nylon waste recycling facilities being opened in Europe in the past. Unfortunately, most of them had to be closed due to the shortage of the waste supply. There is a current absence of nylon waste collection network. That problem has a worldwide scale. Since landfilling of carpet waste is banned across the EU, most of the waste is incinerated. As it has been previously mentioned, this is not the most economically reasonable solution. Carpet consumers should have an opportunity to drop-off their used carpet at the collection point nearby for reasonable fee. The primary effort should be focused on establishing the network of waste collection points. The example of successful carpet waste collection scheme implementation may be CARE initiative in the US. Carpet manufacturers together with local carpet dealers, carpet installation companies, governmental institutes, trade associations, and public agencies joined forces to collect and recycle nylon waste. Government can also force carpet manufacturers to take back and recycle their carpets or force carpet selling dealers deliver discarded carpet waste to the recycler.

Nylon recycling industry is also affected by macro economical reasons. Current low prices of oil make virgin fiber cheap. Current decline of China’s economy also has negative effect on the industry, since China is the world’s largest consumer of recycled nylon (CARE 2015 Annual Report 2016). Carpet manufacturers using recycled fiber in their production should be economically stimulated and have their extra expenses compensated. It can be done in a form of tax reduction, lowering prices for consumed energy resources or other ways.

There is always space for improvement of nylon product quality. Industry should strive for production of a more durable carpet product with superior qualities like stain and fire resistance, soil and water repellence. This will prolong the useful life of a carpet and thus prevent it from disposal. Nylon product developers should focus their research on production of a carpet of a simple structure consisting of only one or two materials without mineral fillings and secondary backings. This will make the process of recycling and product break-down much easier.

Consumers on their behalf can choose carpet suppliers which use recyclable materials in their production. Carpets should be clearly labelled to identify the source of raw materials used for their production.

5 ENVIRONMENTAL STUDY OF NYLON CARPETS

5.1 ISO 14025

The study of three most selling nylon carpet types of a retail carpet store will be based on the ISO 14025 standard. The purpose of the study is to distinguish the most environmentally friendly type of nylon carpets out of all selected for the study. The obtained results will be used in the future during procurement of nylon carpets. ISO 14025 standard is called “Environmental Labels and Declarations”. The standard provides quantified environmental information on a life cycle of a product in order to compare between the products with the same function. Standard can be treated as a tool to assist purchases and users make comparisons between products and encourage improvement of environmental performance of the organization (International Standard ISO 14025 2006).

5.2 Environmental study

For the study three nylon carpets were selected. Sample 1 is nylon 6,6 fiber carpet with vinyl backing manufactured in tiles. EPD of sample 1 is attached as appendix 1 (Westbond N9000 Carpet Tile 2013). Sample 2 is nylon 6 fiber carpet with polyester backing manufactured in tiles. EPD of sample 2 is attached as appendix 2 (Tessera Basis and Teviot Carpet Tile 2013). Sample 3 is nylon 6 fiber carpet with polyester backing designed for entrance areas with dirt and moisture absorbance properties. EPD of sample 3 is attached as appendix 3 (Coral Classic 2013). Product specifications of all three samples are listed in table 8.

TABLE 8. Product specifications of samples 1-3.

Characteristics	**Sample 1**	**Sample 2**	**Sample 3**
Product Thickness (mm)	9	6	10
Product Weight (g/m^2)	4000	3835	3400
Tile Size (cm)	50*50	50*50	-

The compositional structure of all three samples is presented in table 9.

TABLE 9. Compositional structure of samples 1-3.

Component	**Material**	**Amount (%)**	**Component**	**Material**	**Amount (%)**
Sample 1			**Sample 2**		
Carpet Pile	Nylon 6,6	23,75	Yarn	Nylon 6	13
Substrate	Glass Tissue	1,50	Primary backing	Nylon 6 Polyester	1 2
Plasticizer	DINP	6,28	Pre-coat	Synth. Latex Calc. Carbon.	2 14
Backing	Mixed vinyl waste	42,50	Backing	Bitumen Calc. Carbon.	23 42
Polymer	PVC	14,80	Secondary backing	Polyester	3
Fire retardant	Aluminium hydrox-ide	5,88	**Sample 3**		
Filler	Calcium carbonate	3,72	Yarn	Nylon 6	26
Antistat	Antistatic agent	1,37	Primary backing	Nylon 6 Polyester	1 2
Additives	Various chemicals	0,20	Backing	PVC Calc. Carbon. DINP Pigments	25 25 20 1

Comparative table 10 was created as the result of the study. All values were taken for the production stage of the lifecycle only. The value of waste generated, resources consumed and environmental impact are shown for one year usage.

TABLE 10. Comparative table with the results of the study.

Characteristics	**Sample 1**	**Sample 2**	**Sample 3**
Total non-renewable primary energy (MJ/m^2)	448,71	238,47	439,1
Total renewable primary energy (MJ/m^2)	7,7	11,2	12,43
Hazardous waste (kg)	0,00129	0,000236	0,103
Non-hazardous waste (kg)	25,5	11	27,2
Radioactive waste (kg)	0,0094	0,00461	0,0091
Non-renewable resources (kg)	27,19	13,23	29,02
Global Warming Potential (kg CO_2)	34,3	11,1	29,9

5.3 Study results

It may be assumed that sample 2 is the most environmentally friendly choice and has the best environmental performance. It is the carpet with nylon 6 fiber and polyester backing. The amount of consumed non-renewable primary energy per one square meter of that product is almost twice lower than of other two samples. Amounts of generated waste (hazardous, non-hazardous, and radioactive), consumed non-renewable resources and environmental impact are also the lowest out of three.

Second most environmentally friendly option is sample 1. It is a nylon 6,6 carpet with vinyl backing. Amounts of consumed non-renewable primary energy, generated non-hazardous and radioactive wastes, as well as environmental impact are similar of samples 1 and 3. Almost twice less renewable energy is used for production of sample 1 than sample 3. What makes the difference is the amount of hazardous waste generated by sample 3, which is nylon 6 carpet with polyester backing designed for entrance areas. It is 100 times larger than of sample 1. That may be explained by the designed durability, wet and dirt absorption qualities of sample 3. Sample 1 is on the second place for environmental performance after sample 2.

6 DISCUSSION

ISO certification is done on voluntarily basis. EPDs of the actual carpets sold by the carpet retailer store in Tampere, Finland were unavailable, since the company is not ISO 14025 certified. EPDs of similar products with the same carpet architecture and content but produced by other manufacturers were used for the study. It may be assumed that the actual nylon carpets would have the same or similar characteristics. However, some deviation in comparison figures and even final results might occur if true manufacturers would obtain certification and publish their EPDs.

For the environmental study only data for the production stage of the whole lifecycle process was used. This was done since in all the impact categories the production stage has the most significant contribution to the overall impact. It may be assumed that this stage of the lifecycle provides the most important data for comparison. Transport, installation, use and end of life stages contribute little to the overall impact. Transport of materials and products, as well as related energy and water use may vary in different countries and should be adopted for local conditions.

The purpose of the environmental study was to assist the management of the carpet store make the comparison between sold products and distinguish the product with the best environmental performance. However, the provided study can only act as a recommendation or consultation. The further implementation of the results should be carried out by the store management.

The comparison between different recycling methods for the best economical and environmental solution was not carried out and included to the report. This is explained by limitations of the size of the report, the extensiveness of the topic and lack of actual production and recycling data from operating facilities, which is often treated as confidential.

Lifecycle of the nylon consists of the following main steps: nylon polymerization, carpet manufacturing, product use, waste disposal, waste collection and recycling. It can have the closed-loop circular structure under the condition that the nylon waste material is collected and recycled. Nylon waste is a valuable raw material. That is why waste generated by the industry can and should be recycled. Landfilling of nylon waste should be avoided and replaced with recycling process. Nylon carpet has a complex structure. It consists of face fiber, filler and backing materials. Recycling of nylon carpets is also a complex process. Different materials used in caret structure affect the recycling and thus should be treated separately. Industry should strive for production of a more durable carpet product with superior qualities like stain and fire resistance, soil and water repellence, which would prolong the useful life of a carpet and thus prevent it from disposal. Nylon product developers are recommended to focus their research on production of a carpet of a simple structure consisting of only one or two materials without mineral fillings and secondary backings. This will make the process of recycling and product break-down much easier.

Literature and patent reviews suggest that four categories of nylon recycling exist: depolymerization, extraction, melt-blending, and incineration. Each type of recycling is used for particular purposes and for creation of specific products. Nylon waste material recycled by depolymerization is primarily used in carpet re-production, automotive, textile, and construction industries. Extraction method provides valuable polyamide components which are separated from the rest of the carpet. The extracted nylon is then injection molded into other products. Meld blending involves the usage of the carpet material by melting it to a form of a blended mixture. In this way it can be further used in the production of molded polymers or thermoplastics. Incineration allows partly recovery of the energy content of the carpet waste material by burning it.

It may also be assumed that the biggest challenge the industry faces is the lack of waste collection network on a local and global levels to supply recycling facilities with raw materials. Collection of nylon carpet waste should primarily target residential sector where carpets contain larger amount of valuable nylon face fiber. A network of collection sites with the possibility of fiber identification is a successfully operating model of nylon waste handling which should be possible implemented on a larger scale. The second challenge for the industry is the current low price of oil which is the raw material for virgin nylon fiber production. The price of virgin face fiber might be lower than the price of reprocessed waste fiber. As a possible solution support and stimulation of nylon manufacturers by government regulations to use recycled waste for carpet production can be proposed. Government can also force carpet manufacturers to take back and recycle their carpets or force carpet selling dealers deliver discarded carpet waste to the recycler. Consumers on their behalf are recommended to choose carpet suppliers which use recyclable materials in their production.

7 CONCLUSIONS

The environmental study based on environmental product declarations of three nylon carpet products sold at the carpet retailer store in Tampere, Finland reviles that out of three nylon carpet samples studied, the one with nylon 6 face fiber and polyester backing had the best environmental performance. The amount of consumed non-renewable primary energy per one square meter of that product was the lowest. Amounts of generated waste (hazardous, non-hazardous, and radioactive), consumed non-renewable resources and environmental impact were also the lowest out of three. It is recommended for the management of the retail store to purchase this type of nylon carpets and promote it among their customers, since it is the most environmentally friendly out of studied samples. The second place was given to nylon 6,6 fiber carpet with vinyl backing. The third place was given to nylon 6 face fiber carpet with mixed PVC, DINP and polyester backing.

The lifecycle of nylon consists of the following main steps: nylon polymerization, carpet manufacturing, product use, waste disposal, waste collection, recycling.

Four categories of nylon recycling methods are: depolymerisation (primary recycling), extraction (secondary recycling), melt-blending (tertiary recycling), incineration (quaternary recycling).

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APPENDICES

Appendix 1. Life Cycle Inventory Analysis taken from EPD of Sample 1 (Westbond N9000 Carpet Tile 2013).

The total primary energy for one square meter installed Westbond N9000 is presented in table 3 with their specific energy resources.

Table 3: Primary energy for all life cycle stages for Westbond N9000 for one year

Non-renewable primary energy by resources	Unit	Total Life cycle (MJ)	Total Life cycle (%)	Production	Transport	Installation	Use (1 yr)	End of Life
Total non-renewable primary energy	MJ	450.48	100%	448.71	0.74	7.17	5.84	-11.99
Crude oil	MJ	179.37	39.8%	169.77	0.68	2.94	0.63	5.34
Hard coal	MJ	20.79	4.6%	17.86	0	0.23	0.98	1.72
Lignite	MJ	19.99	4.4%	18.07	0	0.22	0.74	0.95
Natural gas	MJ	202.63	45.0%	217.46	0.06	3.62	1.74	-20.24
Uranium	MJ	27.7	6.1%	25.55	0	0.16	1.74	0.25
Renewable primary energy by resources	**Unit**	**Total Life cycle (MJ)**	**Total Life cycle (%)**	**Production**	**Transport**	**Installation**	**Use (1 yr)**	**End of Life**
Total renewable primary energy	MJ	8.12	100%	7.7	0.03	0.1	0.79	-0.5
Geothermical	MJ	0.22	2.7%	0.23	0	0	0.01	-0.01
Hydro power	MJ	2.75	33.9%	2.63	0	0	0.32	-0.2
Solar energy	MJ	2.51	30.9%	2.37	0.03	0.06	0.23	-0.17
Wind power	MJ	2.64	32.5%	2.48	0	0.04	0.23	-0.11

The renewable and non-renewable primary energy is mainly determined by the production stage for a one year usage; within the production stage the main contributors are the raw material production and energy generation.

Waste and non-renewable resource consumption

In table 4 the non-renewable resource consumption and waste production are shown for all life cycle stages for a one year usage.

Table 4: Waste categories and non-renewable resources for Westbond N9000 (one year)

Wastes	Unit	Total Life cycle	Production	Transport	Installation	Use (1yr)	End of Life
Hazardous waste	[kg]	2.30E-03	1.29E-03	0.00E+00	1.01E-03	0.00E+00	0.00E+00
Non-hazardous waste	[kg]	2.90E+01	2.55E+01	2.63E-03	4.57E-01	1.12E+00	1.97E+00
Radioactive waste	[kg]	1.02E-02	9.40E-03	1.03E-06	1.29E-04	7.12E-04	-7.09E-05
Resources	**Unit**	**Total Life cycle**	**Production**	**Transport**	**Installation**	**Use (1yr)**	**End of Life**
Nonrenewable resources	[kg]	33.08	27.19	0	0.5	1.13	4.26

Life Cycle Assessment

In table 5 the environmental impacts for one lifecycle are presented for Westbond N9000. In table 6 the environmental impacts are presented for all the lifecycle stages.

Table 5: Results of the LCA – Environmental impacts one lifecycle (one year) – Westbond N9000

Impact Category : CML 2001 – Nov. 2010	Westbond N9000	Unit
Global Warming Potential (GWP 100 years)	3.43E+01	kg CO2-Equiv.
Ozone Layer Depletion Potential (ODP, steady state)	6.55E-07	kg R11-Equiv.
Acidification Potential (AP)	4.76E-02	kg SO2-Equiv.
Eutrophication Potential (EP)	6.07E-03	kg Phosphate-Equiv.
Photochem. Ozone Creation Potential (POCP)	1.14E-02	kg Ethene-Equiv.
Abiotic Depletion Potential Elements (ADPE)	2.16E-05	kg Sb-Equiv.
Abiotic Depletion Potential Fossil (ADPF)	4.37E+02	[MJ]

Table 6: Results of the LCA – Environmental impact for Westbond N9000 (one year)

Impact Category : CML 2001 – Nov. 2010	Unit	Production	Transport	Installation	Use (1yr)	End of Life
Global Warming Potential	kg CO2-Equiv.	2.50E+01	1.02E-01	7.03E-01	3.22E-01	8.15E+00
Ozone Layer Depletion Potential	kg R11-Equiv.	5.94E-07	9.31E-13	2.67E-09	2.30E-09	5.66E-08
Acidification Potential	kg SO2-Equiv.	3.81E-02	2.22E-04	1.13E-03	1.35E-03	6.76E-03
Eutrophication Potential	kg PSO4-Equiv.	4.63E-03	5.07E-05	1.44E-04	8.29E-05	1.17E-03
Photochem. Ozone Creation Potential	kg Ethene-Equiv.	1.09E-02	-7.67E-05	1.84E-04	9.17E-05	3.24E-04
Abiotic Depletion Elements	kg Sb-Equiv.	1.81E-05	1.99E-09	2.42E-07	6.36E-08	3.23E-06
Abiotic Depletion Fossil	MJ	4.35E+02	7.38E-01	7.16E+00	5.78E+00	-1.23E+01

The relative contribution of each process stage to each impact category for Westbond N9000 is shown in the figure 4.

Appendix 2. Life Cycle Inventory Analysis taken from EPD of Sample 2 (Tessera Basis and Teviot Carpet Tile 2013).

Life Cycle Inventory Analysis

The total primary energy for one square meter installed Basis/Teviot is presented in table 3 with their specific energy resources.

Table 3: Primary energy for all life cycle stages for Basis/Teviot for one year

Non-renewable primary energy by resources	Unit	Total Life cycle (MJ)	Total Life cycle (%)	Production	Transport	Installation	Use (1 yr)	End of Life
Total non-renewable primary energy	MJ	238.06	100%	238.47	1.43	7.13	16.41	-25.39
Crude oil	MJ	124.29	52.2%	113.99	1.31	2.89	0.87	5.23
Hard coal	MJ	12.68	5.3%	7.95	0	0.19	3.27	1.27
Lignite	MJ	10.55	4.4%	7.29	0	0.2	2.44	0.62
Natural gas	MJ	72.21	30.3%	96.36	0.1	3.7	3.98	-31.93
Uranium	MJ	18.28	7.7%	12.88	0	0.15	5.81	-0.56
Renewable primary energy by resources	**Unit**	**Total Life cycle (MJ)**	**Total Life cycle (%)**	**Production**	**Transport**	**Installation**	**Use (1 yr)**	**End of Life**
Total renewable primary energy	MJ	13.17	100%	11.2	0.03	0.1	2.72	-0.88
Geothermical	MJ	0.14	1.1%	0.11	0	0	0.05	-0.02
Hydro power	MJ	2.09	15.9%	1.35	0	0	1.08	-0.36
Solar energy	MJ	9.58	72.7%	8.97	0.03	0.06	0.81	-0.29
Wind power	MJ	1.36	10.3%	0.76	0	0.04	0.77	-0.21

The renewable and non-renewable primary energy is mainly determined by the production stage for a one year usage; within the production stage the main contributors are the raw material production and energy generation

Waste and non-renewable resource consumption

In table 4 the non-renewable resource consumption and waste production are shown for all life cycle stages for a one year usage.

Table 4: Waste categories and non-renewable resources for Basis/Teviot (one year)

Wastes	Unit	Total Life cycle	Production	Transport	Installation	Use (1yr)	End of Life
Hazardous waste	[kg]	1.17E-03	2.36E-04	0.00E+00	9.32E-04	0.00E+00	0.00E+00
Non-hazardous waste	[kg]	1.66E+01	1.10E+01	4.19E-03	4.40E-01	3.69E+00	1.48E+00
Radioactive waste	[kg]	6.73E-03	4.61E-03	1.93E-06	1.18E-04	2.40E-03	-4.00E-04
Resources	**Unit**	**Total Life cycle**	**Production**	**Transport**	**Installation**	**Use (1yr)**	**End of Life**
Nonrenewable resources	[kg]	21.14	13.23	0	0.43	3.71	3.76

Table 5: Results of the LCA – Environmental impacts one lifecycle (one year) – Basis/Teviot

Impact Category : CML 2001 – Nov. 2010	Basis/Teviot	Unit
Global Warming Potential (GWP 100 years)	2.02E+01	kg CO2-Equiv.
Ozone Layer Depletion Potential (ODP. steady state)	4.16E-07	kg R11-Equiv.
Acidification Potential (AP)	4.52E-02	kg SO2-Equiv.
Eutrophication Potential (EP)	5.84E-03	kg Phosphate-Equiv.
Photochem. Ozone Creation Potential (POCP)	1.15E-02	kg Ethene-Equiv.
Abiotic Depletion Potential Elements (ADPE)	7.54E-06	kg Sb-Equiv.
Abiotic Depletion Potential Fossil (ADPF)	2.30E+02	[MJ]

Table 6: Results of the LCA – Environmental impact for Basis/Teviot (one year)

Impact Category : CML 2001 – Nov. 2010	Unit	Production	Transport	Installation	Use (1yr)	End of Life
Global Warming Potential	kg CO2-Equiv.	1.11E+01	1.58E-01	5.52E-01	9.29E-01	7.41E+00
Ozone Layer Depletion Potential	kg R11-Equiv.	3.56E-07	1.37E-12	1.81E-09	9.95E-10	5.69E-08
Acidification Potential	kg SO2-Equiv.	3.22E-02	1.91E-03	1.01E-03	4.39E-03	5.71E-03
Eutrophication Potential	kg PSO4-Equiv.	4.19E-03	2.22E-04	1.26E-04	2.32E-04	1.08E-03
Photochem. Ozone Creation Potential	kg Ethene-Equiv.	1.08E-02	2.28E-05	1.78E-04	2.59E-04	1.95E-04
Abiotic Depletion Elements	kg Sb-Equiv.	4.01E-06	3.41E-09	1.88E-07	1.29E-07	3.21E-06
Abiotic Depletion Fossil	MJ	2.31E+02	1.43E+00	7.13E+00	1.64E+01	-2.58E+01

The relative contribution of each process stage to each impact category for Basis/Teviot is shown in the figures 4.

Appendix 3. Life Cycle Inventory Analysis taken from EPD of Sample 3 (Coral Classic 2013).

Life Cycle Inventory Analysis

The total primary energy for one square meter installed Coral Classic is presented in table 3 with their specific energy resources.

Table 3: Primary energy for all life cycle stages for Coral Classic for one year

Non-renewable primary energy by resources	Unit	Total Life cycle (MJ)	Total Life cycle (%)	Production	Transport	Installation	Use (1 yr)	End of Life
Total non-renewable primary energy	MJ	445.34	100	439.1	1.25	6.3	16.41	-17.72
Crude oil	MJ	169.52	38%	160.81	1.15	2.8	0.87	3.89
Hard coal	MJ	26.92	6%	22.75	0	0.09	3.27	0.81
Lignite	MJ	18.78	4%	15.82	0	0.13	2.44	0.39
Natural gas	MJ	199.81	45%	214.77	0.09	3.31	3.98	-22.34
Uranium	MJ	30.27	7%	24.94	0	-0.02	5.81	-0.46
Renewable primary energy by resources	**Unit**	**Total Life cycle (MJ)**	**Total Life cycle (%)**	**Production**	**Transport**	**Installation**	**Use (1 yr)**	**End of Life**
Total renewable primary energy	MJ	14.59	100	12.43	0.04	0.03	2.72	-0.63
Geothermical	MJ	0.22	2%	0.19	0	0	0.05	-0.02
Hydro power	MJ	8.18	56%	7.38	0	-0.02	1.08	-0.26
Solar energy	MJ	3.33	23%	2.64	0.04	0.04	0.81	-0.2
Wind power	MJ	2.79	19%	2.15	0	0.02	0.77	-0.16

The total amount of renewable and non-renewable primary energy is predominated by the production stage for a one year usage; within the production stage the main contributors are the raw material production and energy generation.

Waste and non-renewable resource consumption

In table 4 the non-renewable resource consumption and waste production are shown for all life cycle stages for a one year usage.

Table 4: Waste categories and non-renewable resources for Coral Classic (one year)

Wastes	Unit	Total Life cycle	Production	Transport	Installation	Use (1yr)	End of Life
Hazardous waste	[kg]	1.49E+00	1.03E-01	0.00E+00	2.77E-02	0.00E+00	0.00E+00
Non-hazardous waste	[kg]	3.27E+01	2.72E+01	4.29E-03	3.98E-01	3.94E+00	2.24E+00
Radioactive waste	[kg]	1.12E-02	9.10E-03	1.73E-06	1.13E-04	2.40E-03	-3.53E-04
Resources	**Unit**	**Total Life cycle**	**Production**	**Transport**	**Installation**	**Use (1yr)**	**End of Life**
Nonrenewable resources	[kg]	35.61	29.02	0.01	0.27	3.71	2.60

Table 5: Results of the LCA – Environmental impacts one lifecycle (one year) – Coral Classic

Impact Category : CML 2001 – Nov. 2010	Coral Classic	Unit
Global Warming Potential (GWP 100 years)	2.99E+01	kg CO2-Equiv.
Ozone Layer Depletion Potential (ODP. steady state)	6.20E-07	kg R11-Equiv.
Acidification Potential (AP)	5.42E-02	kg SO2-Equiv.
Eutrophication Potential (EP)	5.87E-03	kg Phosphate-Equiv.
Photochem. Ozone Creation Potential (POCP)	1.32E-02	kg Ethene-Equiv.
Abiotic Depletion Potential Elements (ADPE)	2.90E-02	kg Sb-Equiv.
Abiotic Depletion Potential Fossil (ADPF)	4.34E+02	[MJ]

Table 6: Results of the LCA – Environmental impact for Coral Classic (one year)

Impact Category : CML 2001 – Nov. 2010	Unit	Production	Transport	Installation	Use (1yr)	End of Life
Global Warming Potential	kg CO2-Equiv.	2.32E+01	1.66E-01	5.25E-01	9.29E-01	5.01E+00
Ozone Layer Depletion Potential	kg R11-Equiv.	5.78E-07	1.50E-12	1.10E-09	9.95E-10	3.97E-08
Acidification Potential	kg SO2-Equiv.	4.44E-02	6.37E-04	8.00E-04	4.39E-03	3.90E-03
Eutrophication Potential	kg PSO4-Equiv.	4.68E-03	1.07E-04	1.06E-04	2.32E-04	7.45E-04
Photochem. Ozone Creation Potential	kg Ethene-Equiv.	1.27E-02	-9.69E-05	1.64E-04	2.59E-04	1.55E-04
Abiotic Depletion Elements	kg Sb-Equiv.	2.90E-02	3.29E-09	1.49E-07	1.29E-07	2.16E-06
Abiotic Depletion Fossil	MJ	4.28E+02	1.25E+00	6.29E+00	1.64E+01	-1.80E+01

The relative contribution of each process stage to each impact category for Coral Classic is shown in figure 3.