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ORIGINAL PAPER

Life Cycle Assessment on a Bus Body Component Based on Hemp Fiber and PTP®

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Abstract The application of renewable raw materials in the automotive sector became more and more interesting in the last years. For the first time, a material system based on natural fibers and PTP®, a vegetable based thermoset resin, was produced and manufactured into a bus body component by Sheet-Moulding-Compound-technology. The Life Cycle Assessment on this component based on renewable raw materials shows advantages especially in the categories fossil resources and global warming. It can be expected that further concepts of development and optimization lead to a more efficient use of materials and so to an additional reduction of environmental impacts.

Keywords Life-Cycle-Assessment · PTP® · Thermoset based on renewable resources · Hemp fiber (*Cannabis sativa* L.) · SMC

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Introduction

The use of renewable resources for industrial materials satisfies many criteria in terms of a sustainable product life cycle. On one hand the carbon dioxide cycle is nearly closed, because after use of the material, the quantity of carbon dioxide is emitted which was assimilated by the plant out of the atmosphere before. On the other hand the vegetable raw materials are renewable helping to save fossil resources. Many products out of renewable raw materials have also the advantage of a good biodegradability. Another point is that the cultivation of renewable raw materials is a further income source in the agricultural sector [1].

Renewable raw materials have an interesting application potential in the automotive sector [2]. The material use of natural fibers covers a broad field of application. So nonwovens, felts and composites out of natural fibers can be found in decor materials, interior casings, insulation products, upholstery etc.

Hitherto, the application of renewable raw materials in composites concentrates mainly on natural fibers, like wood, cotton, flax, jute, hemp, kenaf and sisal. An example for an innovative product, the instrument panel out of natural fiber reinforced polyurethane should be mentioned [3, 4]. Flake et al. have shown that natural fiber composites have ecological benefits concerning the input of material and energy in comparison to the fossil variants [5]. They saw further ecological potential for improvement in the substitution of the petrochemical resin-hardener-system by systems based on renewable raw materials [6].

For the first time, a material system based on natural fibers and PTP®, a vegetable based thermoset resin, was produced in a research and development project community around the 'Ingenieurgemeinschaft für Landwirtschaft and Umwelt' (IGLU, Germany), the 'Faserinstitut Bremen e.V.' (FIBRE, Germany), Bio-Composites and More GmbH (B.A.M., Germany), (NAFGO, Germany), the Institute of Geoecology—Technical University of Braunschweig, Germany and the 'Braunschweiger Kunststofftechnik GmbH' (BKT, Germany). This material system was successfully manufactured into a bus body component by Sheet-Moulding-Compound (SMC)—technology and was successfully tested on-road at a passenger bus of the Braunschweiger Verkehrs-AG for over 1 year [7].

The SMC-technology is characterized by a press-mould procedure from semi-finished products made out of resin-impregnated fiber. In general glass fibers and unsatured polyester resin are used for this purpose. For the manufacturer of the component the procedure offers the advantage that a semi-finished product complete with reaction resin, hardener, reinforcement fibers and filler materials can be procured and moved on directly into further processing. According to [8] the production of SMC showed an upward trend in Europe in 2006, although the trend turned back in 2005 due to the decreasing automobile production and the oil prize increase. The automotive industry is one of the largest market. So, the application of SMC-technology constitutes a most promising perspective for the production of the new material system based on renewable materials. This is stressed by the fact that due to the sharp oil increase, the reinforced plastics industry looked very thoroughly at the potential of natural fibers as reinforcement fibers or as "thinner" for matrices based on oil [8].

The finally in our work realized material was the result of numerous developed variants and the analyses about the technical suitability of these (see [7]). How far this material system based on natural raw materials was more environmentally friendly or not than the alternative material system based on fossil raw materials was analyzed by Life Cycle Assessment (LCA). This contribution shall give a survey of these studies.

Method of Ecological Assessment

The goal of the Life Cycle Assessment (LCA) is the balancing and assessment of all the environmental impacts caused by the entire life cycle of the newly developed component based on renewable raw materials in comparison to the reference component which is conventionally made out of glass fiber reinforced polyester resin.

The LCA realized within the project followed the ISO-norms 14040–14043. The phases of LCA are structured into goal and scope definition, inventory analysis, impact assessment and interpretation (see Fig. 1).

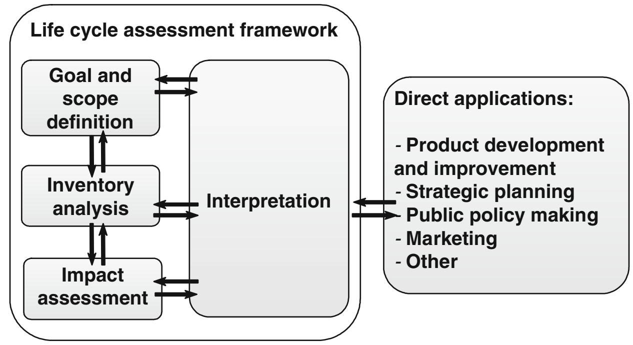

Fig. 1 Framework of the life cycle assessment [9]

Functional Unit

The functional unit is the quantified performance of a product system for use as a reference unit in a life cycle assessment study and is described in the goal and scope definition [9].

In this study the functional unit referred to a body component casing the middle section between the headlights above the fender of a MAN-passenger-bus of the series A10/A11 with the MAN-reference number 81.79.201-6017. Figure 2 shows a drawing of the component and a photo of the realized component assembled at the bus.

With its current material the component weighed 3.6 kg in glass/polyester and was produced by (BKT GmbH, Germany) as part of the spare parts production for bus models. The component was mounted in the visible area on the front of the bus and had to meet a high standard of surface quality. For a detailed analysis of the material properties see [7].

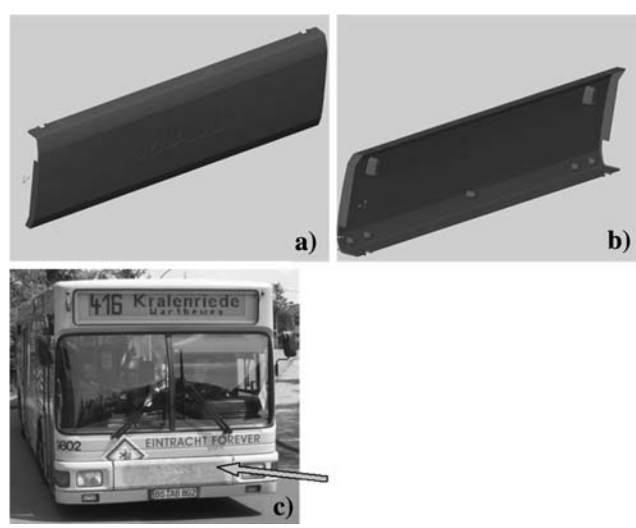

Fig. 2 (**a**) CATIA drawing of the component front, (**b**) back, and (**c**) realized component

System Boundaries

The system boundaries of the scope include all the processes which are integrated into the system to be modeled. The goal is the description of the inputs and outputs as elementary flows at the system boundary, i.e. the material or energy do not suffer any previous or subsequent human transformation.

The scope of the product systems in consideration included the entire life cycle of the bus body component, i.e. the raw materials acquisition, the production of the semi-finished parts (prepregs) and of the body components, the use phase and the disposal. In the following the current material system based on glass fibers and polyester resin is marked as GF-UP. The material system made of natural fibers and the vegetable based thermoset resin is abbreviated as NFK.

In the framework of the comparative LCA the processes were neglected which are identical in all product systems to be studied because these processes did not have any effect on the final results. These negligible processes were intraplant transports, varnishing, assembly and dismantling.

The use phase is very important for the LCA of automotive parts. The reduction of mass of a component leads to a lower consumption of fuel, so that fossil resources are saved and emissions are reduced. In the framework of the project one NFK-variant could be produced which was 0.9 kg lighter (=25% mass reduction) than the GF-UP-component. For the other NFK-variants the same mass as for the GF-UP-prepreg out of glass fiber/polyester was used, so that no difference of the environmental impacts was expected in the use phase and the use phase was neglected in the balancing of these variants.

The product system of the NFK-component based on renewable resources is shown in Fig. 3. The scope of this component differed from the reference-component out of glass fiber/polyester mainly in a way that agricultural prechains were necessary for the supply of the biogenous raw materials.

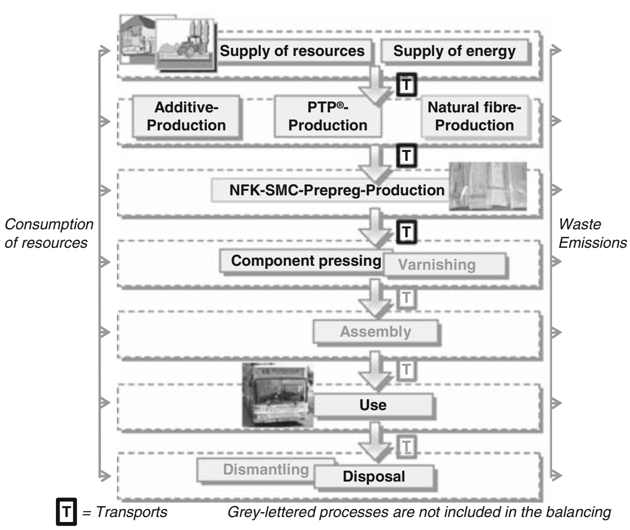

Fig. 3 Product system of the NFK-component

Handling of Co-products and Allocation

Comparing the environmental effects of the product systems it must be considered that all these systems have the same functions. This is not trivial if there is more than one useable product (co-product) in a process. For the warranty of the function equivalent of the systems equivalent processes are determined in the first step. These equivalent processes are primary processes which are substituted by the co-products. In this study the environmental effects of the equivalent processes were subtracted from the effects of the product system, i.e. a credit was carried out. This could possibly lead to negative environmental effects. Figure 4 gives a survey.

If an extension of the system was not possible or recommendable the inputs and outputs of the process would be partitioned or allocated respectively. The allocation could be done according to mass, actual value or other properties of the products.

The agricultural cultivation of renewable raw materials shows a special characteristic. The agricultural cultivation proceeds on areas on which processes occur, either if no renewable raw materials are cultivated (e.g. cultivation of wheat). So in the product system of the reference GF-UP-component the area was not required for the cultivation of hemp, but it was used however. According to [10] who described the problem of choice of the reference system in detail, an annual actively vegetated fallow was chosen and entered negatively in the balance sheet of the NFK-product systems.

Description of the Product Systems and Database—Inventory Analysis

In the inventory analysis the data required for the LCA are collected and calculated. In the phase of preparation a system flow network was developed which contained the modeled unit processes and its interactions. A unit process was the smallest element of a product system. Also the

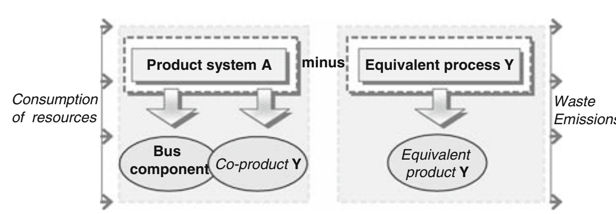

Fig. 4 System boundary of co-products

functions, the inputs and the outputs of the unit processes were described qualitatively and quantitatively. The final result was a balance sheet which contains all material and energy flows which entered or left the product system.

For the modeling of the product systems of the bus body components and the calculation of the environmental impacts the software Umberto® with the additional database Ecoinvent® was used [11].

Table 1 lists the characteristics of the bus component variants analyzed in the LCA.

Production of the Components

NFK-Component The basic materials which were needed for the NFK-SMC-prepreg are natural fibers, resin and hardener system (PTP®) with catalysts and additives.

Hemp Fiber. For the trials hemp (*Cannabis sativa* L.) was selected as suitable natural fiber. The fibers used were provided by the company (NAFGO GmbH, Germany). The hemp variety Fedora was grown near Neerstedt (region Oldenburg, Germany), 2002 and briefly field-retted. The cultivation of the hemp with the prechains of the fertilizer and the agricultural machine-use as well as the nitrogen emissions from the field (N_2O, NH_4) was included in the balancing (see Table 2).

The stems were coarse separated using a DEMTEC® line with four drums (Demaitre B.V., Belgium). For the trials the fibers were cut to a length of 6 and 20 mm

Table 1 Characteristics of the component variants analyzed in the LCA

Abbreviation	Characteristics
GF-UP	Material system based on glass fiber and unsatured polyester resin
NFK I	Material system based on hemp fiber (28 mass%) and PTP®
NFK II	Material system based on hemp fiber (14 mass%), cordenka (14 mass%) and PTP®
NFK opt.	Like NFK I as optimized production conditions (e.g. packaging during the storage)
NFK light	Light version of NFK I with reduced material input

Table 2 Parameter for cultivation of hemp

	Quantity (kg/ha)	Sources
Seed	45	[13]
Fertilizer		
Nitrogen	160	[12]
Phosphor (as P_2O_5)	70	[12]
Potassium (as K_2O)	200	[12]

respectively (details in [7]).The inventory balancing of the fiber component was based on industrial data and [12–14].

Cordenka. Cordenka which was provided by the company (Cordenka GmbH, Germany) was yarn made of rayon fibers—extruded, endless viscose fibers [15]—with the brand name Cordenka. The yarns used in the framework of the trials were Type 700/1840/f1000/Z100. For the main experiments the yarns were cut to a length of 20 mm. In a first approximate step the inventory data of cotton was used which was supplied by the library of Umberto® [11, 16].

PTP® (Polymer Material Made of Triglycerides and Polycarbon Acid Anhydrides). In the trials a newly developed standard paste of the thermoset resin PTP® produced by the company (B.A.M., Germany) was used. According to [17], PTP®, as shown in Fig. 5, may be completely produced on the basis of renewable resources.

In the current SMC-resin variant, substances on the basis of petrochemical products were still present at a proportion of about 10%.

According to the definition in DIN 7728Tl.1 PTP® belongs chemically to the epoxy resins. PTP®s advantages are the characteristic profile that can be adapted according to requirements and the low physiological hazard potential during processing (see Table 3).

The inventory data sets of the partial systems of the epoxydized triglycerides and polycarboxylic acid anhydrides were taken from the LCA-database Ecoinvent®, the Umberto®-library and chemical literature [11, 18]. The additives were substances which are used as flame retardants and support the maturing of the SMC-PTP®-resin-hardener system. The inventory data of these substances were taken from the Ecoinvent® database.

Component Pressing. A detailed description of the manufacturing of the NFK-SMC-prepregs can be found in [7]. After 16 days of maturing the NFK-prepregs were processed at about 180 bars, a temperature of about 135 °C (upper side 140 °C) on the surface of the tool and a

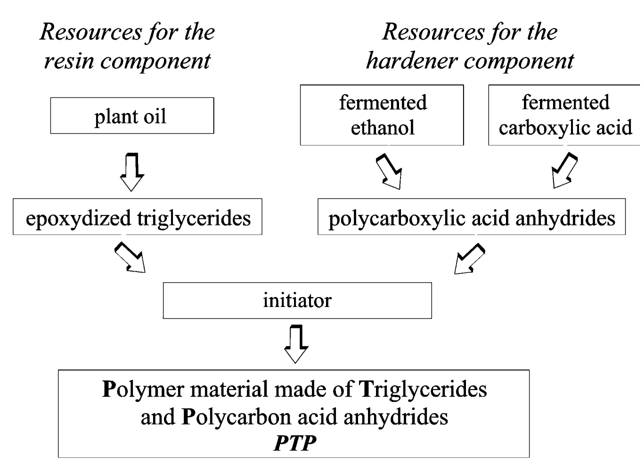

Fig. 5 Substances to produce PTP® [17]

Table 3 Potentially hazardous occupations of standard epoxy resin compared to PTP®

Declaration according to EC regulation		EP resin/hardener	PTP®
Symbol	Xn	–	Harmful
	Xi	Irritant	–
	C	Corrosive	–
	N	Dangerous for environment	–
Risk phrases	R 34	Causes burns	–
	R 36/38	Irritating to eyes and skin	–
	R 41	–	Risk of serious damage to eyes
	R 42	–	May cause sensitization by inhalation
	R 43	May cause sensitization by skin contact	May cause sensitization by skin contact
	R 51/53	Toxic to water organism, long term exposure cause biological damage	–
Safety phrases	S 23	–	Do not breath vapor
	S 26	In case of contact with eyes, rinse immediately with plenty of water and seek medical advice	In case of contact with eyes, rinse immediately with plenty of water and seek medical advice
	S 28	After contact with skin, wash immediately with plenty of water	–
	S 37/39	Wear suitable gloves and eye/face protection	Wear suitable gloves and eye/face protection
	S 38	–	In case of insufficient ventilation, wear suitable respiratory equipment
Transport information		Declaration as dangerous goods required	–
Technical guidance air		II–III	–
Water risk class		1–2	–
Know risks		Allergation, carcinogenic	Allergation

pressure time of 10 min processed at (BKT GmbH, Germany) on a SMC-Press. Volatile substances emitting at processing cannot be quantified.

GF-UP-Component The GF-UP-SMC-Prepregs for the production of the MAN-bus body components at the company BKT were supplied by the companies Menzolit and Lonza Compounds. For the production of the prepregs a homogenous resin paste was first produced by mixing the components in a dissolver. In the next step this resin paste was put on a PE-plastic backing film with the glass fibers and was compressed by a rolling plant.

For the production of the GF-UP-SMC-prepregs no company-specific inventory data were available, so that the relevant material flows were modeled by a unit process of the database of the software GaBi®. The material flow data was based on industrial data and patent-/technical literature. The data quality was described as good [19]. The unit process included the prechains of the supply of the glass fibers and the unsaturated polyester resin.

The inventory data for the production of the components were taken from industrial data of the company (B.K.T., Germany).

The GF-UP-prepregs were pressed for about 6 min. A part of the styrene contained in the polyester resin will emit which can be smelled at a concentration of about 0.15 ppm. The emission of styrene is under suspicion to cause health damages [20]. According to [21], the emission values of styrene are 1% of the resin weight at the processing of UP-press mass. Assuming an average resin mass of 33% the styrene emissions corresponded to a value of 0.33% of the SMC-prepreg mass. Using a mass of the SMC-prepreg of 3.6 kg per component styrene emissions ran up to 12 g per component.

Use Phase

According to [22], the use phase demands in comparison to the production and disposal at 80% the highest part of the energy of the entire life cycle of an automobile due to fuel consumption. Schmidt et al. who analyzed the life cycle of automobile hatchback out of steel, aluminium and SMC obtained similar results [23]. Therefore, it can be assumed that the use phase has an important influence on the damage impacts of the studied product systems.

But most of the NFK-product variants developed in the project do not differ in their mass from the reference product system of glass fiber reinforced polyester resin. Consequently, no relevant results in the use phase were obtained from the comparative analysis of these product systems.

But in case of the particular variant which mass could be reduced by 0.9 kg the use phase had to be considered. The impacts of this variant (NFK Light) in the use phase were assessed by an analysis of the cumulated energy demand.

The under-consumption of fuel was calculated by means of a coefficient for the effect of the mass on the fuel consumption. According to [24], the coefficient is 1.7 l fuel/(100 km * t) for a representative low-floor city bus and an assumed SORT-Cycle (SORT—Standardized On-Road Test Cycles) of type 2. The SORT-Cycle 2 includes assumptions to different parameters of the bus use (e.g. average speed, time of stops, speed-up, stops/km) and characterizes an average traffic in city and suburb. According to [25], it was assumed that the average driving performance was approx. 50,000–60,000 km/year and the use period of the bus ran up to 12–15 years.

Disposal

For the disposal of the bus body component three alternatives are mentioned in [7] which based on the German End-of-life vehicles regulation. Thus, large-area plastic components must be dismantled and recycled after the use phase. In this case the dismantled bus body component is shredded and the material is used as filling material at the production of SMC-components. Furthermore, there is the option that the component remains at the bus body and is shredded together with the bus body, whereas the recycling of the shredder material must be guaranteed. The shredder material is divided into three material fractions: ferrous metals, non-ferrous metals and the shredder-light-fraction. The composite material of the bus body component will be added to the shredder-light-fraction. For the recycling of the shredder-light-fraction two technologies are mainly discussed. On the one hand the shredder-light-fraction can be converted into synthesis gas in a pyrolysis process which is used for the production of methanol. On the other hand the use as reduction material for the furnace technology is accepted in which the conventional reduction material like heavy oil is substituted. In this context the VW-SiCon technology is to be mentioned which is developed by (Volkswagen AG, Germany) and the Engineering company (SiCon, Germany).

In this study the disposal of the body component by the VW-SiCon technology is analyzed as an example, because the additional costs would be probably the lowest [7]. For this technology the shredder material is separated in the fractions ferrous-/non-ferrous metals, polymer granulates PVC, fibers/foam, sand and residues. All these fractions can substitute materials in other processes except the residues. For the body component analyzed in this study the fraction of the polymer granulates is relevant which is used as reduction material for the furnace technology.

Table 4 Substitution factors and substituted mass of heavy oil in the furnace process

	GF-UP-component[a]	NFK-component[a]
Organic fraction in %	40	70
Substitution factor for heavy oil	0.4	0.7
Substituted mass of heavy oil in kg	1.4	2.5

[a] Mass of component: 3.6 kg

The processing of the VW-SiCon-technology is identical for the GF-UP-component and the NFK-variants and will not be considered in the comparative study. But there are differences between the organic fractions of the components and so between the redox potential and the mass of heavy oil respectively which can be substituted in the furnace process. Pitschke et al. assumed that heavy oil and alternative used plastics should mostly be comparable according to the environmental impacts and the redox potential, so that a substitution factor of one is determined [26]. The GF-UP-component was made of approx. 40% organic material. The NFK-component had a higher fraction of about 70% due to the natural fibers. The substitution factors and mass of substituted heavy oil are listed in Table 4. The substituted mass of heavy oil was credited to the product systems.

Besides the different substituted mass of heavy oil the mass of fossil carbon dioxide varies which is emitted at the furnace process. A simple estimation according to [27] proceeds on the assumption that 2.9 kg carbon dioxide per kg reduction material is emitted in the furnace process. In the case of the reference component the emitted carbon dioxide was at 100% of fossil origin. In case of the variants of the NFK-components a high fraction of the carbon dioxide was of regenerative sources which is considered in the balancing correspondingly.

Methodology of the Impact Assessment

Two methodologies of impact assessment were used for the assessment of the material flows of the inventory analysis. The Eco-indicator 99 was applied for a wide assessment of the environmental impacts. The resource efficiency of the light-weight-variant in the use phase was assessed by the cumulated energy demand.

Eco-indicator 99

The Eco-indicator 99 was developed by PRé Consultants B.V. in the Netherlands. The Eco-indicator 99 is a damage-oriented methodology, i.e. the damage caused by emissions and demand of resources on the level of the inventory analysis, is modeled.

The impact assessment with the Eco-indicator 99 includes an extensive framework of assessment and considers the following three types of environmental damages:

- human health,
- ecosystem quality and
- resources.

These environmental damages are quantified by damage models. The damage factors are aggregated to Eco-indicator 99 Points by normalization and weighting. In the following the damage models for each category are described and the phases of normalization and weighting are pointed out. For a more detailed description see [28].

Human Health The category human health includes affections of health like the number of years of disability and anticipated death. The following reasons are considered: respiratory and carcinogenic effects, effects of climate change, ozone layer depletion and ionizing radiation. The unit of the category is quantified in DALYs (Disability-Adjusted Life Years).

Ecosystem Quality In the category ecosystem quality the damage of ecosystems by ecotoxic substances, acidification, eutrophication and by use and transformation of natural space is quantified by the loss of the biodiversity per area and year (PDF—Potentially Disappeared Fraction).

Resources The assessment of the demand of minerals and fossil fuels is done in the category resources benchmarking the quality of future resources. A lost of quality is caused by decreased concentration of the resource, so that a higher energy demand for the extraction is needed. This higher energy demand (MJ surplus energy) is the unit of this category.

Normalization and Weighting In the phase of normalization the same unit for the damage factors of all categories is obtained as a result by division by a reference value. In this methodology European normalization values are used. The normalized values are weighted by the factor 400 for the categories human health and ecosystem quality and by the factor 200 for the category resources and are added to Eco-indicators 99 points in the following.

The Cumulated Energy Demand

The cumulated energy demand (CED) is among others one possible important characteristic value in the ecological balance and comparison of products. It allows the assessment of product systems with regards to energy criteria.

The cumulated energy demand indicates the entire demand of primary energy which arises in relation to production, use and disposal of an economic good [29]. In this study the fossil fuels (gas, oil and coal) were focused and assessed by CED, fossil.

Results and Discussion

The results of impact assessment shown in this article were net values, i.e. the corresponding credits were considered in the balancing.

The following figures show the results of one NFK-Variant (NFK I) which was successfully produced for the on-road test in the developing project, in comparison to the component made out of glass fiber reinforced polyester resin (GF-UP). A further NFK-variant (NFK Opt.) was compared for which an optimized series production was assumed and expected. Furthermore the results of a NFK-variant (NFK Light) realized in lightweight construction concept are shown. For this variant the total of the material mass was reduced without any negative influence on the component properties.

The results of impact assessment were in favor for the NFK-product systems which was mainly due to the lower impacts in the damage categories fossil fuels and climate change (Fig. 6).

At 0.36 points the total impacts of the NFK I-product system were about 50% lower than of the GF-UP-product system (0.74 points). The variant with cordenka (NFK II)

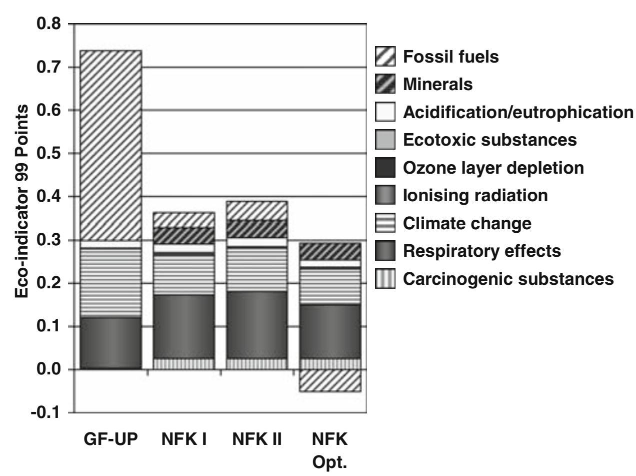

Fig. 6 Results of the impact assessment with the Eco-indicator 99 methodology (incl. credits)

came off a little badly in the LCA than the NFK I-variant with sole hemp fibers. The values of the optimized variant were about 68% lower. The negative values of NFK Opt. in the category fossil fuels were due to the credit of fuels in the disposal phase. For all product systems the impacts occurred mainly in the categories resources, acidification/eutrophication, climate change, respiratory effects and carcinogenic substances. Ozone layer depletion, ionizing radiation and ecotoxic emissions were less relevant. In comparison to the GF-UP-product system the impact values of the categories minerals and carcinogenic substances were higher for the NFK-variants. The analysis of the dominating processes in these impact categories showed that the production of the flame retardant had a significant influence with shares at 99% (category minerals) and at 87% (category carcinogenic substances). It should be noticed that the inventory of the GF-UP-prepreg system was only based on one aggregated data set which did not allow a detailed analysis unfortunately.

Figure 7 underlines that the natural raw materials, in this case the PTP®-system, had lower values in the damage category human health actually. These values referred to the life cycle of 1 kg resin (production, emissions at processing, disposal). The results of PTP® in the sub-category global warming are at 54%, in the sub-categories respiratory effects and carcinogenic substances at one third lower compared to the values of the unsatured polyester resin. The potential risk of carcinogenic impact of styrene which was described in [20] was not implemented in the impact assessment yet.

The analysis of the partial processes of the NFK-component production (without credits of equivalent processes in the disposal phase) showed that the PTP®-system (35–43%) and the additives/packing (47–56%) were dominating (see Fig. 8). The supply of the natural fibers had at 2–4% a

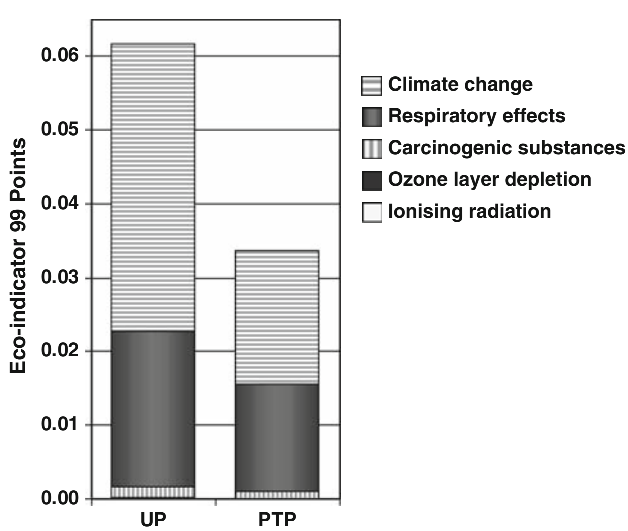

Fig. 7 Results of the damage category human health (incl. credits) for PTP® versus UP

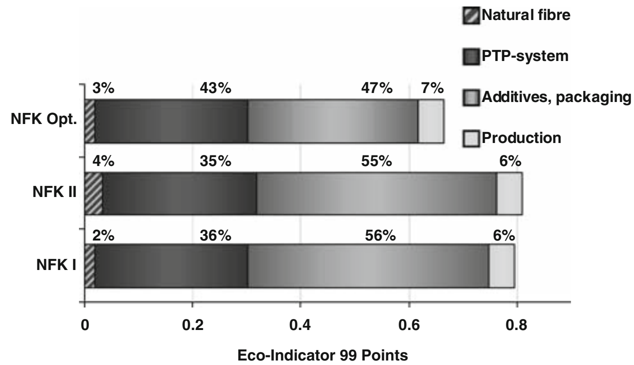

Fig. 8 Dominance analysis of the partial processess of the NFK-product systems

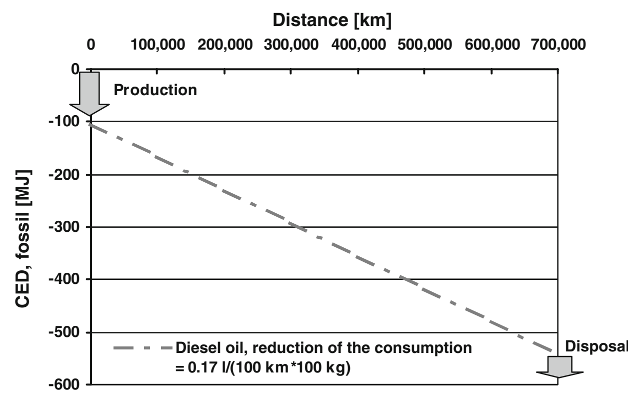

Fig. 9 Reduction of primary energy by using of the NFK Light compared to GF-UP-variant, shown by the cumulated energy demand (CED, fossil)

less effect. The application of cordenka (NFK II) doubled the share of natural fibers from 2% to 4%.

A further NFK-variant (NFK Light) was produced in the project which in contrast to the other variants was lighter than the reference component based on glass fiber reinforced polyester without impairing the property profile. Benefits in the ecobalancing were the lower material input and the reduced emissions in the production phase on one hand and on the other hand the lower fuel consumption in the use phase. Figure 9 shows this context by the cumulated, fossil energy demand (CED, fossil).

The reduced mass of the NFK-variant (0.9 kg) will lead to a fuel saving of approx. 10 l diesel fuel for an average driving route of 650,000 km of a public-transit bus. This corresponded to a CED, fossil = 512 MJ. An additional energetic benefit was obtained by the higher organic fraction of the component in the disposal phase.

Conclusion and Recommendations

The LCA analyzed the environmental impacts caused by the bus body component based on renewable raw materials in comparison to the conventionally used product system made of glass fiber reinforced polyester resin. The product systems got several credits in the production, use and disposal phase.

The impact assessment was realized using the methodology of the Eco-indicator 99 in which the results of the damage categories human health, ecosystem quality and resources were calculated. These values were normalized and weighted and finally aggregated to Eco-indicator 99 points.

The results of the impact assessment in the damage categories human health and ecosystem quality could not be interpreted definitely in advantage or disadvantage of the product system based on renewable raw materials. But the results of the damage category resources were significant: the product system based on renewable raw materials had lower environment impacts (approx. factor six) in comparison to the reference component.

This ecobalanced benefit dominated the neutral results of the other categories and consequently reduced the damage impacts of the NFK-variant I on level of the Eco-indicator 99 by 50% in comparison to the reference system.

From the point of view of the LCA the optimized material input (variants NFK Opt. and NFK Light) should be focused in the further development in order to achieve a relevant reduction of the environmental impacts in the production and use phase.

Furthermore the implementation of the inventory data of a future serial production of the NFK-prepregs to the LCA and a more detailed modeling of the GF-UP-prepreg production were recommendable.

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References

1. LWK (2001) Möglichkeiten und Chancen für den Industrie- und Energiepflanzenanbau. Landwirtschaftskammer Hannover und Weser-Ems, Hannover, Germany (in German)
2. Riedel U, Gassan J, Karrus M, Müssig J, Prömper E, Schönberger D, Sperber V (2005) Technical and economical framework for parts based on natural fiber composites. In: Arbeitsgemeinschaft Verstärkte Kunststoffe – Technische Vereinigung e.V. (AVK-TV) (ed) 8. Internationale AVK-TV Tagung für verstärkte Kunststoffe und duroplastische Formmassen 2005-09-27/28. Baden-Baden, Germany, pp A3-8–A3-11
3. Hinrichs A (2003) Instrumententafel für Oberklasse Pkw – Hardware und Airbag-Qualifizierung, Nachhaltige Mobilität – Naturfaserwerkstoffe für die Verkehrstechnik, Neue Materialien Niedersachsen e.V. 2003-11-13 at the fair Agritechnica, Hannover, German. http://www.riko.net/download/kwst2003_hinrichs.pdf. Cited 2006-07-01 (in German)
4. Müssig J, Herrmann AS (2001) Pilotprojekt: Träger im KFZ-Innenraum – Qualität und Konstruktion aus der Sicht der Entwicklung und des Engineering –, Neue Materialien Niedersachsen e.V. 2001-11-15 at the fair Agritechnica, Hannover, Germany. http://nmn-ev.de/Download/011115muessig_herrmann.pdf. Cited 2006-07-01 (in German)
5. Flake M, Fleissner T, Hansen A (2000) Ökologische Bewertung des Einsatzes nachwachsender Rohstoffe für Verkleidungskomponenten im Automobilbau – Lebensweganalyse verschiedener Faserverbundwerkstoffe. Landschaftsökologie und Umweltforschung Heft 34, Selbstverlag. Institut für Geoökologie der Technischen Universität Braunschweig, Germany (in German)
6. Wötzel K, Wirth R, Flake M (1999) Life cycle studies on hemp fibre reinforced components and ABS for automotive parts. Die Angewandte Makromolekulare Chemie 272:121–127
7. Müssig J, Schmehl M, von Buttlar H-B, Schönfeld U, Arndt K (2006) Exterior components based on renewable resources produced with SMC technology – considering a bus component as example. Ind Crops Prod 24:132–145 (ISSN 0926-6690)
8. Bültjer U (2006) Production of GRP and thermosets in Europe 2005–2006. In: Arbeitsgemeinschaft Verstärkte Kunststoffe (AVK) (ed) 9. Internationale AVK Tagung für verstärkte Kunststoffe und duroplastische Formmassen, 2006-09-19.-20. Essen, Germany, pp P3-1–P3-10
9. CEN (1997) EN ISO 14040: Umweltmanagement – Ökobilanz – Prinzipien und allgemeine Anforderungen. Comité Européan de Normalisation, Brüssel, Belgium
10. Kaltschmitt M, Reinhardt GA (1997) Nachwachsende Energieträger – Grundlagen, Verfahren, ökologische Bilanzierungen. Vieweg-Verlag, Braunschweig, Germany (in German)
11. IFEU & IFU (Institut für Energie- und Umweltforschung GmbH Heidelberg & Institut für Umweltinformatik GmbH Hamburg) (2001) Umberto® 4, Software zum Stoffstrommanagement. Heidelberg, Hamburg, Germany
12. TLL (Thüringer Landesanstalt für Landwirtschaft) (2003) Anbautelegramm für Hanf (*Cannabis sativa* L.) -02/2003-. Thüringer Zentrum Nachwachsende Rohstoffe der Thüringer Landesanstalt für Landwirtschaft, Jena, Germany (in German)
13. Stolzenburg K (2001) Forchheimer Steckbrief – Anbau von Hanf zur Stroh- und Kombinationsnutzung. Landesanstalt für Pflanzenbau, Infodienst Baden-Württemberg, Forchheim, Germany (in German)
14. KTBL (Kuratorium für Technik und Bauwesen in der Landwirtschaft) (2002) KTBL-Taschenbuch Landwirtschaft – Daten für betriebliche Kalkulationen in der Landwirtschaft, 21. Auflage 2003/2003. Landwirtschaftsverlag GmbH, Münster, Germany (in German)
15. Schnegelsberg G (1999) Handbuch der Faser – Theorie und Systematik der Faser. Deutscher Fachverlag, Frankfurt, Germany (in German)
16. Bremer Baumwollbörse (1995) Daten zur Baumwollwirtschaft der Bundesrepublik Deutschland 1994. Bremen, Germany (in German)
17. Schönfeld U (2000) Epoxydharz aus nachwachsenden Rohstoffen. In: C.A.R.M.E.N. (ed) 8. Symposium "Im Kreislauf der

Natur – Naturstoff für die moderne Gesellschaft" Nachwachsende Rohstoffe auf dem Weg ins 21. Jahrhundert 2000-07-03/04. C.A.R.M.E.N., proceedings, Würzburg, Germany (in German)
18. Ullmann (1977) Encyclopädie der technischen Chemie. Band 13 Hormone bis Keramik. VCH Verlagsgesellschaft, Weinheim, Germany (in German)
19. PE & IKP (Product Engineering GmbH & Institut für Kunststofftechnik Universität Stuttgart) (1998) GaBi 3, Software zur Ganzheitlichen Bilanzierung. Dettlingen/Teck, Stuttgart, Germany
20. BfR (Bundesamt für Risikobewertung) (2006) Hinweise auf tumorauslösende Wirkung von Styrol beim Menschen, Pressemitteilung 25/2006 from BfR on 2006-08-31 (in German)
21. Aurer JH, Kasper A (2003) Ungesättigte Polyesterharze. Die Bibliothek der Technik Band 242. verlag moderne industrie, Landsberg/Lech, Germany (in German)
22. Schweimer GW, Schuckert M (1996) Sachbilanz eines Golf, VDI-Berichte 1307. VDI-Verlag, Düsseldorf, Germany (in German)
23. Schmidt S, Pérez A, Handels B (2004) Life Cycle Analysis und Life Cycle Costing von SMC Teilen. European Alliance for SMC, Frankfurt, Germany (in German)
24. UITP (International association of public transport) (2004) SORT – standardised on-road tests cycles. Brüssel, Belgium
25. Neoman (2005) Personal communication with Mr. Folger on 2005-10-17. Neoman Bus GmbH. München, Germany
26. Pitschke T, Roth U, Hottenroth S, Rommel W (2004) Ökoeffizienz von öffentlichen Entsorgungsstrukturen. BlfA-Text Nr. 30. Bayerisches Institut für angewandte Umweltforschung und -technik GmbH, Augsburg, Germany. http://www.bifa.de/download/bifatext30.pdf. Cited 2006-07-01 (in German)
27. Fritsche U et al (2004) Gesamt-Emissions-Modell Integrierter Systeme (GEMIS), Version 4.2. Öko-Institut, Freiburg. http://www.oeko.de/service/gemis. Cited 2006-07-01
28. Goedkoop M, Spriensma R (2001) The Eco-indicator 99 – a damage oriented method for life cycle impact assessment. PRé Consultans B.V., Amersfoort. http://www.pre.nl. Cited 2006-07-01
29. VDI (1997) Richtlinie VDI 4600 – Kumulierter Energieaufwand – Begriffe, Definitionen, Berechnungsmethoden. Verein Deutscher Ingenieure, Düsseldorf, Germany