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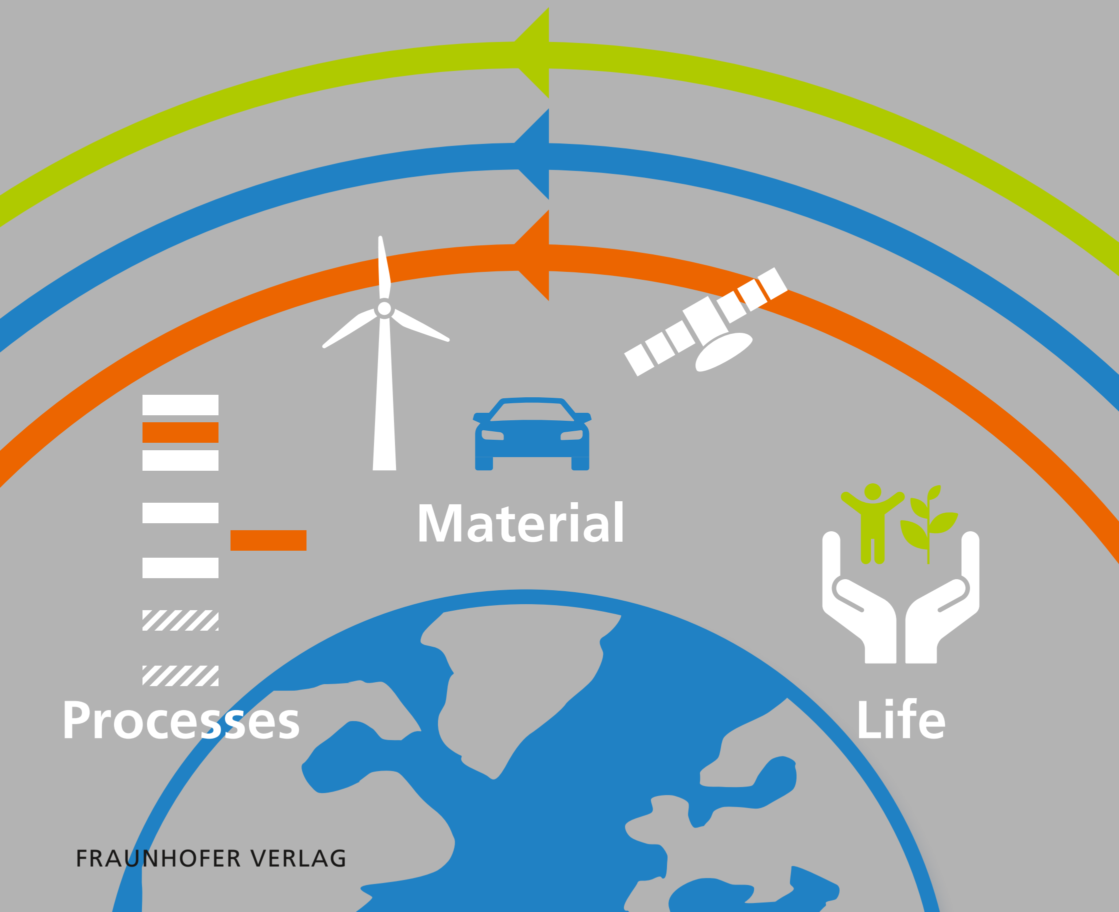
CIRCULAR ECONOMY AND ADHESIVE BONDING TECHNOLOGY

Study by the Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM



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External service providers:

Graphics, typesetting and layout
Jens Oertel Design, Bremen (Germany)

DOI: 10.24406/ifam-n-603186

Translation from the German language edition:
Kreislaufwirtschaft und Klebtechnik
by Bernd Mayer, Andreas Gross,
© Fraunhofer Verlag, 2020,
DOI: 10.24406/ifam-n-596949

FRAUNHOFER VERLAG, 2020
Fraunhofer Information Center for Planning
and Building IRB
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Preliminary remark of the editors

The idea of sustainability influences the way we think and act in all areas of our lives. This also applies to the use of adhesive bonding technology, as it is used in almost all areas of life. Against this background, the present study describes the role of adhesive bonding technology in the context of the circular economy across all industries and classifies this joining technology within the political framework conditions from both a global and a European perspective. A comprehensive approach is followed. On the one hand, it includes not only the effectiveness of the circular economy but also aspects relevant to the life cycle assessment of adhesives used in adhesively bonded products. On the other hand, it presents the function of adhesive bonding technology as a partner for meeting the requirements of a circular economy. The adhesive as such is also considered, but the study focuses on the adhesively bonded (end) products. This is the decisive perspective for the evaluation of the technology "adhesive bonding" with regard to its relevance for the circular economy, since the adhesive content in adhesively bonded products is usually low and therefore hardly relevant in the balance sheet.

The study does not consider the product life cycles "production", "use" and "disposal" of adhesively bonded products separately, but rather in their interactions with each other. This is the only way to correctly present the potentials of adhesive bonding technology for the circular economy as well as the effects on corresponding life cycle assessments from the point of view of the team of authors. These potentials will be illustrated using selected applications as examples and can be transferred to other adhesive bonding technology applications with regard to the overriding statements that are made using these examples.

Each joining technology also includes separation. This is also dealt with in the study with regard to repair and recycling as a consideration point for the circular economy. However, the recycling of the separated joining partners and the necessary prerequisites, boundary conditions and processes are not the subject of the study.

From a perspective of sustainability, the study considers a possible procedure for evaluating the environmental impacts of adhesively bonded products. At this point, an option for determining the effectiveness of the circular economy is presented. In order to support the effectiveness, strategies regarding the development of adhesives, product design, dismantling processes and the digitalisation of adhesively bonded products are presented.

Many thanks to all those who were involved in the preparation of the study, especially the team of authors at Fraunhofer IFAM.

Bremen, 31-05-2020

Prof. Dr. Bernd Mayer

Prof. Dr. Andreas Groß

Summary

The design spaces in industry and trade are subject to a continuous process of change due to constantly changing technical, social and legal conditions. This change particularly affects adhesive bonding, as this is now an essential joining technology in almost all areas and sectors. The range of applications of adhesive bonding technology is based on its unique ability to join different material combinations long-term stablility and safe while maintaining product-relevant joining part material properties and to integrate additional functions into the adhesively bonded product that go beyond mere joining.

Continuous inventions and innovations of the players in the development of raw materials, adhesives and adhesively bonded products have enabled a dynamic development in the past decades. In particular, numerous new groundbreaking solutions have been developed to meet the ever increasing regulatory requirements for certain substances (e. g. from the group of solvents, plasticizers, monomers and biocides).

Through its function as a driver of more sustainable developments, adhesive bonding technology enables new, more environmentally friendly products and applications as well as improved resource efficiency in many areas. For example, the development of alternative energy sources without adhesive bonding (e. g. sealing solar cells, joining the rotor blades of wind turbines) is just as unthinkable as electromobility (including the construction of the magnetic cores for the electric motors from electro-packaging sheets, sealing the battery cells, heat management of the batteries with heat-conducting adhesives) and the fuel cell (e. g. hermetic sealing, joining the bipolar plates). In addition, adhesives can lead to material savings in a combination of improved product properties, even in areas as diverse as food packaging (e. g. shelf life extension with minimized material usage) and mobility (lightweight construction).

Especially for lightweight construction, adhesive bonding is a key technology. In the automotive sector, the use of adhesive bonding technology (e. g. adhesive bonding of car windshields,

bonding of stiffening profiles, bonding in the car body) supports the use of thinner sheets to save material and energy during the use phase. In rail vehicle construction, the product life cycle phase "utilisation", i.e. the driving operation compared to the product life cycle phases "production" and "disposal", represents the determining factor with regard to energy and emission reduction: The use of lightweight construction materials in adhesive bonding technology reduces energy consumption and thus the specific CO_2 equivalent emissions per passenger or tonne-kilometre. The long-term stability of adhesively bonded joints also supports the service life of adhesively bonded products. The service life of a car increases, a rail vehicle runs up to 40 years, an aircraft flies up to 30 years. Adhesive bonding thus enables building and construction principles with improved life cycle assessments in the holistic view of life cycles.

In the course of the current socio-political changes, the "European Green Deal" in particular will bring additional requirements and thus new challenges for adhesive bonding technology.
It envisages that Europe will become the first climate-neutral continent by 2050. In terms of economic principles, one component of this project is the transition from a linear economy to a circular economy. It minimises the use of resources, the generation of waste and emissions and the inefficient utilisation of energy. This is to be achieved by avoiding and reducing the need for resources, extending useful lives, reprocessing and closing energy and material cycles. Implementation tools for this are especially longevity constructions, maintenance, refurbishment, repair (capability), reuse, remanufacturing and recycling based on different approaches.

Adhesive technology has the potential to answer these new requirements with technical innovations. In the future, the value-added chains of adhesively bonded products must be viewed holistically in the product life cycles "production", "utilisation" and "disposal". This includes in particular making the "end of life" concept of adhesively bonded products an integral part of product development as early as the product planning and design phase. These new challenges resulting from the idea of closed-loop systems will therefore require even more intensive communication and cooperation in the future, and thus even closer networking of all players along value chains. Raw material and adhesive manufacturers, adhesive users, product manufacturers, end customers and recyclers as part of the "adhesive bonding" system along the life cycle of adhesively bonded products will form future value-added cycles. The holistic consideration of adhesively bonded products with regard to ecological improvements along value chains or cycles is made possible by Life Cycle Assessment (LCA), currently the most comprehensive assessment method for environmental impacts.

Against the background of the holistic approach, future developments of adhesively bonded products must be carried out in the sense of controlled longevity. This combines the control of product integrity during the product life cycle phase "utilisation" with the targeted separation of materials in the product life cycle phase "disposal". Targeted material separation is a prerequisite for material recycling. In addition, it is necessary for dismantling and rebuilding as well as for repair work and thus serves to increase the life or service life of a product. The repair of windscreens in means of transport has long been state of the art. The repair of display screens on mobile phones can now often be carried out by skilled laymen. The detachment of an adhesively bonded joint is caused by at least one external trigger which does not occur during normal use of the adhesively bonded joint and therefore does not affect the safe use of the adhesively bonded product.

The separation / disassembly of adhesively bonded products can be achieved by the adhesive or cohesive influence of an adhesively bonded joint. Since, according to the current state of science and technology, influencing adhesion, especially in the case of adhesively bonded joints relevant to safety, still requires considerable fundamental research, cohesion-related influencing is currently preferred. Cohesive dismantling strategies using local stimuli such as heating and mechanical overload are particularly targeted. With chemically curing adhesives, softening of the polymeric adhesive layer can also be achieved by swelling. Another possibility is the degradation of the polymer network. The user of the adhesively bonded product as well as the recycler must be aware of the disassembly option specified by the manufacturer; this also applies analogously to repair processes. Digital information sources make it technically possible to pass on these specifications. When mechanically (materially) recycling plastic parts to be joined, it is helpful if the adhesive is as compatible as possible with the plastics. As a necessary supplement to mechanical/material recycling and as the preferred alternative to purely energetic recycling, chemical (raw material) recycling opens up a future-oriented perspective for adhesively bonded joints with plastic joining partners – including those that may still be contaminated with adhesive and paint.

Industrially feasible disassembly processes of adhesively bonded products for raw material recovery or repair will in future be a major focus of the development process and product testing. From microelectronics to large structures in the building industry, the requirements for product designs that are suitable for recycling and have a positive impact on the ecological balance sheet, taking disassembly into account, should be listed in future specifications. Triggers for the adhesive solution and constructive measures to improve the economic efficiency of disassembly processes must be considered at an early stage of product development. In the case of a high number of variants, small dimensions and high quantities, shredding can be a variant of the disassembly process, which enables separation according to material type. Large component dimensions with a high dead weight of the single-variety components favour the application of mechanical loosening of adhesively bonded joints. Accessibility for disassembly equipment must be ensured as early as the design or construction phase. Power-intensive processes can be carried out or supported mechanically by automatic machines or robots. Disassembly by heat input is a disassembly option for adhesively bonded products, both in combination with mechanical disassembly and on its own. Disassembly through media influence has already been successfully applied both in the trade (e. g. removal of wallpaper) and in series production (e. g. removal of labels from returnable bottles). Adhesive bonding technology has long been an indispensable, positively eco-balance-relevant factor for the realisation of lightweight construction through multi-material construction. In the future, adhesive bonding technology will also be a key to ensuring that products can be repaired and recycled. Consequently, adhesive bonding does not prevent the disassembly of products, but offers promising possibilities for detaching the joints.

Digitalisation supports adhesive bonding technology decisions for a more sustainable effectiveness of the circular economy. Digital tools and the availability of detailed material- and process-related data along entire value-added chains or cycles will in future allow the developers of adhesively bonded joints to identify environmentally friendly options with regard to resource and cost efficiency within the framework of a life cycle-overlapping consideration. Cyberphysical systems digitize product and process information and pass it along production processes. Digital twins, for example, enable the selection of an optimally suitable disassembly process. Adhesively bonded products can be fitted with an RFID chip that can be used to retrieve all data on materials and adhesives for disassembly. The high experimental verification effort involved in the process integration of adhesive bonding technology into a production process can also be reduced with the aid of suitably calibrated, digital material and component models. Verifiable life cycle predictions that reduce maintenance costs, lead to more resource-saving replacement of wear parts and significantly increase safety gains require the development of structural health monitoring / SHM systems. The necessary sensor technology and the ways in which this information can be stored and read out are the subject of current research activities.

The adhesive itself can also contribute to more sustainable recycling by using alternative components. For example, those components based on recycled materials can be suitable raw materials for adhesives. In addition, bio-based adhesives are already being used today in certain mass applications. However, many of the necessary property profiles of synthetic adhesives cannot yet be fully represented by biobased adhesives, which currently limit their applicability. Adhesives are an ideal product group especially for the use of alternative or renewable raw materials. The moderate quantities are sufficient so that raw material syntheses could still be economically feasible and the ecological impact could be large enough. Although the development of renewable raw materials for broad utilisation in adhesives is well underway, there is still a huge need for research to reach the performance level of fully synthetic adhesives. The extraction of alternative components using CO_2 and from chemical recycling is also conceivable. Degradable adhesives based on various renewable materials such as starch, cellulose or proteins have long been used industrially, for example in the labelling of foodstuffs.

The view “from material to product” combines the aspects of safety, technological performance and controlled long-term stability with the social requirements of a more sustainable circular economy along value chains and cycles.

In this area of conflict, adhesive bonding technology has the necessary technological and ecological capabilities and thus offers the potential to become the leading joining technology of the 21st century.

1

Introduction: adhesive bonding technology – definition, possibilities and current limits

1.1
Increasing product requirements – the role of materials

Our living environment is subject to a continuous process of change. This change is constantly accelerating and affects all the decisive design areas of the present and future. Industry and trade are facing up to this increasingly complex task in order to meet the challenges of the future and to continue to offer marketable products.

The complexity in product development is additionally increased by rising customer expectations. Examples of this are the better quality of a product, higher functionality, lower weight or contemporary design.[1, 2]

The demands on products are constantly changing.

Product innovations successful on the market meet these complex requirement profiles. In addition to necessary sales investments such as market research, advertising, the development of the customer service organisation and the design of sales channels[3], this success is based on three core elements:

- technological superiority
- economic balance
- ecological compatibility.

1 O.-D. Hennemann, A. Groß, M. Bauer, Spektrum der Wissenschaft 1993, 9, 84–89, Innovationen durch vielseitige Fuegetechnik.

2 O.-D. Hennemann, A. Groß In Schweißen und Schneiden ’94, Vortraege der gleichnamigen Großen Schweißtechnischen Tagung, Bremen, Deutschland, 28.–30. September 1994, DVS-Berichte Band 162, Deutscher Verlag fuer Schweißtechnik: Duesseldorf, 1994, S. 273–278, Kleben – Schluesseltechnologie fuer Industrie und Handwerk.

3 P. Kenning, Absatzweg – Ausfuehrliche Definition. https://wirtschaftslexikon.gabler.de/definition/absatzweg-29823 (Access April 30, 2020)

Successful and responsibly acting companies combine these three seemingly contradictory core elements in the development, optimisation and production of their products: A purely technological (further) development, which exclusively meets increasing technical requirements, is not enough. The economic balance of the customer's price/performance expectations must be considered just as much as the ecological production, use and disposal of the product. Ecological compatibility is not only demanded by legal requirements, but increasingly by a changed consciousness of the buyer.

The realisation of these ever more complex requirements for products, parts and components is not only achieved by functional or design changes. Groundbreaking possibilities also result from the new or further development of materials with increasingly requirement-specific properties. In addition to the classic metals, a variety of more specific metal alloys, plastics, ceramics and glasses are used. The permanent further development of new special materials is therefore necessary to develop technologically superior, economically balanced and ecologically compatible products.
→ **see Fig. 1**[4]

> **Increasing product requirements are implemented through materials.**

> **Materials are at the heart of meeting requirements that are more complex.**

Materials are an important factor in meeting future requirement profiles. New types of requirement profiles are a driving force in materials science. They originate from the major future fields of energy, climate and environmental protection, resource conservation, mobility, health, safety or communication. To this end, materials science combines an interdisciplinary approach, which in the field of materials science is more knowledge-oriented and natural science-based, with an approach, which in the field of materials technology is more application-oriented and engineering-based.

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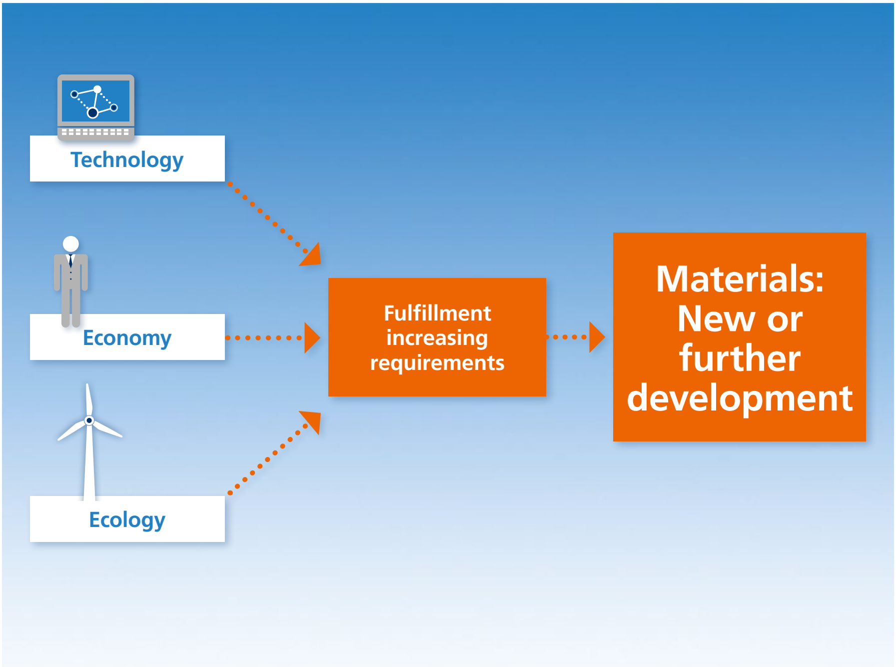


Fig. 1
Meeting increasing requirements through materials

Both constantly lead to research results, without which continuous progress, for example in the fields of mechanical engineering, transport engineering, aviation industry, chemical industry, medical technology, energy technology or environmental protection, would be unthinkable.[5] It is therefore not without reason that current studies show the direct or indirect dependence of a large proportion of technical innovations on the respective material.[6]

The consequence of materials development is that the variety of special materials for the manufacture of products is increasing in order to meet the growing demands on products.

The number of materials to meet requirements that are more complex will continue to increase.

5 W. Schatt, H. Worch In Werkstoffwissenschaft. Wiley-VCH Verlag: Weinheim 2011

6 Bundesministerium fuer Bildung und Forschung (BMBF), Referat Neue Werkstoffe, Nanotechnologie, KIT, Vom Material zur Innovation, 01-2015

1.2 New product requirements – the role of joining technologies

However, the complexity of the requirements to be met is usually so high that a single material with its specific properties alone is not able to meet these requirements. In contrast to universal materials such as some steels, novel, highly developed and highly specified materials do indeed meet certain requirements excellently, but at the same time they also have weaknesses. This specialisation of a material at the expense of universality is known from natural materials: Wood has a high strength when subjected to tensile stress in the direction of the grain, but perpendicular to the grain, wood has only limited tensile strength.

These new materials unfold their innovative power by combining them into a product. Components made of different materials are joined to form a product by means of a joining technique. Each joining technology has its specific advantages and disadvantages. Adhesive bonding technology is particularly suitable for long-term resistant joining of materials with different properties (see chapters 1.3 and 1.5). Consequently, composite systems made up of different materials, so-called multi-component materials, will undoubtedly continue to be necessary in the future. The following two examples illustrate this.

> **The importance of combining materials to meet requirements that are more complex will also continue to grow.**

In the first automobile (1886/→ **see Fig. 2** [7]), solid rubber tires satisfied the requirements of the time in terms of safety, long-term durability, speed and comfort. Some 130 years later, these requirements have increased significantly (→ **see Fig. 3**). Today's

7 Daimler AG

Fig. 2
The first car with solid rubber tyres

motorists have much higher safety requirements. At the same time, the service life of the vehicle is much longer – and so is the mileage in kilometers.[8] The requirements for speeds are definitely no longer comparable with those of the 19th century. The same applies to the requirements for product comfort. As far as tyres are concerned, the consequence is that the modern car tyre can only meet today's requirement profile by combining many different materials into a "joined car tyre". → **see Fig. 3**[9]

Another example from a completely different area may also illustrate the importance of the material combination: → **see Fig. 4**[10] (left) shows a sub-millimeter radio telescope with a high-precision parabolic mirror, the diameter of which is about 10 m. Due to the laws of physics, the mirror may not deviate from the calculated surface by more than 17 µm (= 0.017 mm), regardless of the respective weather conditions (storm, rain, snow, drought, high / low temperatures, solar radiation, high / low humidity). In simple terms: the mounting bracket (→ **see Fig. 4, right**) of the mirror must be constructed absolutely rigid.

8 B. Engel; PS Welt. 2018, Werden Autos bald fuer die Ewigkeit gebaut? https://www.welt.de/motor/article181378662/Werden-Autos-bald-fuer-die-Ewigkeit-gebaut.html (Access April 30, 2020)

9 M. Jordan, Wikipedia, Lizenz: CC BY-SA 3.0

10 Thyssenkrupp AG

Fig. 3
Today's requirements, on the other hand, can only be met by combining many different materials into a composite car tyre

This is not possible with conventional materials such as steel and aluminium. To meet the increased demands on the dimensional accuracy of the radio telescope product, new, highly rigid and at the same time low thermal expansion materials are used. In this case, carbon fibre reinforced plastics (CFRP) for the pipe connectors and for the structural connection nodes are the material "Invar" (→ see Fig. 5), a special steel alloy consisting of 64 % iron and 36 % nickel.[11] Both materials have low coefficients of thermal expansion.

In order to achieve the requirements, the anomalous behaviour of the C-fibre (shrinkage on temperature increase / expansion on temperature decrease) was combined with the normal behaviour of the matrix resin (expansion on temperature increase / shrinkage on temperature decrease) in the design of the CFRP material in such a way that a new material with a desired coefficient of thermal expansion of almost zero is created for this application. Thus, the cleverly selected material compound can meet the increased requirements.

> **Materials and materials development occupy a key position.**

Fig. 4
Submillimeter radio telescope with high-precision parabolic mirror (model, left) / Connection of Invar (nodes) with CFRP tubes (right)

11 U. Huebschmann, E. Left In Tabellen zur Chemie, Verlag Handwerk und Technik: Hamburg, 1991; S. 35, Ausdehnungskoeffizienten von Metalllegierungen (Werkstoffen, Glaesern und anorganischen Materialien.

Fig. 5
Joining special materials with zero thermal expansion [4]

However, one thing is of crucial importance in this context: materials only become usable when

- not only their properties contribute to the fulfilment of the requirement profile,
- but they can be joined to themselves or to other materials in the product or in the component.

> **Only the joining technology makes the material usable.**

From an application technology point of view, joining technology is thus of the same importance as material development. Consequently, application-oriented material development must always be combined with joining technology that is suitable for the material in order to be able to use it. Only when both materials and joining technology are compatible will innovations become possible. These innovations then fulfil the complex requirements for products in technological, economic and ecological terms.

> **Products of the future will be made of material compounds: The development of a material and the development of its suitable joining technology must be regarded as equal.**

It should be noted, however, that in general, the sensitivity of a material increases the higher a material is developed. A joining technology suitable for the material must take this sensitivity into account. In this context, "joining technology suitable for the material" actually means "joining technology suitable for the material properties" (→ see Fig. 6). The properties of the materials must be retained despite the use of a joining technology in order to meet the required requirement profile.

> **A central task of joining technology is to maintain the properties of the material in the joint.**

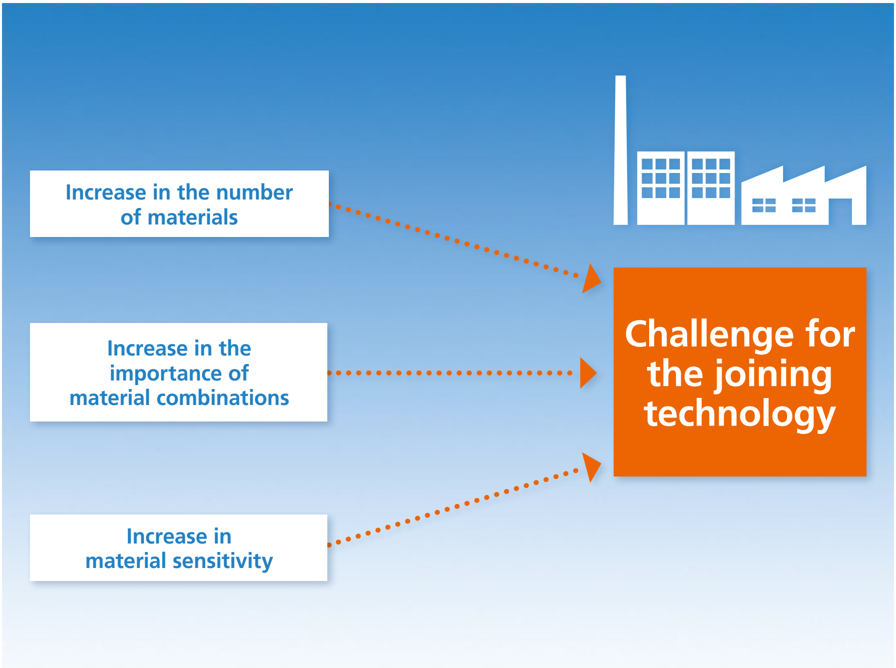


Fig. 6
As a result of the material developments: the challenge for joining technology[4]

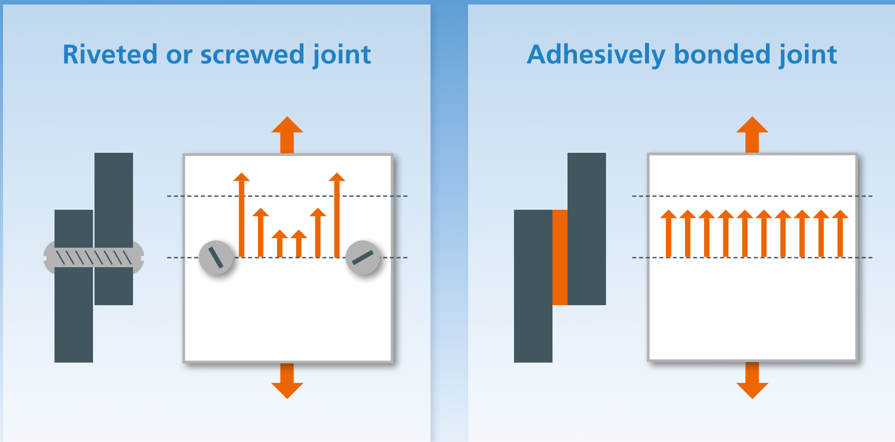
1.3
New product requirements – the role of "adhesive bonding" joining technology

Traditional joining technologies often fail to preserve the material properties when joining with itself and/or other materials: In thermal processes such as welding, the material changes its specific properties within the heat-affected zone. Although the original properties are retained in the base material, the physical material properties change in the heat-affected zone due to grain growth, phase transformations, precipitation processes at the grain boundaries or even hardening. In the weld metal, this occurs through crystallisation (formation of a cast structure), dissolution of accompanying elements, precipitation processes, increases, shrinkage and resulting internal stresses. This means that in the heat-affected zone the material has different properties after the welding process (melting/solidification) than in the base material. These changed properties influence the properties of the joint as a whole. Often the joint therefore fails not in the weld seam but in the heat-affected zone.[12]

Mechanical methods such as rivets or bolts, on the other hand, only allow a punctiform transmission of force at the connection point. In addition, holes must be drilled in the workpieces to be joined, thus damaging and weakening the material. In use, mechanical loads, i. e. the load cases that occur, cause so-called stress peaks. In addition, these stress peaks limit the strength of the joint. If these are exceeded under load, the material will crack where they occur (→ **see Fig. 7, left**).

Adhesive bonding technology, on the other hand, does not have the disadvantages described above. It therefore plays a key role in this context for four main reasons (→ **see Fig. 8**):

12 G. Schulze In Die Metallurgie des Schweißens; Springer: Berlin und Heidelberg 2010: S. 237–297, Einfluss des Schweißprozesses auf die Eigenschaften der Verbindung.



1. With the joining technology "adhesive bonding" it is possible to join almost all material combinations both of the same as well as of different materials in a long-term resistant way and thus to realize material combinations that meet the increased demands on the product.

2. Adhesive bonding does not change the material properties of the joined parts in an inadmissible way. As a rule, they remain unchanged: The adhesive bonding process, even with hot-curing adhesives, is a relatively low-heat compared to welding or soldering, and there is no damage to the joined parts through perforation as with riveting or bolting. The stress distribution in the load case is approximately uniform (→ see Fig. 7, right).

3. Material combination and preservation of the material properties enable the specific material properties to be used optimally for the component. Possibilities for new construction methods (e. g. lightweight construction, miniaturisation) are thus given.

Fig. 7
Mode of operation of connections under mechanical load

Left [4]: Riveted or bolted joint – occurrence of stress peaks that limit the strength of the joint

Right [4]: Adhesively bonded joint – the stress distribution is uniform, therefore no stress peaks occur, which limit the strength of the joint

4. The adhesive can be used to integrate additional properties into the component. These properties go beyond the main function of joining and can be relevant for the circular economy (see chapter 1.5).

> **With adhesive bonding technology, it is possible to join all materials with themselves and others long-term stable while retaining their properties, thus achieving the desired product characteristics.**

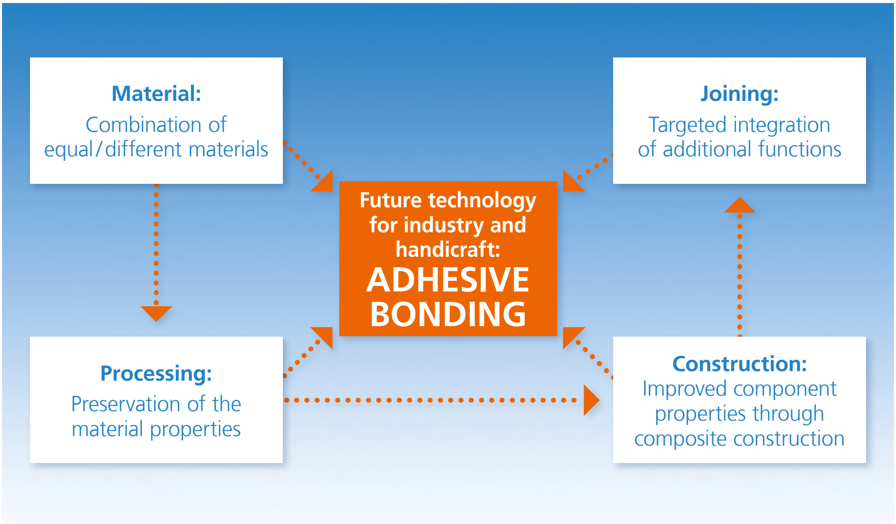


Fig. 8
Reasons for the key position of the adhesive bonding technology [4]

1.4 The joining technology "adhesive bonding" – a classification and explanation

1.4.1 Adhesive bonding – a historical view

Adhesives and adhesive bonding are not a new invention. Thousands of years ago, people were already joining different materials with each other using natural adhesive materials. At that time, they produced these natural adhesives from animal skins and bones or from plants.

Around 5000 B.C., i.e. in the later Stone Age, people used birch resin to fasten spear and axe tips. For example, when the glacier man "Oetzi" was discovered in 1991, an axe made from a yew trunk was found among his equipment and clothing. The blade of the axe was attached with birch pitch glue and leather strips.

Around 2000 B.C., gelatine glues began to be used in the Near East for furniture production. In the Middle Ages, it was the craft of the bird catcher to catch small birds with glue rods. The birds were lured with berries and fruits and were caught in the sticky branches.

In the 17th century, adhesives gained great importance in many households, as Chinese wallpapers were first delivered to Europe and became fashionable. The necessary adhesive, wallpaper paste, was developed for this purpose at the beginning of the 17th century. This is a vivid example of how social changes lead to the development of new materials. However, large quantities of glue were not only needed for attaching wallpaper to the wall, but also in the wallpaper printing plants at that time. This included parchment glue, for example, which was made from parchment chips. It served as a white primer for the wallpaper to preserve the brilliance of the printed colours.

In 1748, the first patent for a fish glue was granted in England. Due to the great demand, glue factories were established in many cities at the beginning of the 18th century. They were often found near leather tanneries, as the glue was boiled from the waste products produced there. The company Gillon fils & Thorailler in Paris, a flourishing wallpaper factory, consumed 1500 kilograms of glue daily around 1850!

1.4.2 Adhesive bonding – Milestones in development

In the last 100 years or so, the chemical industry has made great strides in the field of adhesives. In 1909, Leo Hendrik Baekeland (1863 – 1944) presented a novelty that had never been seen before in the entire history of mankind: phenol-formaldehyde resin was the first purely artificially synthesized polymer that was not based on natural substances. It came onto the market under the name "Bakelite".[13] The basis of the following upswing was the basic principles of macromolecular chemistry presented by Hermann Staudinger (1881 – 1965) in the 1920s. This was followed by the rapid development of bakelite:

1931	The first stable plastic dispersion, i.e. a very fine distribution of a plastic in a solvent, was developed.
1936	With epoxides, Pierre Castan invented a group of adhesives that is still important today, including for vehicle and aircraft construction.
1937	First synthesis of polyurethanes, which today are widely used in the automotive industry, in rail vehicle and shipbuilding and in many other areas.
1940	The methacrylate adhesives, which are used for the adhesive bonding of metals and plastics, among other things, have been patented.
1953	The first anaerobic curing adhesives came onto the market.

13 Entry for Phenolharze In: Roempp Online. Georg Thieme Verlag, https://roempp.thieme.de/lexicon/RD-16-01590 (Abruf April 30, 2020)

1958	A "superglue", the cyanoacrylate, came onto the market in the USA.
1968	The development of moisture-curing polyurethanes, whose successors are still adhesively bonded to car windows today, began.
1970	First UV light-curing acrylic formulations (radiation-curing adhesives) were developed. The same applies to silane-modified adhesives based on polyether in Japan (MS polymers).
1980	The reactive hot melt adhesives were presented for the first time.
End of the 1980s	High-strength adhesives have been developed that even allow the adhesive bonding of oiled metal sheets.
Since 1990	Development of various adhesives with multiple curing mechanisms, which, for example, are first cured by UV radiation and then by air humidity.
1993	Development of adhesives whose curing is initiated by oxygen (aerobically curing adhesives).
1995	Development of silane crosslinking polyurethane prepolymers (SMP adhesives).
Ab 2000	Development of redetachable adhesive systems with high adhesive strength for repair and recycling.
Ab 2012	Colour reactions with which the condition of an adhesive (fresh, superimposed, cured) can be visually recognised.
2014	Pre-applicable, chemically curing adhesives with the main function of transmitting mechanical loads. In this process, components are provided by the supplier with a solid adhesive, which is not sticky in this state, which then cures quickly in the subsequent assembly process.

From the very beginning, a particular challenge for the chemical industry was to precisely control the solidification of the adhesives. For this purpose, various adhesives with combined solidification mechanisms were introduced to the market from the 1980s onwards. Since the turn of the millennium, the adhesives industry has concentrated on the development of re-solvable adhesive systems, among other things, in addition to accelerating curing reactions and increasing production process reliability. These should enable repairs and pure recycling. In recent years, there have been many innovations far beyond the familiar everyday field of pressure-sensitive adhesives (such as labels or self-adhesive notepads). The field of application of adhesives affects almost all areas of our lives. Products with adhesively bonded joins have proven that they can be used without problems for at least 15 years, possibly even 30 years.

1.4.3 Adhesive bonding – a model in nature

Adhesive bonding is not an invention of technology and not a human invention: In nature, adhesive bonding has always been firmly anchored. A basic requirement of adhesive bonding is the adhesion of materials to surfaces, scientifically known as "adhesion". Good adhesion to certain surfaces is also a prerequisite for the natural life cycle: Through selective adhesion, the fertilized egg can implant itself in the uterus.

For adhesive bonding technology, nature was, is and remains the greatest role model and the most important source of ideas. Bees (→ **see Fig. 9**[14]**, left**), for example, rely on the principle of hot-melt adhesives: they heat wax (their adhesive) in their body and apply the liquid wax to their honeycombs. As soon as the wax cools down to room temperature, it solidifies and adheres to the surface (adhesion). The inner strength is scientifically called "cohesion". In terms of adhesion and cohesion, beeswax behaves like a technical hot melt adhesive.

The adhesive of the mussel is also interesting (→ **see Fig. 9, right**). The mussel has the special ability of adhesive bonding under water and thus attaches itself to rocks or ship hulls. The mussel adhesive must be able to withstand extremely high salt concentrations, high waves and high water flow velocities. These are challenges that many synthetically produced adhesives cannot meet. Tests have shown that mussels even stick to anti-adhesion layers made

14 AdobeStock 271140465

Fig. 9
Adhesive bonding in nature – the bees and the blue musse[4]

of Teflon (Polytetrafluoroethylene – PTFE). This is a particular challenge even for modern industrial adhesives.

The mussels produce a natural underwater adhesive that forms long-term adhesion under water and then hardens. In addition, it has a high strength, but is also sufficiently elastic. For this reason, the adhesive bonding technology relevant components of the mussel's adhesive are the focus of past and current research projects.[15, 16] These are so-called "catechols", the functional group of the key amino acid DOPA, which is present in the mussel adhesive.[17] First potential applications of these adhesives can be found in the field of medicine.[18, 19]

Nature is therefore not only the model for adhesives, but also for its application. Adhesive secretion mechanisms adapted from the animal kingdom are models for automated production processes. In industrial production, liquid adhesives are precisely

15 K. Rischka, K. Richter, A. Hartwig, M. Kozielec, M. Slenzka, R. Sader, I. Grunwald, I. (2010) "Bio-inspired Polyphenolic Adhesives for Medical and Technical Applications". In: von Byern J., Grunwald I. (eds) Biological Adhesive Systems. Springer, Vienna, doi:10.1007/978-3-7091-0286-2_13

16 K. H. Park, K. Y. Seong, S. Y. Yang, S. Seo, Biomater Res. 2017; 21:16, doi: 10.1186/s40824-017-0101-y, Advances in medical adhesives inspired by aquatic organisms' adhesion.

17 J. Saiz-Poseu, J. Mancebo-Aracil, F. Nador, F. Busqué, D. Ruiz-Molina, Angew Chem Int Ed Engl. 2019; 58(3):696–714. doi: 10.1002/anie.201801063, The Chemistry behind Catechol-Based Adhesion.

18 D. W. R. Balkenende, S. M. Winkler, P. B. Messersmith, Europ. Polym. J. 2019, 116, 134–143. Doi: 10.1016/j.eurpolymj.2019.03.059, Marine-inspired polymers in medical adhesion.

19 O. Guo, J. Chen, J. Wang, H. Zeng, J. Yu", Nanoscale 2020, 12, 1307–1324. Doi: 10.1039/C9NR09780E, Recent progress in synthesis and application of mussel-inspired adhesives.

dosed and applied in dots or lines using special nozzles to ensure high reproducibility.

1.4.4 Adhesive bonding – Classification as joining technology

Joining technology" generally describes the constructive methods of assembling machines, plants, apparatus, equipment and modern buildings from their individual parts. The process of joining is an element of manufacturing technology.[20] In manufacturing technology, "joining" represents the fourth of the six main manufacturing groups (original forms: Creating cohesion/forming: Maintaining Cohesion/Separating: Reduce Cohesion/Joining: Increase Cohesion/Coating, Increase Cohesion/Change Material Properties).[21]

Intermediate note

The main manufacturing group "Joining" can be divided according to physical principles of action (→ **see Fig. 10**) into force fit joints such as bolted and riveted joints, which are held together by static friction between the components to be joined; positive fit joints such as clinch, seam, bolt and snap-fit joints, in which the shape and geometry of the components is exploited for joining; and material fit joints such as welded and soldered joints, which when joined produce a connection via atomic or molecular forces in the material itself.[22] In this context, adhesive bonding technology is one of the material fit joints[23] and is referred to as "heterogeneous material fit".

Joining technologies work via material fit, positive fit and force fit.

20 M. Neitzel, P. Mitschang, U. Breuer (Ed.) In Handbuch Verbundwerkstoffe: Werkstoffe, Verarbeitung, Anwendung; Hanser Verlag: Muenchen, 2014, 2. aktualisierte und erweiterte Auflage.

21 DIN 8580:2003-08, Manufacturing processes – Terms and definitions, division, Beuth-Verlag: Berlin, 2003

22 W. Skolaut (Ed.), Maschinenbau, Springer Verlag: Berlin, 2014

23 DIN 8593-0:2003-09, Manufacturing processes joining – Part 0: General; Classification, subdivision, terms and definitions, Beuth-Verlag: Berlin, 2003

Fig. 10
Systematics of joining technologies[4]

Adhesive bonding is the only joining technology capable of being combined with other joining methods (→ **see Fig. 11**). The mixed forms as a combination of an "elementary" joining method is called hybrid joining. Examples are: Adhesive bonding and spot welding, adhesive bonding and clinching, adhesive bonding and folding as well as adhesive bonding and riveting. Hybrid joining offers the advantage of supplementing the strengths of the elementary joining technique adhesive bonding and reducing weaknesses. For example, a hybrid joining connection consisting of adhesive bonding and clinching can provide the high performance of adhesive bonding and at the same time is fixed by the clinching point immediately after joining.

The joining technology "adhesive bonding" itself is first defined simply as the "joining of two materials (parts to be joined) with an adhesive".[24] The adhesive is a non-metallic material that joins two parts by means of adhesion (surface adhesion) and cohesion (internal strength) (→ **see Fig. 12**).[25]

24 DIN EN 923:2016-03, Adhesives – Terms and definitions, Beuth-Verlag: Berlin, 2016

25 following quotation 23

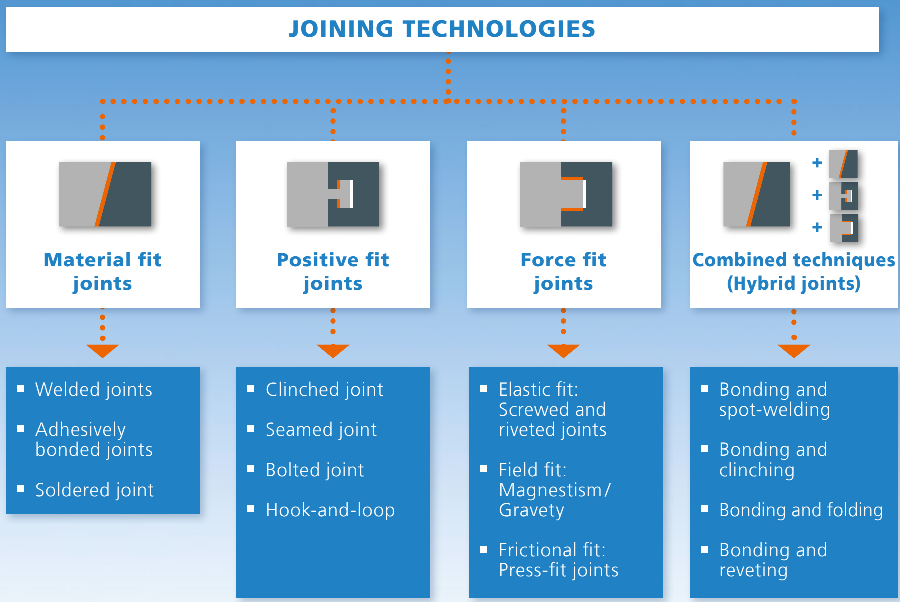


Fig. 11
Classification of joining technologies [4]

Adhesive bonding is the joining of materials with an adhesive.

An adhesive is a non-metal that joins materials by means of adhesion (surface adhesion) and internal strength (cohesion).

Adhesion is here the technical term for the interactions (adhesion forces) between the adhesive and the surfaces of the parts to be joined. It takes place in nm dimensions (1 nm corresponds to the millionth part of a millimeter = 0,0000001 mm). These adhesion forces include physical interactions, chemical bonds and micromechanical adhesion. The cohesion describes the internal strength of the solidified adhesive. Cohesion forces hold the molecules of an adhesive together. These forces are based on physical forces of attraction between the polymer chains, the entanglement of

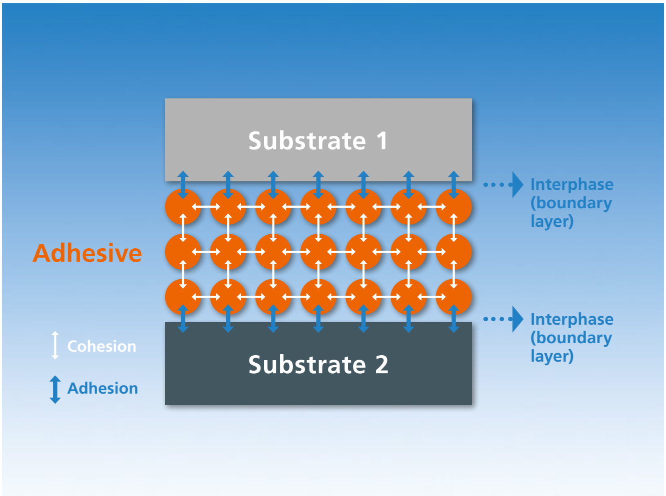


Fig. 12
Principle mode of action of an adhesive in an adhesively bonded joint[4]

the polymer chains and chemical bonds within and between the adhesive-polymer chains.

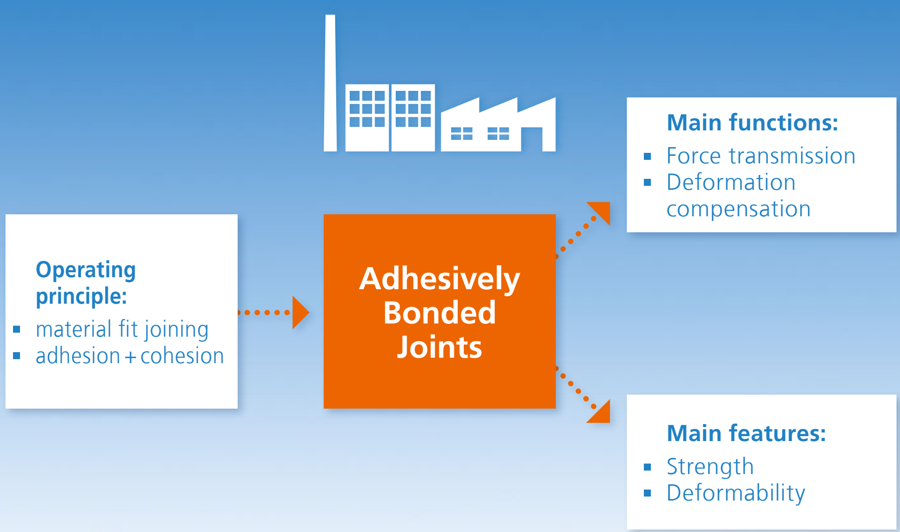
However, adhesive bonding, which is based on the active principle of a heterogeneous material fit by means of adhesion and cohesion as described above, clearly goes beyond simply joining materials. An adhesively bonded joint fulfils two main functions: Power transmission (to transfer loads) and deformation compensation (to compensate for different joining part dynamics). This then leads to the main properties of an adhesively bonded joint: its strength and its deformability (→ **see Fig. 13**).

> **Beyond the mere joining of materials, adhesive bonding is characterized by the main functions of "force transmission" and "deformation compensation".**

For example, the adhesive between a bathroom tile and plastic towel rail fulfils these two main functions: The adhesive transfers the weight force from the holder to the tile and compensates for the different thermal expansions of the ceramic tile and the plastic holder.

Fig. 13
Function and mode of action of adhesively bonded joints [4]

The main functions of force transmission and deformation compensation of an adhesively bonded joint lead to the main properties "strength" and "deformability".



1.5 "Adhesive bonding" joining technology – advantages compared to other joining technologies

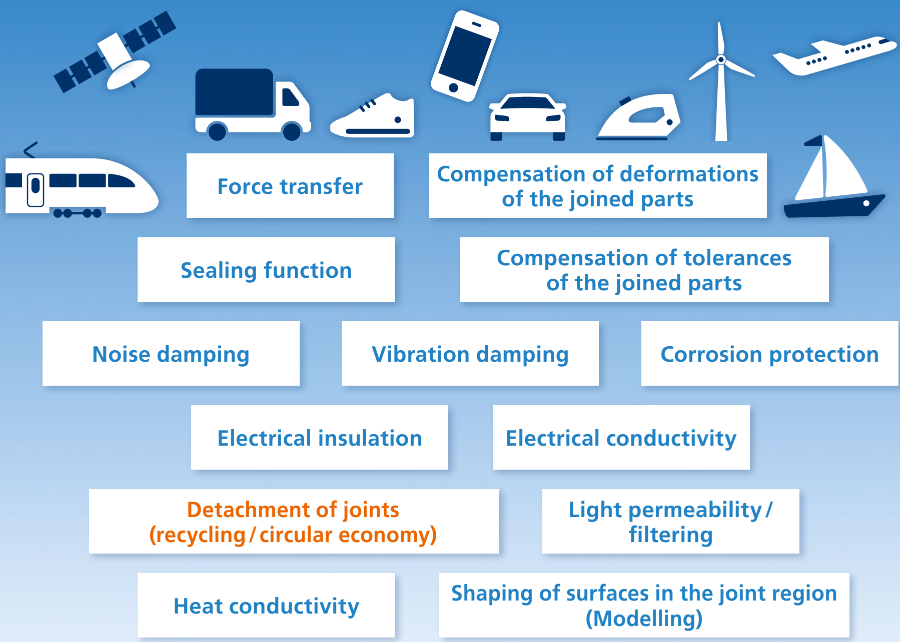
Adhesive bonding technology shows a number of further advantages compared to other joining technologies. In addition to the pure joining of materials and the main functions of "force transmission" and "deformation compensation", adhesive bonding technology offers a number of additional functions (→ see Fig. 14).

> **In addition to the main functions of force transmission and deformation compensation, adhesive bonding technology offers a number of advantageous additional functions.**

An adhesive can compensate for joint tolerances. It can also seal an adhesively bonded joint against liquids and possibly against gases. Elastic adhesives provide sound insulation and vibration damping. When bonding metallic materials, the adhesive can act as corrosion protection in the adhesively bonded joint. Many adhesives are based on organic polymers which are non-conductive. These adhesives can provide electrical insulation. Metal powder (usually silver powder) is added to other adhesives. Adhesives modified in this way have very good conductivity. They are used, for example, in micro-electronics for the transmission of electric current. Other adhesives are specially modified for heat transfer and have a high thermal conductivity.

Modern adhesives can be developed in such a way that they allow light of the desired wavelengths to pass through the adhesively bonded joint or even filter it out. Each adhesively bonded joint can be released again (see also chapter 2.6), so that the materials of the joint can be reused after recycling. Adhesive bonding also offers a high degree of design freedom. This also applies to the design of surfaces in the joint area. In addition, joining thin, small and sometimes complicatedly shaped components is possible. An adhesively bonded joint can be designed in such a way that it remains hidden from the eye of the beholder and does not interfere with the design of the overall product.

Fig. 14
Possible functions of an adhesive in an adhesively bonded joint [4]



1.6 "Adhesive bonding" joining technology – limiting factors compared to other joining technologies

Like any technology, adhesive bonding has its limits, of course. If these limiting factors are not known to the designer or are not observed by the user, there is a risk of joint failure.

Probably the best known example of such a failure is the crash of the Icarus (→ see Fig. 15[26]). According to Greek mythology, Icarus and Daedalus were imprisoned in the labyrinth of the Minotaur on Crete. Daedalus invented wings for himself and his son Icarus by bonding feathers to a pole with wax (i.e. a "hot-melt adhesive"). The boundary conditions were given: not too high and not too low flight altitudes. If the flight altitudes were too high, the heat of the sun would cause the wax to soften and thus lead to a crash. If the flight altitude is too low, the humidity of the sea causes the feathers to detach. Nevertheless, Ikarus exposed the adhesively bonded joints of his wings to conditions for which they were not designed: He climbed so high that the sun melted the wax, the adhesively bonded joints separated and he crashed into the sea. Even today the place of the accident is called Ikaria, the sea around it is called the "Icarian Sea".[27]

Fig. 15
The crash of Icarus

The example shows the limits in the application of adhesive bonding technology. These are in detail:

- Adhesives, and thus adhesively bonded joints, have only a limited thermal load-bearing capacity.
- The long-term stability of adhesively bonded joints is limited by ageing processes (degradation).

26 La caída de Ícaro, Madrid, Museo del Prado from Jacob Peter Gowy. Wikicommons (Access April 30, 2020)

27 following: O. Hoefer In Ausfuehrliches Lexikon der griechischen und roemischen Mythologie; W. H. Roscher (Ed.); Leipzig 1894, Band 2,1, Sp. 114–117, Ikaros 1.

- When producing an adhesively bonded joint, the time required to achieve manual strength varies from a few seconds to many hours. Fixings may be necessary.
- The adhesively bonded joint can in principle be seperated again, but this may involve some effort.

Not only at Ikarus, but also today, adhesively bonded joints can only withstand limited thermal stress. Modern adhesives are organic polymers and silicones. With them, the energy of a chemical carbon-carbon or silicon-oxygen bond is limited to approx. 350 kJ/mol or approx. 370 kJ/mol. If this bonding energy is exceeded, decomposition inevitably occurs. But even before decomposition, the adhesive polymer changes its mechanical-technological properties such as strength and deformability: When a specific elevated temperature is reached, the polymer softens. The strength decreases and the deformability increases.

On the other hand, if the temperature falls below a specific low temperature, the adhesive polymer becomes brittle. The strength increases and the formability decreases. To counter these limiting factors, the engineer only uses adhesives in design that are suitable for the temperature range intended for the product. If there is no corresponding adhesive, adhesive bonding is an unsuitable joining technology for this application.

The bond energies of organic polymers and silicones are also the reason for the limited long-term stability of adhesively bonded joints. Like other plastics, adhesives – and thus the adhesively bonded joints – are subject to ageing processes caused by moisture, UV radiation, temperature, external media, etc. These influencing factors can occur individually, but also in combination. For the adhesive user it is crucial that they know the possible degradation processes for the product to be bonded and takes appropriate countermeasures. For example, it is known that the polyurethane adhesives normally used for adhesive bonding of car windshields are not stable against sunlight. The UV component of sunlight causes the polyurethane bonded joint to age. The measure to counteract this degradation process exists – state of the art! – is to coat the adhesive bonding surface on the pane with a UV-impermeable ceramic screen print before adhesive bonding. The ceramic screen printing protects the adhesively bonded joint from UV light.

As a rule, an adhesively bonded joint cannot be used immediately. The reason for this is the interplay between wetting of the surface and the internal strength of the adhesive: An adhesive must completely wet the material surface during application in order to build up adhesion. To do this, the adhesive must have sufficient flowability to penetrate the microstructure (adhesion surface) of the material surface at all. The internal strength of the adhesive may only be built up after wetting and the subsequent build-up of the surface adhesion. This is done by chemical or physical solidification of the adhesive. Solidification is a process, which, depending on the adhesive used, can take more or less time and requires the workpieces to be fixed during this process.

In principle, any adhesively bonded joint can also be separated again (see chapter 2.6). However, as with a riveted or welded joint, this can be a time-consuming and costly process. More details are given in chapter 2.6.

> **The limits of adhesive bonding technology must be known to the user.**

1.7 "Adhesive bonding" joining technology –- examples of typical areas of application

1.7.1 Adhesive bonding in daily life

Without us being aware of it, adhesive bonding technology has long been a constant companion. Often down-to-earth as well: Tiles, parquet, carpeting – everything is adhesively bonded, guaranteed. Adhesive bonding technology has long since developed into a technology of the future, without which almost nothing works. Adhesives can be used to join everyday objects and highly complicated special products (see chapter 1.7.2). Nevertheless, adhesives are often underestimated. One of their technical advantages is also a disadvantage for their image: adhesives are often not visible to the consumer.

It is difficult to imagine how much adhesive is in everyday objects. In Germany alone, more than one million metric tons of adhesive bonding and sealing materials were produced in 2019 (see Chapter 1.8), and the trend is rising. Germany is even the world champion in adhesive bonding: the average per capita consumption in 2019 was 10.8 kilograms.[28] Without being aware of it, we are surrounded by many different adhesives and adhesive bonding technology applications in everyday life, for example on shoes, mobile phones and other electronic devices, on books and magazines, furniture, window panes, bottle labels, price tags, packaging, tooth crowns, diapers, fingernails and plasters. → see Fig. 16[29, 30, 31]

28 Information Industrieverband Klebstoffe e.V., 2020

29 AdobeStock 2758638

30 Andreas Groß, private

31 "Ettore Sottsass Tribute" – art by NO CURVES / www.nocurves.ws / photo courtesy: Marco "Sfrevol" Montanari

Fig. 16
Adhesive bonding technology in everyday life – adhesively bonded fingernails [29], pfasters [4], adhesively bonded bread roll bag with adhesively bonded handles [30], tape-art picture of the artist NO CURVES [31]

Plasters, for example, are perceived as "everyday products", everyone needs them now and then. Above all, they must cover the wound and protect it from contamination. To do this, they must be adhesively bonded to the skin, but they must also be painlessly removed. At the same time, they should be able to move with the patient, tolerate water and absorb wound fluid or blood. Many requirements for a product that only appears simple. Another everyday example: the paper bread roll bag is, of course, adhesively bonded. In the example in Figure 16, bottom left, the carrying handles are also adhesively bonded. Modern artists also use adhesive bonding technology to realize their ideas. Figure 16 bottom right shows the example of the artist Marco Montanari. The picture shows the architect Ettore Sottsass (1917–2007).

Nowadays there are hardly any areas in which the joining technology "adhesive bonding" is not used. In the following chapter 1.7.2 examples of industrial adhesive bonding are given, some of which are explained in more detail to illustrate this.

1.7.2 Industrial adhesive bonding

Aircraft construction

However, adhesives are not only found in everyday life. They are also indispensable in industrial production. One example is the aircraft industry (→ see Fig. 16 [32]). So-called composite materials are used to reduce operating costs per passenger and aircraft and to lower fuel consumption. These materials, which consist of layers of glass fiber reinforced plastic and aluminium, are joined together with high-performance adhesives.

Fig. 17
Adhesive bonding technology – modern aircraft construction would be inconceivable without it

Vehicle construction

Today, between 15 and 20 kg of adhesive are used in a passenger car (→ see Fig. 18 [33, 34]).

A typical application is the adhesive bonding of car windshields (→ see Fig. 18, right), which has long been state of the art in automotive engineering. In contrast to the past, the windshield is no longer inserted, but adhesively bonded with elastic polyurethane adhesive. Since the adhesive can transfer forces in the adhesively bonded joint, the window pane becomes a design element for the

32 AdobeStock 128490717

33 AdobeStock 50101004, AdobeStock 45667995, AdobeStock 50101006

34 AdobeStock 142408206

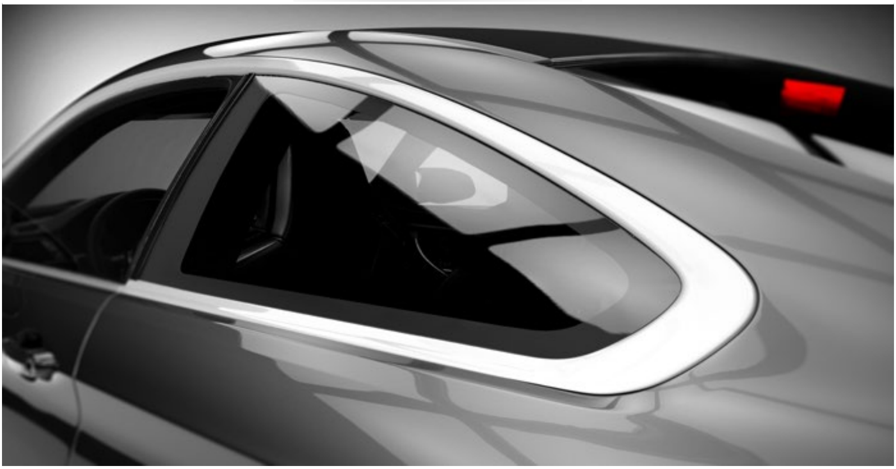


Fig. 18
Adhesive bonding technology – modern automotive engineering would be inconceivable without it: The adhesive bonding of car windshields in modern automotive engineering (right) is state of the art

entire bodywork. The advantage is that the adhesively bonded joint between the windscreen and the bodywork increases the torsional stiffness of the vehicle by 15–20 % compared to the inserted window. This, in turn, makes it possible to use thinner, i. e. lighter, sheets of metal and results in a weight reduction of the vehicle.

In automotive body construction, adhesive bonding is also used: spot-weld bonding (hybrid joining, see Chapter 1.3) is now state of the art there. The advantage of spot-weld bonding is that it combines power transmission and immediate fixing. Responsible for the high power transmission is adhesive bonding. Welding spots only allow a spot-shaped force transmission (→ **see Fig. 7, left**). In the case of exclusively spot-welded joints, the force transmission is therefore concentrated on a few points and a small area. If too much force is applied, the weld spots can be "torn out" of the sheet. The adhesively bonded joint is made over the entire surface of the joint and thus enables force transmission over the entire surface. In addition, the weld spots prevent the adhesively bonded joint from peeling. In many modern German vehicles, adhesive is

Fig. 19
Hybrid joining (spot-weld adhesive bonding) in car body construction: Increased crash stability = increased passenger safety

even largely responsible for crash safety and thus for the survival of the occupants in an accident (→ see Fig. 19[35, 36]).

Adhesive bonding is also increasingly used in commercial vehicle construction. Figure 20[37] shows the example of a truck. The outer elements of the driver's cab are made of glass fiber reinforced plastic (GRP) and are adhesively bonded to the body.

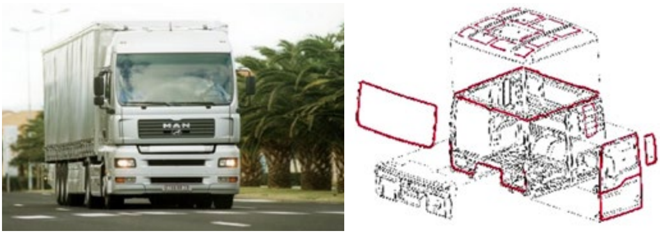


Fig. 20
Adhesive bonding technology in commercial vehicle construction: the GRP outer elements of the driver's cab are adhesively bonded (left) / the red lines show the adhesive bonding seams (right)

Rail vehicle construction

Rail vehicle construction has also become an important area of adhesive bonding technology (→ see Fig. 21[38] and 22). In the case of rail vehicles, the increase in requirements consists, among many other factors, in the increase in speed and transport comfort. To achieve this, the vehicles must become lighter and at the same time be able to withstand higher loads (see also Chapters 2.5.3 and 2.5.4).

The development of adhesive bonding technology in rail vehicles continues to make progress. The adhesive bonding technology

35 AdobeStock 243726087

36 AdobeStock 243726169

37 MAN AG

38 MBD Design / Bombardier

enables modern design, and design is also an important sales argument in rail vehicle construction.

Fig. 21
Tram Marseille (France): adhesive bonding technology enables modern design

The scope of adhesive bonding technology in rail vehicle construction has now reached such a level that a standard (DIN 6701[39]/see Chapter 1.9) for quality assurance of the organisation and implementation of bonding processes in rail vehicle construction was developed on the initiative of the German Federal Railway Authority and introduced in 2006. Although it is a national standard, in the meantime (as of 31.12.2019) more than 700 companies worldwide are working according to this standard and are certified according to the standard. → **see Fig. 22**[40]

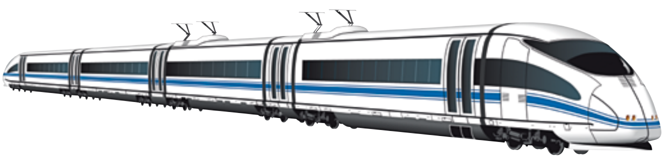


Fig. 22
Rail vehicle construction / Example ICE – the adhesive bonding technology has now reached such a level that a quality assurance standard (DIN 6701)39 has been introduced analogous to welding

39 Standards series DIN 6701, Adhesive bonding of railway vehicles and parts, Beuth-Verlag: Berlin, 2006 – 2015

40 AdobeStock 51103001

Fig. 23
Shipbuilding – the passenger window panes of polycarbonate and the rows of seats (right) are adhesively bonded

Shipbuilding
As early as 2000, the Lürssen shipyard in Lemwerder (Germany) built high-speed ferries for an Indonesian customer (→ see Fig. 23[41]), which operate at a speed of 40 knots (> 70 km/h), the highest speed ever in this sector. In heavy seas, these ferries are exposed to violent impacts. The rows of seats are therefore bonded to the decks with moisture-curing, rubber-elastic adhesives. Instead of punctual joining, such as rivets or screws, adhesive bonding prevents the seats from tearing out due to the two-dimensional transmission of force. In addition, the adhesive has a vibration-damping effect, which in turn increases driving comfort. In addition, around one ton of weight has been saved because the passenger deck windows are no longer made of glass but of polycarbonate. The plastic windows were also adhesively bonded with polyurethane adhesives. Over the product life of a ship, the long-term stability of the multi-material lightweight construction achieved by the adhesive bonding technology dramatically reduces the CO_2 footprint.

41 all photos: Fr. Luerssen Werft GmbH & Co. KG, Lemwerder / Henkel AG & Co. KGaA, Duesseldorf

Wind energy

Wind energy is an important area for shaping the future. In order to realize more and more efficient wind turbines (→ see Fig. 24), the rotor blades are completely adhesively bonded. The rotor blades of the turbines consist of glass fibre reinforced plastic (GFRP), a material with comparatively high stiffness at comparatively low weight. According to conventional design, the rotor blades are made of two half-shells, which are then completely joined to form a complete rotor blade using adhesive bonding technology. Depending on the size of a rotor blade, several hundred kilograms of epoxy resin adhesive are used.

Fig. 24
Wind turbines – the rotor blades made of FRP are adhesively bonded[30]

Joining the rotor blade half-shells would be inconceivable without adhesive bonding technology. Welding would destroy rotor blade materials, and point-like mechanical joining techniques would lead to material damage in the rotor blade by drilling holes. The extreme mechanical loads occurring during operation at speeds of up to 390 km/h[42] alone would have fatal consequences. For this reason, highly dynamic structural adhesives have been developed that can withstand these extreme loads. Consequently, the adhesive bonding technology enables the necessary prevention of material damage and thus the realisation of these plants for the generation of regenerative energy in the first place.

42 enercity AG, https://www.enercity.de/windenergie/wissen-windenergie/windraeder/index.html (Access April 30, 2020)

Fig. 25
Adhesive bonding technology in optics – adapted light transmission allows the use of adhesives in the beam path of optics [4]

Optics

For optics and high-performance optics, adhesive bonding technology is an essential joining process (→ see Fig. 25). It enables the tension-free joining of the various optical elements. The absence of tension is often required, as it allows an uninterrupted, unaffected beam path.

Medical technology

The adhesively bonded optics of an endoscope is an example of the extensive use of adhesive bonding technology in various areas of medical technology (→ see Fig. 26). Endoscopes are manufactured for minimally invasive use. The tube diameter of an endoscope is approximately 2 mm. The adhesive bonding is done with a UV-curing adhesive of an adjusted wavelength, which allows an undisturbed passage of light during the examination.

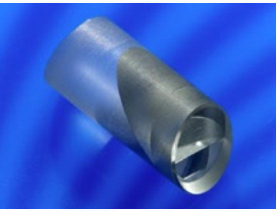


Fig. 26
Adhesive bonding technology in medical technology – adhesively bonded optics of an endoscope for minimally invasive use (tube diameter approx. 2 mm, UV-curing adhesive) [4]

The use of adhesive bonding technology in dentistry (→ see Fig. 27 [43]) is also standard. It must be taken into account that the oral mouthnflora places the highest demands on the long-term stability of an adhesively bonded joint. Radiation-curing adhesives are used, which were developed precisely for this application area.

Fig. 27
Adhesive bonding technology in medical technology – Use of adhesive bonding technology in dentistry

43 AdobeStock 26812232 (left), 169282841 (right)

Household appliances (“white goods”)

In the household sector, adhesive bonding technology is also widely used (→ see Fig. 28[44]).

Fig. 28
Adhesive bonding of household products

One example is the cooker, where the ceramic hob (→ see Fig. 29[45], centre) and the glass panel and design parts of the cooker hood (→ see Fig. 29[46], left) are adhesively bonded. → see Fig. 29[47], right, shows an oven in which the front panel, door and design parts are adhesively bonded with heat-resistant silicone adhesive (up to 250 °C).

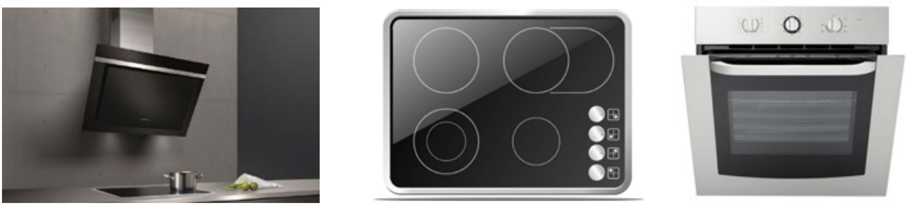


Fig. 29
Adhesive bonding technology in the household – adhesively bonded glass pane and design parts of the cooker hood (left), adhesively bonded ceramic hob (middle) and adhesively bonded door and design parts of the oven (right)

44 AdobeStock 57110605

45 AdobeStock 27997579

46 BSH Hausgeraete GmbH

47 AdobeStock 123650428

Fig. 30
Adhesive bonding technology in the acoustics industry – adhesively bonded loudspeaker membranes

Acoustics industry

The production of acoustic boxes is no longer conceivable without the use of adhesive bonding technology. By gluing in speaker membranes, the highest quality standards are achieved (→ see Fig. 30[48]).

Footwear industry

Adhesive bonding technology is also indispensable in the production of shoes. It enables a flat and tight joining of the individual parts made of different materials (→ see Fig. 31).

At the same time, it enables the repair of the shoes, which significantly increases the product life (→ see Fig. 32[49]).

Fig. 31
Adhesive bonding technology in shoe manufacturing – adhesively bonded laminate structure of a sports shoe[4]

Fig. 32
Adhesive bonding technology in shoe repair

48 AdobeStock 79864289

49 AdobeStock 32143097 (left), AdobeStock 1326609423 (Middle), AdobeStock 266601382 (right)

Sports area

A very memorable example of the use of adhesive bonding technology in the field of sports is the FIFA World Cup balls. The original football was made from the natural material leather (hence "leather pill") by sewing the individual leather parts together (→ see Fig. 33, left). Even though since the 1986 World Cup the World Cup balls were no longer made of leather but of plastic, the joining technology remained the same: sewing was continued.

The Teamgeist (Team Spirit/→ see Fig. 33, right), the ball of the 2006 FIFA World Cup ("the summer fairy tale") was the first World Cup ball to be manufactured in a material-compatible manner. There were no more material injuries due to holes drilled for sewing and no more punctiform power transmissions, but rather flat adhesively bonded joints. The team spirit was the first completely adhesively bonded football of a FIFA World Cup.

Fig. 33
Adhesive bonding technology in sports – From the leather pill to the high-tech ball:

Left: Ball of the 1954 World Cup (the "Miracle of Bern"): the ball consists of 18 leather segments sewn together [30]

Right: Teamgeist (Team Spirit / World Cup 2006 – the "summer fairytale"): the first completely adhesively bonded football [30]

1.8 Adhesive bonding – economic significance of this joining technology

Modern adhesive bonding technology has thus long been an integral part of innovative technological development in almost all areas.[50] Due to its technological potential, it makes economic contributions to the stabilisation and expansion of Germany as a business location. It is not without reason that Germany is the world leader in the field of adhesive bonding technology.

In 2018, 1,137,000 tonnes per year of adhesives and sealants were produced (adhesives: 955,000 t / sealants 182,000 t), cement-based construction adhesives are not included. The most important product types in this context in terms of production volume in 2018 were dispersion adhesives with a production volume of around 423,000 tonnes. This is followed by reactive adhesive systems with approx. 300,000 tonnes and hot melt adhesives with approx. 142,000 tonnes. Added to this are 35,000 tonnes of casein and bone glues, starch, dextrins and vegetable adhesives and 55,000 tonnes of solvent-based adhesives as well as 1,055 million m^2 of adhesive tapes.[51] The latter is equivalent to an area of about 150,000 international match-compliant[52] football pitches.

The above-mentioned production volume corresponds to a turnover of around € 4 billion for adhesives. The decisive factor for the national economy, however, is that adhesive bonding in 2018 led

50 A. Wagner; A. Stett In Sicheres Kleben – Herausforderungen in der klebtechnischen Praxis: NMI – Naturwissenschaftliches und Medizinisches Institut an der Universitaet Tuebingen: Reutlingen, 2015

51 Information Industrieverband Klebstoffe e.V., 2020

52 Union des Association Européennes de Football (UEFA) (Ed.) In UEFA-Stadioninfrastruktur-Reglement, Ausgabe 2010, Artikel 29

to an indirectly generated value added of approx. 450 billion €.[53] It can be assumed that there are about 33,000 different adhesive products on the market in Germany, from which the most suitable one can be selected for the most diverse products. Only the so-called "all-purpose adhesive" does not exist, nor does the "universal bolt" or the "global rivet".

> **There is no "all-purpose glue" any more than there is a "universal screw".**

53 B. Tasche, A. van Halteren In Press release Industrieverband Klebstoffe; Duesseldorf, 2019; Deutsche Klebstoffindustrie: Verlangsamtes Wachstum.

1.9 Adhesive bonding – but safe: the development and implementation of quality standards to ensure safe adhesive bonding

1.9.1 Introduction

Due to the breadth and scope of its use, adhesive bonding technology is irreplaceable for German industry and for our private everyday life. The economic significance of the added value indirectly generated by adhesive bonding technology is extremely high (see chapter 1.8). Nevertheless, the technological performance potential and the image of the adhesive bonding technology in the general public does not have the deserved significance. The reasons for this are complex and can be illustrated by two examples.

1. Adhesive bonding is used for handicraft work, for example with wood and paper. From this it is derived that adhesive bonding technology is "child's play". The adhesive bonding system successfully used for handicraft work is transferred to professional applications, this usually turns out to be a fallacy. However, the fallacy is not due to the "adhesive" and certainly not to the "adhesive bonding technology", but to the "adhesive bonder", i. e. the person carrying out the work. The "adhesive bonder" has abstracted incorrectly due to a lack of adhesive bonding competence and has arrived at false transfer conclusions.

2. Adhesive bonding technology is often only considered as a joining technology when the use of the intended joining technology is not feasible from a higher-level point of view in production. In this case, adhesive bonding technology is thought of as a last resort solution. It is often expected that it can be used without testing the materials to be joined for

their ability to be adhesively bonded, treating the surfaces to be joined for adhesion (see Chapter 1.4.4.), determining the compatibility of the adhesive solidification; boundary conditions of production, and without designing the joint in a manner suitable for adhesive bonding. Failure is pre-programmed here: If the basic technological requirements necessary for successful adhesive bonding are not met, the adhesive bonding cannot work.

However, both examples – and the list could be extended almost indefinitely – have one thing in common: For the evaluation of the failure that is inevitable under these conditions, the blame is assigned to the "adhesive" or the "adhesive bonding technology". This false and unreflected impression shapes the image of adhesive bonding technology. It prevents the necessary basis for future operations: trust! [54] This is not a specific feature of adhesive bonding. The basic rule is: It is better not to use things you do not trust.

There is an outstanding example of this in the history of joining technology: The joining technology no. 1 of the 19th century in metal construction was riveting technology.[55] It was trusted and therefore it was used.[56] It is not without reason that the best known, purely riveted and still existing exhibit is the Eiffel Tower in Paris. Welding technology was viewed extremely critically when it was introduced into metal construction at the turn of the 19th and 20th centuries. Although welding technology had a superior potential to riveting technology, its use was hampered by its lack of a positive image. The reason was quite simple: Riveting technology was given exactly the trust that welding technology lacked at that time due to the positive experiences with it.

54 A. Gross, In Proceedings 2nd Symposium on Adhesion and Bonding Research, Tokyo, Japan, December 6, 2018, Reed Exhibition Japan Ltd (Ed.); Tokyo, 2018, Contemporary quality requirements for adhesive bonding processes.

55 H. Behnisch, G. Aichele In Die Schweißtechnik im Wandel der Zeiten; DVS-Verlag GmbH: Duesseldorf, 2006; S. 210–219, Kapitel: Nieten – die wichtigste Verbindungstechnik im 19. Jahrhundert.

56 L. Klasen, In Handbuch – Der Hochbau – Constructionen in Eisen und anderen Metallen fuer Architekten, Ingenieure, Constructeure, Bau-Handwerker und Technische Lehranstalten; Verlag Engelmann: Leipzig, 1876

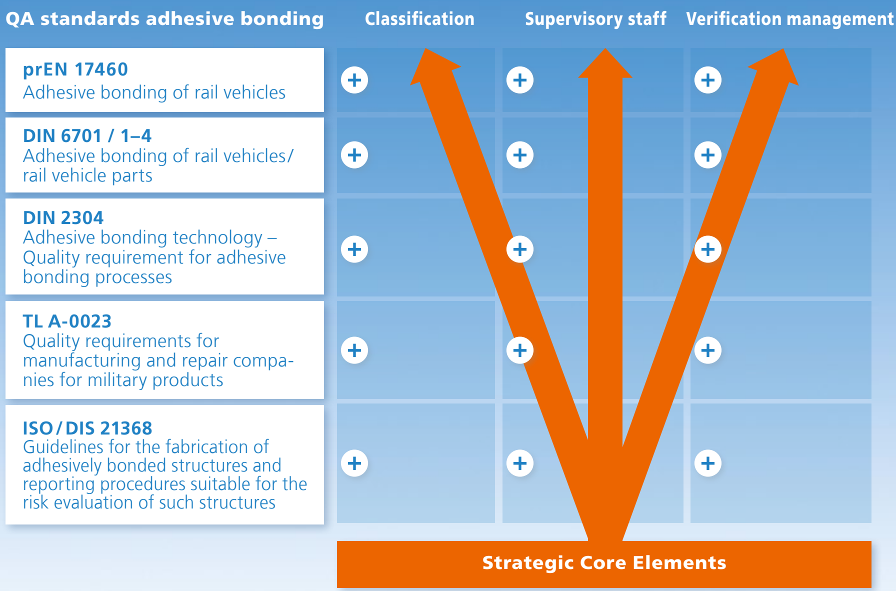


Fig. 34
Examples of welding regulations for quality assurance [4]

However, it is also indisputable that the image of welding technology – even in the common sense – has completely changed in the course of the 20th century and welding technology has become the no. 1 joining technology of the 20th century.[57, 58, 59] The reason for this is also quite simple: Welding technology is trusted because of the positive experiences with its use, which is necessary to use a – originally also “new” – technology in the industrial sector on a broad scale.[60]

57 H. Behnisch, G. Aichele In Die Schweißtechnik im Wandel der Zeiten; DVS-Verlag GmbH: Duesseldorf, 2006; S. 219–228, Kapitel: Von der genieteten zur geschweißten Stahlkonstruktion

58 N. Witte, Elektroschweißung 1 1930, 7, 140 –142, Die erste geschweißte Reichsbahnbruecke.

59 M. Beckert, Schweißen und Schneiden 54 2002, 2, 95–97, Aus der Geschichte des Schweißens im Schiffbau.

60 H. Buettemeier In Sonderband 100 Jahre DVS; DVS-Verlag: Duesseldorf, 1997, S. 218–226, Schweißtechnische Fertigung am Beispiel des Schienenfahrzeugbaus

Building trust is the basis of this image change. The image change naturally includes continuous research and development to improve the technology. However, the welders have built up trust strongly by designing and implementing quality assurance measures and regulations for the use of their technology at an early stage (→ see Fig. 34[61, 62, 63, 64, 65, 66]) As a result, application errors were increasingly avoided and the path to motivating experiences of success was opened. These experiences of success then led to increasing security in the application and thus ultimately to trust in the technology. This trust formed the basis for further innovations.

Trust is therefore essential, as welding according to ISO 9001 is a "special process".[67] This refers to processes and process steps whose faultlessness cannot be verified one hundred percent using non-destructive testing. For such "special processes", ISO 9001 requires the implementation of a quality management system for the comprehensive prevention of defects which cannot be verified one hundred percent non-destructively. In this context, the ISO and CEN QS welding standards listed in Figure 34 have the function of specifying the ISO 9001 core idea of error prevention in technological terms. Consequently, these regulations are exclusively a technology-specific supplement to an existing quality management system. The QA standards on welding technology

61 Standards series DIN EN ISO 3834, Quality requirements for fusion welding of metallic materials, Beuth-Verlag: Berlin, 2006

62 DIN EN 1090:2012-02, Execution of steel structures and aluminium structures, Beuth-Verlag: Berlin, 2012

63 DIN EN 13455:2012-07, Unfired pressure vessels, Beuth-Verlag: Berlin, 2012

64 Standards series DIN EN 15085, Railway applications – welding of railway vehicles and components, Beuth-Verlag: Berlin, 2008

65 Standards series DIN EN ISO 15607, Specification and qualification of welding procedures for metallic materials, Beuth-Verlag: Berlin, 2004–2018

66 H. Behnisch, G. Aichele In Die Schweißtechnik im Wandel der Zeiten; DVS-Verlag GmbH: Duesseldorf, 2006; S. 251–252, Kapitel: Regelwerke wurden angepasst.

67 DIN EN ISO 9001:2000, Quality management systems – Requirements, Beuth-Verlag: Berlin, 2000, Clause 7.5.2, Validation of processes for production and service provision

shown in Figure 34 as examples show the three strategic core elements of classification, supervisory personnel and verification for their welding-specific QMS specifications. Rules and regulations of this type are state of the art in the field of welding technology and are internationally accepted.

1.9.2 Quality standards for adhesive bonding technology – Status of developments

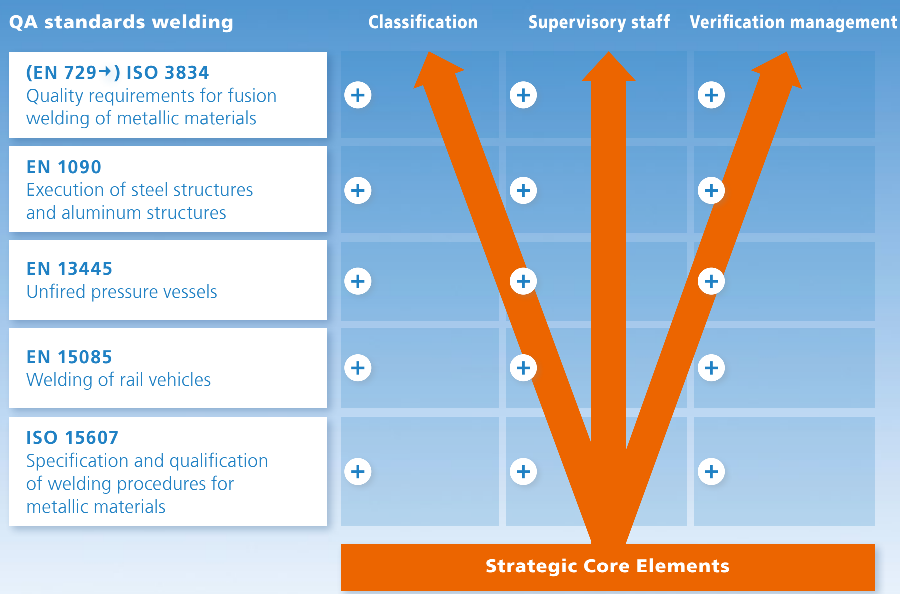
Like welding, adhesive bonding is also classified as a "special process". However, the number of quality influencing factors is higher with adhesive bonding than with welding and often the effects on the quality of the joint are more significant.[68]

In order to increase confidence in adhesive bonding technology further, the same path has therefore been followed in adhesive bonding technology since the year 2000. Initially, on the initiative of the Federal Railway Authority, a standard for the "adhesive bonding of rail vehicles and rail vehicle parts" was developed. Gradually, in analogy to the welding technology, further regulations for the quality assurance of adhesive bonding technology processes in almost all application areas were developed and implemented.[69]

Today's adhesives are high-tech products and generally enable zero-defect production. However, adhesive defects still occur, more than 90 % of which are due to application errors. It is precisely this contradiction that adhesive bonding technology quality assurance standards listed below address. If the main reason is not adhesive errors but application errors, improvements must be made in the application area. Consequently, these rules and regulations are user standards with the aim of organising adhesive bonding technology application processes in such a way that the entire adhesive

68 A. Groß, H. Lohse; Mittelstand konkret / Gesetze und Regularien; FARBE UND LACK 2015, 12, 2–3, DIN 2304: Kleben – aber sicher.

69 A. Gross, Proceedings of the 4th China Bonding Days, Hangzhou, China, May 20–21, 2019, Y. Zhang (Ed.); Eigendruck: Shanghai YIFA Bonding Training Center, Shanghai, 2019, Contemporary quality requirements for adhesive bonding processes.



bonding process is "mastered". They apply to all classes of adhesives, irrespective of their solidification mechanism and mechanical-technological properties in the adhesively bonded joint, to all combinations of materials and to all batch sizes in production.[70]

Fig. 35
Examples of adhesive bonding technology regulations for quality assurance[4]

70 A. Groß, H. Lohse, Adhaesion kleben + dichten 2015, 6, 14–20, Die neue DIN 2304 und ihr Nutzen fuer die Praxis.

To date (as of 30.04.2020/Figure 35), these regulations include the following documents:

- DIN 670139
- DIN 2304 [71]
- DIN SPEC 2305/Parts 1–3 [72, 73, 74]
- TL A0023 [75]
- prEN 17460 [76]
- ISO/DIS 21368 [77]

The basis in all cases is a quality management system (QMS), e.g. according to ISO 9001, with the core idea: If it is not possible to check one hundred percent for errors non-destructively and thus a so-called "special process" exists (see above), all possibilities of errors must be excluded. The regulations concretise the existing QMS and define the "state of the art" for the professional implementation of adhesive bonding processes, which is binding under product safety law. They define both the requirements for a quality-compliant execution of adhesively bonded joints and the

71 DIN 2304:2016-03, Adhesive bonding technology – Quality requirements for adhesive bonding processes, Beuth-Verlag: Berlin, 2008

72 DIN SPEC 2305-1:2018-05, Adhesive bonding technology – Process chain adhesive bonding – Part 1: Advice für manufacturing, Beuth-Verlag: Berlin, 2018

73 DIN SPEC 2305-2:2018-10, Adhesive bonding technology – Quality requirements for adhesive bonding processes – Part 2: Adhesive bonding of fibre composite materials, Beuth-Verlag: Berlin, 2018

74 DIN SPEC 2305-3:2019-02, Adhesive bonding technology – Quality requirements for adhesive bonding processes – Part 3: Requirements fort he adhesive bonding personnel, Beuth-Verlag: Berlin, 2019

75 Technische Lieferbedingungen TL A0023, Kleben und verwandte Prozesse – Qualitaetsanforderungen an Herstell- und Instandsetzungsbetriebe fuer militaerische Produkte, Urheber: Bund 2017, zu beziehen beim: BAAINBw, Koblenz, www.baainbw.de/TL

76 prEN 17460, Railway applications — Adhesive bonding of rail vehicles and parts, CEN-CENELEC Management Centre: Rue de la Science 23, B-1040 Brussels, 2019

77 ISO/DIS 21368:2019 (E), Adhesives — Guidelines for the fabrication of adhesively bonded structures and reportingprocedures suitable for the risk evaluation of such structures, ISO copyright office, CP 401, Ch. de Blandonnet 8, CH-1214 Vernier, Geneva, 2019

general organisational, contractual and manufacturing principles for the production of adhesively bonded products.[78]

All documents mentioned are pure user standards. They are compatible with each other in terms of content and structure and contain the three strategic core elements classification, supervisory personnel and verification.[79]

Core element 1: Classification of adhesively bonded joints
For the classification of the adhesively bonded joint according to safety requirements, the regulations/standards consider only one question: What happens if the adhesively bonded joint fails? The classification of the adhesively bonded joint is made exclusively with regard to potential effects on the failure of the bond and therefore represents an analysis of the damage sequence. All adhesively bonded joints must be classified in the safety classes by the adhesive user, not by the adhesive manufacturer:

- Class 1: direct/indirect danger to life and limb
- Class 2: possible danger to life and limb, major environmental damage
- Class 3: probably no personal injury or major environmental damage, maximum loss of comfort/performance
- Class 4: definitely no personal injury or environmental damage, maximum loss of comfort/performance

78 A. Groß In 4. Klebtechnisches Kolloquium: Aktuelle Entwicklungen in der Klebtechnik, Ulm, 30. Oktober, 2014; Eigendruck: Hochschule Ulm, 2014, ISO 9001 und Klebtechnik – eine unloesbare Verbindung.

79 A. Groß, E. Meiß In Dichtungstechnik Jahrbuch 2019; K-F. Berger, S. Kiefer (Ed.); ISGATEC gmbH: Mannheim / Silber Druck oHG: Niestetal, 2018; S. 367 – 374, Wissen und verstehen, was man tut – Das Potenzial der Klebtechnik und die Notwendigkeit der Qualitaetssicherung

Core element 2: Bonding supervisory personnel

The adhesive bonding supervisory staff comprises employees with proven adhesive bonding technology qualifications [80, 81, 82, 83, 84, 85] and is responsible for the adhesive bonding technology and all related activities in the company. The adhesive bonding supervisors are the central point of contact for all factors influencing the quality of the entire "special process" of adhesive bonding.

Core element 3: Verification of real stress < maximum stress

The joining is to be dimensioned with the assistance of the adhesive bonding supervisor in such a way that over the entire product life, its real stress is always less than the maximum stress. This must be comprehensibly documented. The verification itself can be carried out in the following ways:

1. dimensioning,
2. component testing,
3. documented experience or
4. combination of 1. – 3.

80 DIN EN ISO/IEC 17024:2012-11, Conformity assessment – General requirements for bodies operating certification of, persons, Beuth-Verlag: Berlin, 2012

81 Richtlinie DVS®-EWF 3305 Europaeischer Klebpraktiker, DVS Media: Duesseldorf, 2019 / EWF-515r2-19 European Adhesive Bonder (EAB), EWF Management Team, Porto Salvo, Portugal, 2019

82 Richtlinie DVS®-EWF 3301 Europaeische Klebfachkraft, DVS Media: Duesseldorf, 2019 / Guideline for European Adhesive Engineer (EAE) and European Adhesive Specialist (EAS) EWF-662r0-19, EWF Management Team, Porto Salvo, Portugal, 2019

83 Richtlinie DVS®-EWF 3309 Europaeischer Klebfachingenieur, DVS Media: Duesseldorf, 2019

84 Richtlinie DVS® 3308 DVS®-Bildungseinrichtungen auf dem Gebiet der Klebtechnik Zulassung-Schulung-UEberwachung, DVS Media: Duesseldorf, 2011

85 Richtlinie DVS® 3306 Planung und Einrichtung von klebtechnischen Kursstaetten, DVS Media: Duesseldorf, 2011

The aim of the user standards is to organise adhesive bonding technology application processes in such a way that the user is able to design the entire process and product life cycle in a robust and reproducible manner, i.e. to "master" it in the sense of the standards. In addition to this specific objective, the overriding aim of the regulations is to further develop the application areas of the key technology of adhesive bonding in a qualified manner by means of qualified adhesive applications and thus to improve the image of adhesive bonding, which in some areas can still be improved in the long term.[86]

86 A. Gross, H. Lohse, adhesion ADHESIVES & SEALANTS 2015, 4, 12–17, Topic of the month: New DIN 2304 standard and its use in practice.

1.10 "Adhesive bonding" joining technology – its potential as No. 1 joining technology of the 21st century

As the application examples in Chapter 1.7 show, there is hardly any area of industry, craftsmanship or the home today in which the joining technology "adhesive bonding" is not used. Adhesive bonding technology already surrounds us in most areas of our lives (→ **see Fig. 36**). In spite of these successes, the technological potential of adhesive bonding technology can still be greatly expanded.

Fig. 36
Adhesive bonding – hardly an area in which it is not used [4]

There are hardly any areas in which adhesive bonding is not used today. With adhesive bonding technology, all materials can be joined to themselves and others with long-term stability.

The need to fulfil complex requirements for products (see chapter 1.1) is inevitably, joining new or further developed materials with specific properties required in the product.[87] However, the individual material is not able to cope with the increasing complexity of the requirements, so that the combination of materials is becoming more and more important. The requirements provoke the further development of multi-material design and multi-component materials. At the same time, however, the sensitivity of highly developed materials is increasing, which consequently requires a joining technology that is appropriate for the material and also guarantees the material properties of the product necessary to meet the requirements.

The decisive potential of the "adhesive bonding" joining technology lies in maintaining the material properties in the product.

Moreover, this is exactly where the potential of adhesive bonding technology lies: all materials can be joined together with long-term stability while maintaining the material properties. Maintaining the material properties during adhesive bonding opens up new construction methods that are not possible with other joining methods. Adhesive bonding fulfils the main functions of "force transmission" and "deformation compensation". Beyond joining materials, additional functions can be integrated into the adhesively bonded joint.

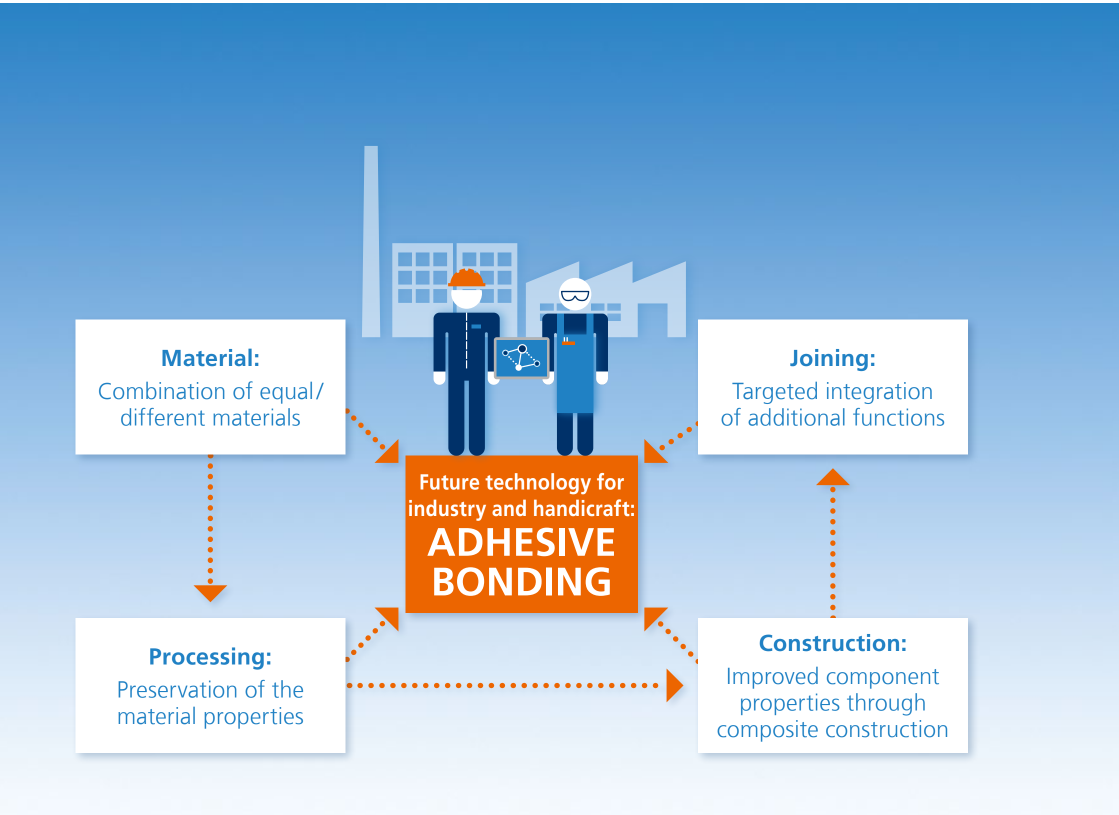
Adhesive bonding enables new construction methods that are not possible with conventional joining technologies.

87 K. Kristof, C. Liedtke, T. Lemken, C. Baedeker In Materialeffizienz & Ressourcenschonung; K. Kristof, P. Hennicke (Ed.); Wuppertal Institut fuer Klima, Umwelt, Energie GmbH: Wuppertal, 2007, Paper 8.1, Kapitel 3.1.2, S. 13, Werkstoffauswahl, neue Werkstoffe und werkstoffgerechte Konstruktion.

Ensuring the functions of the circular economy and eco-balance effectiveness of mixed material construction methods through adhesive bonding will become increasingly important.[88]

Fig. 37
Adhesive bonding – potential as the no. 1 joining technology of the 21st century[4]

The adhesive bonding technology has the potential to become the no. 1 joining technology of the 21st century!



88 O.-D. Hennemann, A. Groß In: Kunststueck Innovation; H.-J. Warnecke et al., Ed.; Springer-Verlag: Berlin, 2003, S. 165 – 172, Kleben – Eine Fuegetechnik setzt sich durch.

2

Challenges of adhesive bonding technology in the context of Circular Economy and Ecodesign

2.1 Political framework from a global perspective

The "Agenda 2030 for Sustainable Development" [89] adopted by the United Nations General Assembly takes the form of a global treaty on the future of the world.[90] Its core element is an ambitious catalogue of 17 sustainable development goals (SDGs/see Figure 38). For the first time, these take into account all three dimensions of sustainability: social, environmental and economic aspects are indivisible and interdependent. Five core messages are preceded by the "5 Ps" as guiding principles for action: People, planet, prosperity, peace and partnership.[91] → **see Fig. 38**[92, 93]

Agenda 2030 is the first international agreement to link the principle of sustainability both to poverty reduction and to economic, environmental and social development.[94] It provides a new global framework in which countries declare their intention to eradicate poverty and to achieve sustainable development worldwide by 2030. No one should be left behind; all people worldwide should be able to live in dignity. The Agenda 2030 is intended to promote peace and to contribute to all people being able to live in freedom and an intact environment.

89 United Nations; General Assembly resolution adopted on 25 September 2015; A/RES/70/1 – Transforming our world: the Agenda 2030 for sustainable development

90 B. Bornhorst In Politik & Kultur; O. Zimmermann, T. Geißler (Ed.), ConBrio Verlagsgesellschaft mbH: Regensburg, 2018; Vol 1, S. 21, Der Weltzukunftsvertrag Kultur und Agenda 2030 – (wie) passt das zusammen?

91 A/RES/70/1

92 www.unesco.de (Access April 30, 2020)

93 Bundesministerium fuer wirtschaftliche Zusammenarbeit und Entwicklung (BMZ), Referat OEffentlichkeitsarbeit, digitale Kommunikation, Besucherdienst (Ed.); BMZ: Bonn, 2017; Der Zukunftsvertrag fuer die Welt – Die Agenda 2030 fuer nachhaltige Entwicklung

94 See citation 93

Fig. 38
The 17 goals of the "UN Sustainable Development Goals – SDGs"

The agenda is addressed to all states of the world community. They are equally called upon to commit themselves to the development goals formulated in the Agenda – there is no division into "donors" and "recipients" or into "first", "second" and "third world" in this agreement. Agenda 2030 applies to all countries of the world. Developing countries, emerging economies and industrialised countries: All must do their bit.[95]

The 17 goals of Agenda 2030 take account of the economic, social and ecological dimensions of sustainable development in the sense of a three-pillar model (see Figure 39).[96] They contain concrete objectives for the coming years and focus, among other things, on human dignity, regional and global stability, just and resilient societies, flourishing economies and a healthy environment.

95 United nations, A/RES/70/1 https://www.un.org/Depts/german/gv-70/band1/ar70001.pdf (Access April 30, 2020)

96 Final report of the der Enquete-Kommission "Schutz des Menschen und der Umwelt – Ziele und Rahmenbedingungen einer nachhaltig zukunftsvertraeglichen Entwicklung, Drucksache 13/11200; Bundesanzeiger Verlagsgesellschaft Bonner Universitaetsdruckerei: Bonn, 1998

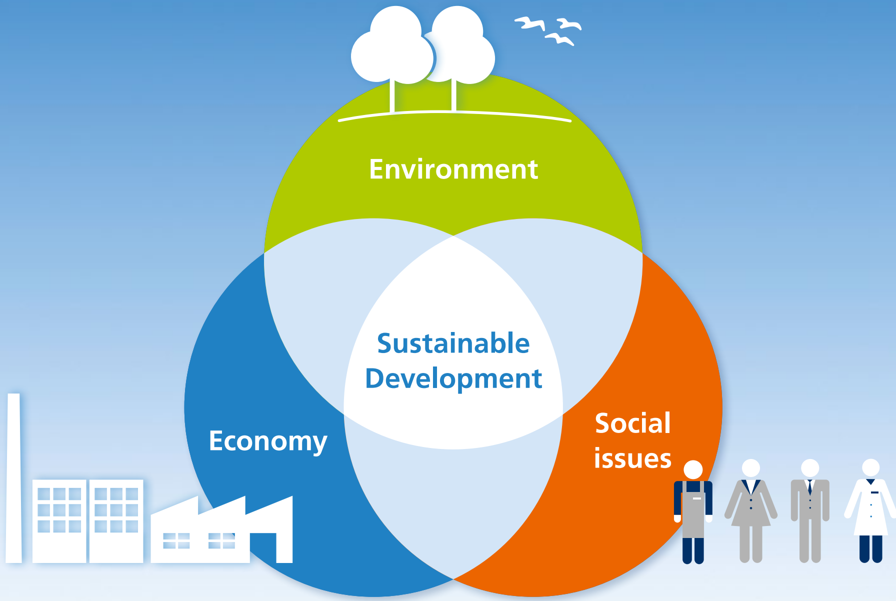


Fig. 39
Three-pillar model of sustainability [4]

With the Agenda 2030 for sustainable development, the international community of states expresses its conviction that the global challenges can only be solved together. The Agenda creates the basis for shaping global economic progress in harmony with social justice and within the ecological limits of the earth.[97]

As a successor to the Kyoto Protocol, just under three months after the adoption of Agenda 2030, 197 parties to the United Nations Framework Convention on Climate Change (UNFCCC) agreed on the goal of climate protection in the "Paris Agreement" (→ see Fig. 40).[98] The Paris Agreement provides for limiting

97 Die Bundesregierung; Agenda 2030 – Ziele fuer eine nachhaltige Entwicklung weltweit, https://www.bundesregierung.de/breg-de/themen/nachhaltigkeitspolitik/ziele-fuer-eine-nachhaltige-entwicklung-weltweit-35596 (Access April 30, 2020)

98 Bundesministerium fuer Wirtschaft und Energie; Abkommen von Paris, 2015 https://www.bmwi.de/Redaktion/DE/Artikel/Industrie/klimaschutz-abkommen-von-paris.html (Access April 30, 2020)

man-made global warming to well below 2 °C compared with pre-industrial levels.[99] The goals are:

- to significantly reduce the risks and effects of climate change
- to increase the capacity to adapt to the adverse effects of climate change
- to increase resistance to climate change
- to initiate a development that is associated with low greenhouse gas emissions and at the s ame time does not threaten food production.

It also addresses the compatibility of a growing economy with low greenhouse gas emissions and climate-resistant developments.[100, 101] → **see Fig. 38**[102]

PARIS2015
UN CLIMATE CHANGE CONFERENCE
COP21·CMP11

Fig. 40
Paris agreement on climate protection

99 United Nations Framework Convention on Climate Change – UNFCCC (Ed.); Historic Paris Agreement on Climate Change: 195 Nations Set Path to Keep Temperature Rise Well Below 2 Degrees Celsius, Article/ 13 Dec, 2015; https://unfccc.int/news/finale-cop21 (Access April 30, 2020)

100 FCCC/CP/2015/L.9/Rev.1, 12. Dezember 2015, ADOPTION OF THE PARIS AGREEMENT https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf (Access April 30, 2020)

101 Bundesministerium fuer Wirtschaft und Energie, Abkommen von Paris. https://www.bmwi.de/Redaktion/DE/Artikel/Industrie/klimaschutz-abkommen-von-paris.html (Access April 30, 2020)

102 https://de.cleanpng.com/png-du2y2l/download-png.html (Access April 30, 2020)

2.2
Political framework from a European perspective: The EU action plan for the circular economy under the Green Deal

The EU Commission will implement a "European Green Deal" according to the ideas of its new chairperson Ursula von der Leyen and others.[103] → see Fig. 41[104] This envisages that Europe will become the first climate-neutral continent by 2050. The idea is that the first European climate law should be brought into force. To date, the target is to reduce Europe's emissions by 40 % by 2030 compared to 1990 levels. According to the EU Commission, the emission reductions should be increased to 50 % and 55 % respectively. The plan will be based on social, economic and environmental impact assessments ensuring a level playing field and promote innovation, competitiveness and employment.

> **The "Green Deal" aims to make Europe the first climate-neutral continent by 2050.**

According to the plan, carbon emissions will be priced and the emissions trading system extended to maritime transport. Free emissions trading allowances allocated to airlines will be reduced over time and this approach will be extended to transport and the construction industry. The preservation of the EU's competitiveness, the creation of equal conditions of competition and the prevention of carbon leakage are to be achieved through a CO_2 border tax. The tax should fully comply with WTO rules. Selected

103 U. von der Leyen In Politische Leitlinien fuer die kuenftige Europaeische Kommission / Eine Union, die mehr erreichen will – Meine Agenda fuer Europa; 2019; S. 4–9, Ein europaeischer Gruener Deal.

104 Compare European Compost Network ECN, 2020, https://www.compost-network.info/eu-green-deal (Access April 30, 2020)

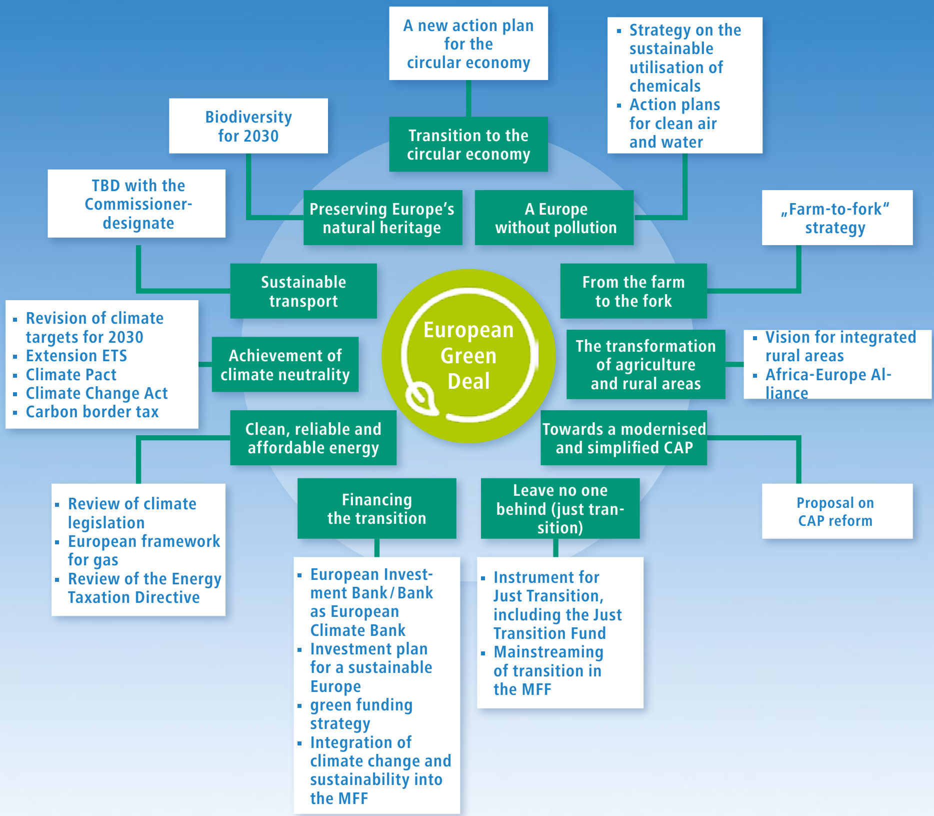


Fig. 41
Classification of the EU action plan for the circular economy to fulfil the Green Deal

areas will start and then gradually expanded. Furthermore, the adoption of an energy tax directive is to be examined.

The objectives of the Paris Agreement (see chapter 2.1) are related to the EU strategy on circular economy. In its basic considerations, this strategy for a circular economy is based on the simple fact that in the closed system "Earth", i.e. in a materially finite world, the common production processes, which generally follow the "linear economy" (→ see Fig. 42) without any real material cycle, do not shape our future for two reasons:

- In the foreseeable future, the fossil, i.e. non-renewable, resources used so far will be exhausted as sources.
- The available areas for landfilling waste and residues from industrial production will be exhausted.

The EU action plan on circular economy focuses on measures at EU level with high added value. However, the implementation of the circular economy requires long-term involvement at all levels, from Member States, regions and cities to companies and citizens. Member States are invited to participate in EU actions, integrate them and complement them with national measures.

The circular economy must be developed globally. Greater policy coherence between the EU's internal and external measures in this area will increase the globalisation of the circular economy. Global commitments by the European Union and the EU Member States, such as Agenda 2030 and the G7 Alliance on Resource Efficiency, are essential.[105] The EU Action Plan on the Circular Economy is therefore directly linked to Agenda 2030's objective 12 (SDG 12): "Sustainable consumption and production". It aims to close the cycle of the respective product life cycles: from production and consumption to waste disposal and the market for secondary raw materials. The action plan focuses primarily on the areas listed below with the aim of accelerating the transition to a circular economy along its value chain[106]:

- Electronics and information and communication technology
- Batteries and vehicles
- Packaging
- Plastics
- Textiles
- Civil engineering and buildings
- Food.

A clear focus is on building a solid foundation on which investment and innovation can flourish.

105 Bundesministerium fuer Bildung und Forschung – BMBF, https://www.bmbf.de/de/g7-allianz-fuer-ressourceneffizienz-beschlossen-1168.html (Access April 30, 2020)

106 Europaeische Kommission, Fuer laenger haltbare und nachhaltigere Produkte: Neuer EU-Aktionsplan zur Kreislaufwirtschaft, https://ec.europa.eu/germany/news/20200311-kreislaufwirtschaft_de (Access April 30, 2020)

The circular economy takes the material cycle of nature as a model and tries to use materials and energy as long and sensibly as possible through intelligent, cascading uses without waste (ideal: zero waste) and without emissions (ideal: zero emission).

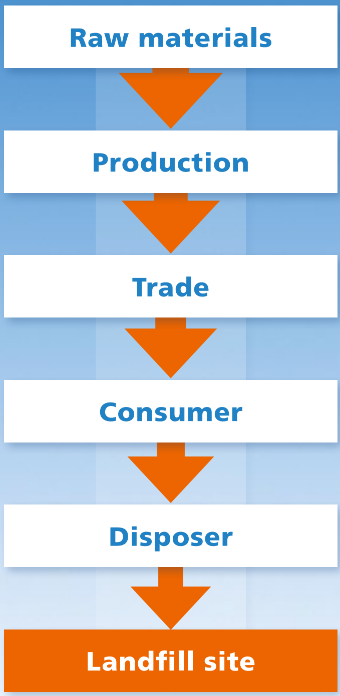
The "circular economy" represents the opposite of the "linear economy".

The circular economy therefore represents the opposite of the currently still predominant principle of industrial production of the "linear economy" (often also called "throw-away economy" → **see Fig. 42, left**). In the linear economy, a large proportion of the raw materials used are landfilled or incinerated after the respective useful life of the products. Only a small proportion is reused.[107]

In contrast to the linear economy, the circular economy (→ **see Fig. 42, right**) represents a regenerative, renewable system. It minimizes the use of resources, the production of waste and emissions and the waste of energy. This is achieved by slowing down, reducing and closing energy and material cycles. Instruments for implementation include durable construction, maintenance, refurbishment, repair (capability), reuse, reprocessing and reuse (recycling).[108]

107 F. Laepple: Abfall- und kreislaufwirtschaftlicher Transformationsprozess in Deutschland und in China: Analyse – Vergleich – Uebertragbarkeit, Dissertation, Fakultaet fuer Wirtschafts- und Sozialwissenschaften der Ruprecht-Karls-Universitaet Heidelberg, 2007

108 M. Geissdoerfer, P. Savaget, N. M. P. Bocken, E. J. Hultink, Journal of Cleaner Production 2017, Band 143, 757–768, The Circular Economy – A new sustainability paradigm?



THROW-AWAY ECONOMY — LINEAR ECONOMY

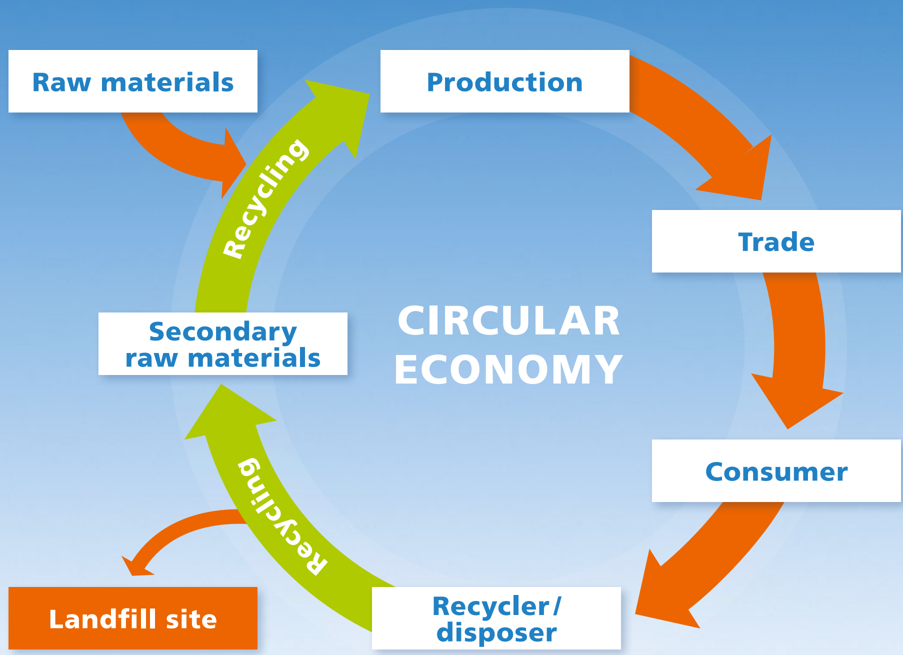


Fig. 42
Schemes [4] of the linear economy ("throw-away economy") and circular econom

2.3 Ecodesign within the framework of the circular economy strategy of the European Union

2.3.1 Definition "Ecodesign"

"Ecodesign" is an element of the EU's circular economy strategy. The meaning of the term "ecodesign" can be approached by means of a definition of the term "design": "Design … has the aim of making the world a better place for the benefit of mankind … Design shapes communication and creates identity. It is conscious action to create meaningful order and thus part of our culture"[109].

"Ecodesign" extends the above-mentioned design concept to include making the world a better place for the benefit of mankind with a view to the environment. Ecodesign involves "a systematic approach aimed at integrating ecological aspects into the product planning, development and design process as early as possible. (…) In short, ecodesign leads to products, systems, infrastructures and services that require a minimum amount of resources, energy and space to achieve the desired benefits, while minimising the use and emission of pollutants and waste – throughout the entire product life cycle"[110].

Ecodesign refers to the environmentally sound design of products in such a way that their impact on the environment is minimised. In its definition of the term ecodesign, the Federal Office for the Environment (UBA) takes this holistic approach to the design methodology. This approach calls for the reduction of environmental pollution over the entire product life cycle from planning,

109 B. Schneider: Design – eine Einfuehrung: Entwurf im sozialen, kulturellen und wirtschaftlichen Kontext, Birkhaeuser Verlag: Basel, 2009, S. 9

110 U. Tischner; E. Schmincke; F. Rubik; M. Proesler: Was ist Ecodesign?, Ein Handbuch fuer oekologische und oekonomische Gestaltung; form-praxis: Frankfurt a.M., 2000, S. 12

production and use to the disposal of the product, for whatever reason, which is no longer usable or no longer used.[111]

This means that environmental aspects must already be integrated into the development of products and the environmental impact must be assessed by the product manufacturer right from the start over the entire product life cycle including disposal ("end of life").[112]

> **Ecodesign requires that the environmental impact of a product's entire life cycle, including end-of-life, be considered at the design and product development stages.**

2.3.2 Summary of the state of European regulation relating to joining technologies in the manufacture of energy-related products – EU Ecodesign Work Programme

The Ecodesign Work Programme is part of the EU action plan on circular economy. It sets out ecodesign as a means of achieving a circular economy[113], as the German Advisory Council on the Environment also points out[114]. A number of measures will promote the creation of a more closed-loop economy in the EU, covering

111 U. Tischner; H. Moser In Was ist Ecodesign? – Praxishandbuch fuer Ecodesign inclusive Toolbox, Verlag Umweltbundesamt: Berlin, 2015

112 S. Schaltegger, C. Herzig, O. Kleiber, T. Klinke, J. Mueller In Nachhaltigkeitsmanagement in Unternehmen – Von der Idee zur Praxis: Managementansaetze zur Umsetzung von Corporate Social Responsibility und Corporate Sustainability; Bundesumweltministerium (BMU) / Referat Oeffentlichkeitsarbeit (Ed.); Volkswagen ServiceFactory: 2007, S. 103 – 104, Design for the Environment (DfE), Sustainable Design.

113 D. Jepsen, L. Spengler und L. Augsberg In Delivering resource-efficient products; C. Wachholz, S. Arditi, S. Pant (European Environmental Bureau / Ed.), 2015, S. 24 – 38., downloadable from https://mk0eeborgicuypctuf7e.kinstacdn.com/wp-content/uploads/2019/05/Delivering-resource-efficient-products.pdf (Access April 30, 2020)

114 Sachverstaendigenrat fuer Umweltfragen (Ed.); Umweltgutachten 2016 – Impulse fuer eine integrative Umweltpolitik; Hausdruck: 2016, S. 50 – 56, Kreislaufwirtschaft, downloadable from https://www.umweltrat.de/SharedDocs/Downloads/DE/01_Umweltgutachten/2016_2020/2016_Umweltgutachten_HD.pdf?__blob=publicationFile (Access April 30, 2020)

the entire life cycle of products and materials. Improving the efficiency of materials, resources and products (see chapter 2.5) in the EU is increasingly necessary and a political priority. A key role is played by product design. It influences the entire life cycle of a product and is a key factor in determining whether the product is easy (and useful!) to repair, reuse or recycle.

Ecodesign is a means to realize circular economy.

In this context, the Ecodesign Directive [115] continues to set ecodesign requirements for "energy-related products". Economic and social aspects are not ignored.[116] The Ecodesign Directive extends its scope to all products, in addition to products that use energy directly [117], to all products whose use in some form is "energy-related". As well as to direct energy-using equipment such as street lighting, TVs, vacuum cleaners, air-conditioning and refrigerators, etc., it also includes products that do not use energy themselves but which indirectly affect energy consumption during their use *. Examples include building materials and windows, low rolling resistance car tyres, shower heads and taps, insulation materials, etc.[118] The objectives of the Ecodesign Directive include

* The connection between energy-related products and the importance of adhesive bonding technology in this context is dealt with in Chapter 2.5 (basically: Chapters 2.5.1 – 2.5.2 / exemplary: Chapters 2.5.3 – 2.5.5).

115 Amtsblatt der Europaeischen Union, Richtlinie 2009/125/EG des Europaeischen Parlaments und des Rates, 21. Oktober 2009, L 285/10 – L 285/35

116 C. Thomas In: I. Haertel (Ed.): Nachhaltigkeit, Energiewende, Klimawandel, Welternaehrung; Nomos Verlagsgesellschaft: Baden-Baden, 2014; S. 168 – 193, Die OEkodesign-Richtlinie der Europaeischen Union als Konkretisierung des Nachhaltigkeitsprinzips.

117 Amtsblatt der Europaeischen Union; Richtlinie 2005/32/EG des Europaeischen Parlaments und des Rates vom 6. Juli 2005 zur Schaffung eines Rahmens fuer die Festlegung von Anforderungen an die umweltgerechte Gestaltung energiebetriebener Produkte und zur AEnderung der Richtlinie 92/42/EWG des Rates sowie der Richtlinien 96/57/EG und 2000/55/EG des Europaeischen Parlaments und des Rates; downloadable from https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2005:191:0029:0058:DE:PDF (Access April 30, 2020)

118 Bundesministerium fuer Wirtschaft und Energie (Ed.); Energieverbrauchsrelevante-Produkte-Gesetz – EVPG Gesetz ueber die umweltgerechte Gestaltung energieverbrauchsrelevanter Produkte; 25.11.2011; downloadable from https://www.bmwi.de/Redaktion/DE/Gesetze/Energie/evpg.html (Access April 30, 2020)

contributing to sustainable development and increasing resource efficiency (see chapter 2.5.1).

Even though the Ecodesign Directive does not directly mention the term “circular economy”, it provides the possibility for binding definitions of waste-related properties and of setting resource management requirements in such a way that these resources can be used further, again or sparingly after their first use.[119] The Ecodesign Directive achieves the return to the material or product cycle above all by increasing the recyclability and dismantlability[120] of products and their components and by promoting reuse. In this way, ecodesign is expected to make a much greater contribution to the circular economy in the future, for example by focusing more systematically on questions of material/resource efficiency (see Chapter 2.5.1), durability and recyclability. Ecodesign is a key driver for a functioning circular economy.[121]

The manufacture, use and disposal of products is a significant part of resource consumption.[122] The Ecodesign Directive takes a holistic view of the life cycle of a product, i.e. from planning/development to manufacture and disposal. Despite the recognition of an overall consideration of all environmental effects, it places the reduction of greenhouse gas emissions in the foreground. The primary objective is (see Chapter 2.5.1) to save energy and other resources (including raw materials and their environmental impact during manufacture/production, etc.) in the manufacture, operation (including durability, reparability) and disposal (including recyclability, reusability, environmental impact during manufacture/production of secondary

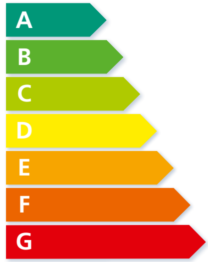


Fig. 43
Ecodesign Directive and energy labelling / “A“: low – “G“: high [4]

119 M. Alt In Oekodesign und Kreislaufwirtschaft, Nomos Verlagsgesellschaft: Baden-Baden, 2018, 1. Auflage, S. 67–72, Systematik der OEkodesign-RL.

120 See for this Chapter 2.6 and 5.3

121 A. Reichel; M. De Schoenmakere; J. Gillabel In EEA Report 2/2016: Circular Economy in Europe; European Environmental Agency (Ed.); Luxembourg Publications Office of the European Union: Luxembourg, 2016; S. 18, Eco-design. downloadable from http://www.eea.europa.eu/publications/circular-economy-in-europe (Access April 30, 2020)

122 H. Wilts In Deutschland auf dem Weg in die Kreislaufwirtschaft; Friedrich-Ebert-Stiftung (Ed.); Druck: www.bub-bonn.de, 2016, S. 13–17, Wo steht Deutschland auf dem Weg zur Kreislaufwirtschaft?. downloadable from https://library.fes.de/pdf-files/wiso/12576.pdf (Access April 30, 2020)

raw materials, etc.) of energy-related products (→ **see Fig. 43**). Environmental impacts are largely specified during the planning and design phase. [123, 124] According to the EU, this phase influences 80 % of the impact of a product.[125] The consumption of resources is also defined in this phase.[126]

> **The design phase has a decisive influence on environmental impacts and resource consumption.**

123 S. Toelle In Der Rightrahmen fuer den Erlass von OEkodesign-Anforderungen; Nomos Verlagsgesellschaft: Baden-Baden, 2016, S. 17 f

124 C. Thomas In Nachhaltigkeit, Energiewende, Klimawandel, Welternaehrung; I. Haertel (Ed.); Nomos Verlagsgesellschaft: Baden-Baden, 2014; S. 168, 169 f, Die Oekodesign-Richtlinie der Europaeischen Union als Konkretisierung des Nachhaltigkeitsprinzips.

125 7. Umweltaktionsprogramm: "Gut leben innerhalb der Belastungsgrenzen unseres Planeten", Beschluss Nr. 1386/2013/EU, ABIEU 354/171, Angang Rz. 36

126 C. Wachholz; S. Arditi; Sébastien Pant / European Environmental Bureau (Ed.), Delivering resource-efficient products – How Ecodesign can drive a circular economy in Europe; 2015; S. 24 – 38, Adressing Resource Use Through Decisions. downloadable from https://mk0eeborgicuypctuf7e.kinstacdn.com/wp-content/uploads/2019/05/Delivering-resource-efficient-products.pdf (Access April 30, 2020)

2.4 Further legislation relevant to the joining technology "adhesive bonding" within the framework of the circular economy strategy of the European Union

2.4.1 EU Plastics Strategy

For the first time, the EU Plastics Strategy [127] focuses on the material-specific life cycle in order to integrate cycle-oriented product design, use and reuse of materials and recycling into the plastics value chains. The handling of plastics in terms of a circular economy must be improved. The strategy contains quantifiable targets at EU level. One goal is that by 2030 all plastic packaging placed on the market in the EU should be reusable or recyclable.

The strategy also identifies key actions to involve a wide range of stakeholders along the value chain. It aims to ensure that 10 million tonnes of recycled plastics are processed into new products by 2025. This target will be achieved if the voluntary commitments by suppliers of recycled plastics are met as expected: The demand for recycled plastics is expected to increase to around 6.2 million tonnes per year by 2025 as a result of the industry's voluntary commitments.

The demand for recycled plastic will increase.

127 Bericht der Kommission an das Europaeische Parlament, den Rat, den Europaeischen Wirtschafts- und Sozialausschuss und den Ausschuss der Regionen ueber die Umsetzung des Aktionsplans fuer die Kreislaufwirtschaft {SWD(2019) 90 final; Kapitel 2.5 – Ein systematischer Ansatz: die EZU-Strategie fuer Kunststoffe in der Kreislaufwirtschaft, S. 7 – 9

Important milestones have already been reached with regard to improving the quality of plastics recycling. These include

- the new recycling target of 55 % by 2030 for plastic packaging,
- the obligations to collect plastics separately, and
- the improvement of extended producer responsibility systems.

Manufacturers are expected to promote recyclable design. Future improvements will result from the revision of the essential requirements for packaging planned for the end of 2020.

The strategy should ensure synergies between economic and environmental objectives. The obvious potential risks to health and the environment from microplastic pollution justify limiting the targeted addition of microplastics and gaining knowledge on measurement and labelling in case of accidental release of microplastics. In addition, a framework for the biodegradability of plastics should be developed. It is necessary to ensure that the development and use of plastic products is only promoted where this has a positive impact on the environment. Waste management systems and food safety must not be affected.

The EU Plastics Strategy promotes change beyond the borders of Europe. The EU has taken a leading role with actions, in particular in relation to disposable plastics, thus making a significant contribution to the international dynamics of plastics. In parallel, the EU is supporting developing countries in their efforts to tackle environmental pollution from plastics.

Tailor-made measures are:

- a ban on disposable plastic and oxo-degradable plastic products
- Measures to reduce the consumption of plastic food containers and drink cups and the specific marking and labelling of certain products
- the target of 30 % recycled plastic in beverage bottles by 2030 and 25 % in PET bottles by 2025
- a minimum target of 90 % for the separate collection of plastic bottles by 2029

- introduction of regulations for product design, according to which the lids must be firmly attached to beverage bottles
- extended producer responsibility schemes to cover the costs of waste disposal for products such as tobacco filters and fishing gear
- measures to reduce plastic waste from ships, e. g. by introducing a flat-rate fee for ship-generated waste
- the strengthening of the reporting obligation for lost gear and the obligation to identify and control fishing gear for recreational fisheries.

2.4.2 EU Waste Regulation

A central component of the Recycling Act and at the same time the link between ecodesign and circular economy is the five-level waste hierarchy (→ see Fig. 44) [128]. Its primary objective is to avoid waste and is committed to this. [129, 130] Waste prevention measures aim to promote a product design that makes the product in question resource-efficient, durable, repairable, reusable or updatable. If waste avoidance is not possible, the recycling of so-called municipal and packaging waste is increased considerably. The regulations will lead to a gradual phase-out of waste disposal. The use of economic instruments such as extended producer responsibility is encouraged. The new legislation strengthens the five-level "waste hierarchy". It obliges EU Member States to adopt specific measures that focus on prevention, re-use and recycling rather than landfill and incineration.[131]

128 Gesetz zur Foerderung der Kreislaufwirtschaft und Sicherung der umweltvertraeglichen Bewirtschaftung von Abfaellen (Kreislaufwirtschaftsgesetz – KrWG), § 6 / Richtlinie 2008/98/EG des Europaeischen Parlaments und des Rates vom 19. November 2008 ueber Abfaelle und zur Aufhebung bestimmter Richtlinien

129 Gesetz zur Foerderung der Kreislaufwirtschaft und Sicherung der umweltvertraeglichen Bewirtschaftung von Abfaellen (Kreislaufwirtschaftsgesetz – KrWG), § 7, Abs. 1

130 Gesetz zur Foerderung der Kreislaufwirtschaft und Sicherung der umweltvertraeglichen Bewirtschaftung von Abfaellen (Kreislaufwirtschaftsgesetz – KrWG), § 13, 24, 25

131 Press release – Europaeische Kommission, Bruessel, 22.05.2018 / IP/18/3846

This is primarily aimed at manufacturers of all kinds of goods. If waste prevention is not possible, they should endeavour to use only recyclable materials and then actually recycle them. The rest must be disposed of in an environmentally friendly way.

The five levels of the waste hierarchy in detail:

The prevention of waste has the highest priority.[132] It is achieved through measures to be taken before a substance, material or product has become waste. These measures are intended to reduce the amount of waste. Examples of this are the reuse of products or the extension of their service life. In addition, the harmful effects of generated waste on the environment and human health are to be reduced. The same applies to the content of harmful substances in materials and products.

The second stage is preparation for re-use. It describes 'any process whereby products or components other than waste are reused for the same purpose for which they were originally intended'[133]. In this context, 'any recovery operation involving the testing, cleaning or repair of products or components of products which have become waste shall be considered in such a way that they can be reused without further pre-treatment'[134].

Recycling is only in third place in the waste hierarchy. It includes all processes "by which waste materials are transformed into products, materials or substances either for the original purpose or for other purposes"[135]. It excludes energy recovery as well as

132 European Commission, Changing our patterns of production and consumption: new action plan for circular economy paves the way to a climate-neutral and competitive economy with responsible consumers, downloadable from https://ec.europa.eu/commission/presscorner/detail/de/IP_20_420 (Access April 30, 2020)

133 Gesetz zur Foerderung der Kreislaufwirtschaft und Sicherung der umweltvertraeglichen Bewirtschaftung von Abfaellen (Kreislaufwirtschaftsgesetz – KrWG), § 3, Absatz 21

134 Official Journal of the European Union L 150/109, DIRECTIVE (EU) 2018/851 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 30 May 2018 amending Directive 2008/98/EC on waste

135 Gesetz zur Foerderung der Kreislaufwirtschaft und Sicherung der umweltvertraeglichen Bewirtschaftung von Abfaellen (Kreislaufwirtschaftsgesetz – KrWG), § 3, Absatz 25

processing into materials for use as fuel or for backfilling.[136] This leaves two recycling paths (→ see Fig. 45): mechanical (material) recycling, which is carried out using physical processes, and, as a supplement, chemical (raw material) recycling based on chemical processes (see Chapter 5.1).

Even though the recycling of goods is assigned to the third level of the waste hierarchy, it plays an essential role in achieving a circular economy.[137] → see Fig. 45[138]

Chemical recycling will complement mechanical recycling in the future.

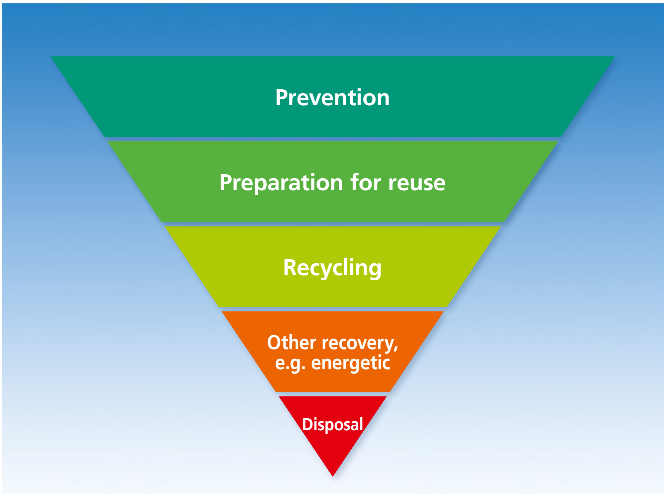


Fig. 44
Waste hierarchy of the EU[4]

136 See citation 134

137 M. Geissdoerfer, P. Savaget, N. M. P. Bocken, E. J. Hultink, Journal of Cleaner Production 2017; 143; 757–768; The Circular Economy – A new sustainability paradigm.

138 U. Tillmann; Nachhaltigkeit braucht mehr Chemie, nicht weniger, 11. Juni 2018, https://www.vci.de/themen/energie-klima-rohstoffe/klimaschutz/vci-hauptgeschaeftsfuehrer-utz-tillmann-auf-presskonferenz-eroeff-nung-achema-2018-nachhaltigkeit-braucht-mehr-chemie-nicht-weniger.jsp (Access April 30, 2020)

For the purposes of the Directive, "other recovery" (stage 4) means any operation by which waste is "put to a useful purpose within the facility or in the wider economy by replacing other materials which would otherwise have been used to fulfil a specific function, or by preparing the waste to fulfil that function"[139].
In contrast to Step 3 (recycling), "other recovery" includes, inter alia, the primary use as a fuel, the recovery of organic substances other than solvents, the recycling/reclamation of metals and other inorganic materials, the regeneration of acids and bases, the re-refining or other reuses of oil, and the application to land for agricultural purposes or for environmental improvement/disposal.[140]

Waste disposal is only at the fifth and last place in the waste hierarchy. It includes all processes[141] that do not lead to recovery. Whether the process in question has the secondary consequence that substances or energy are recovered is not important. According to the Directive, examples of disposal operations are:

- landfilling in or on the ground (e.g. landfills, etc.),
- treatment in the ground (e.g. biodegradation of liquid or sludgy waste in soil),
- specially constructed landfills such as disposal in sealed,
- separate spaces which are sealed and isolated from each other and from the environment,
- injection (e.g. pumpable waste into boreholes, salt domes or natural cavities),
- discharge into a body of water, seas/oceans including injection into the seabed,
- incineration on land and at sea, and
- permanent storage, e.g. in a mine.

139 Gesetz zur Foerderung der Kreislaufwirtschaft und Sicherung der umweltvertraeglichen Bewirtschaftung von Abfaellen (Kreislaufwirtschaftsgesetz – KrWG), § 3, Absatz 23

140 Umwelt-Bundesamt – UBA; Verwertung und Entsorgung ausgewaehlter Abfallarten, https://www.umweltbundesamt.de/daten/ressourcen-abfall/verwertung-entsorgung-ausgewaehlter-abfallarten, 18.09.2019 (Access April 30, 2020)

141 Gesetz zur Foerderung der Kreislaufwirtschaft und Sicherung der umweltvertraeglichen Bewirtschaftung von Abfaellen (Kreislaufwirtschaftsgesetz – KrWG), § 3, Absatz 26

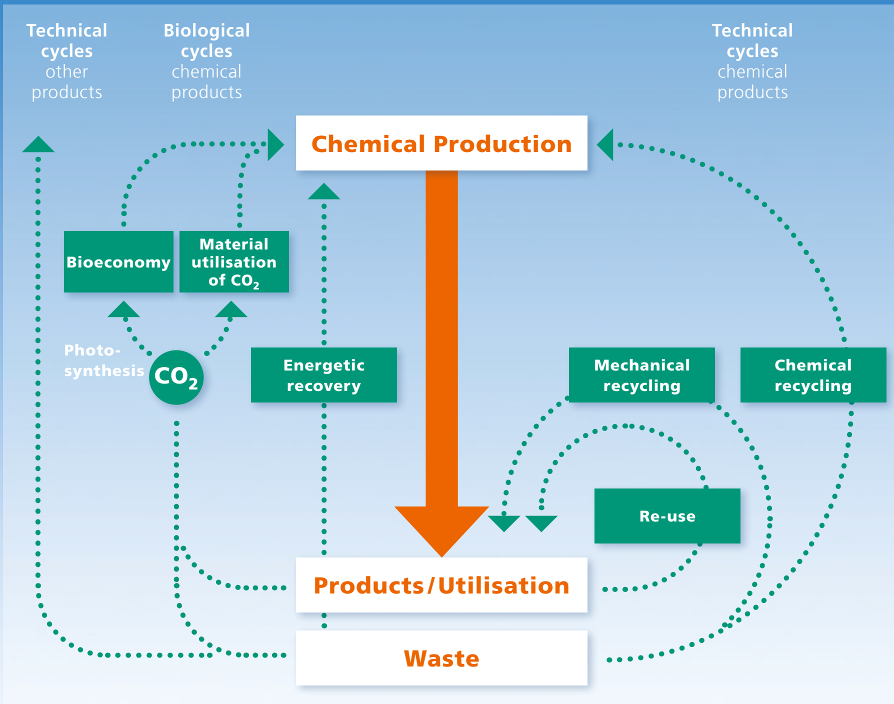


Fig. 45
Circular economy and recycling

2.4.3 EU Construction Products Regulation

Directive 89/106/EEC was replaced by the EU Construction Products Directive[142] on 9th March 2011. This defines conditions for the marketing and placing on the market of construction products by establishing harmonised rules and basic requirements. This is intended to harmonise the marketing of construction products, including the necessary conditions, to simplify their free movement and to remove barriers to trade in the EU internal market.

For the purposes of the Regulation, construction products are defined as products which are permanently incorporated in

142 Regulation (EU) No 305/2011 of the European Parliament and of the Council of 9 March 2011 laying down harmonised conditions for the marketing of the construction products and repealing Council Directive 89/106/EEC https://eur-lex.europa.eu/legal-content/DE/TXT/PDF/?uri=CELEX:02011R0305-20140616 (Access April 30, 2020)

construction works (or parts thereof) and whose performance affects the basic requirements for construction works. These basic requirements cover a very wide range: fulfilling stability, fire safety, hygiene, health, environmental protection, safety, accessibility, sound insulation, thermal insulation and energy saving, up to the sustainable use of natural resources. Consequently, the construction works must be designed and built in such a way:

- the stability during construction and use of the building is guaranteed and deformations that occur do not restrict the serviceability
- in the event of fire, the load-bearing capacity of the structure is maintained for a defined period of time
- the generation and spread of fire and smoke is limited and the inhabitants can flee or be rescued
- does not endanger the hygiene or the health and safety of workers, occupants or residents during its entire life cycle
- there are no unacceptable accident hazards during use or operation, such as slipping, falling or impact accidents, burns, electric shocks or explosion injuries
- the use of the building by people with disabilities is guaranteed by a barrier-free design
- the perceived sound is maintained at a level which does not endanger health and at which satisfactory night-time rest, leisure and working conditions are ensured
- the installations and equipment for heating, cooling, lighting and ventilation consume as little energy as possible during use and during assembly and dismantling
- the durability of the structure in question is guaranteed and the environmentally compatible construction and raw materials can be reused or recycled after demolition.

Structures must meet these basic requirements under normal maintenance conditions for an economically reasonable period. Depending on the category, this may be several decades to a century. This period does not only include the actual life of the structure. In the sense of a more holistic view of the entire life cycle, it also includes the dismantling or recycling of the building materials. In this context, the EU Construction Products Directive [142] therefore attaches particular importance to the sustainable use of natural resources. It focuses on the recyclability of the building, its building materials and demolition parts as well as the use of environmentally friendly raw materials. The assessment of the performance of construction products is to be carried out on the basis of harmonised technical specifications, which include tests, calculation methods and other instruments, which in turn are graded according to requirements.

In order to fulfil the essential requirements, Product Contact Points should provide information on the provisions free of charge. In addition, the EU regulation aims to ensure that the criteria for CE marking are met for construction products. To avoid repeating tests already carried out, manufacturers are allowed to use test results obtained by third parties. Manufacturers of construction products are obliged to draw up a declaration of performance and to provide their products with a CE marking. In addition, manufacturers must ensure, by appropriate procedures, that their declared performance is also guaranteed in series production. Before making a product available on the market distributors shall verify that the product bears the CE marking and is accompanied by other documents such as instructions and safety information. Other points in the Regulation deal with financing and monitoring.

Adhesives can also be building products.

In principle, adhesives are also a building product. The applicability of an adhesive in the building industry must be verifiably tested by comparing the basic requirements for building products mentioned above with the performance spectrum of the adhesive to be used. The following focal points in particular must be be taken into account:

- In the event of fire, the load-bearing capacity under thermal stress during the load-bearing period defined in the specification for the respective structure must be verified.
- Adhesives that are classified as hazardous substances must be processed by qualified personnel qualified in adhesive bonding technology, such that during processing any risk to the employee and, consequently, any negative effects on his or her health are excluded.
- The adhesive bonding technology can join not only identical but also different materials in a long-term stability while maintaining the material properties indispensable for the product (see chapter 1.9). For recycling or reusability of the adhesively bonded building materials, the separability of the different materials must be taken into account as early as the development and construction phase.

2.4.4 EU Bio-economic Strategy

The bio-economy is the sum of sectors and services that use biological resources such as plants, animals and micro-organisms. The bio-economy represents an essential component of a post-fossil economy and describes the paradigm shift from a petroleum-based market economy to a market economy in which fossil resources are substituted by various renewable raw materials. Against the background that biological resources and ecosystems are finite, innovative ways of supplying food, goods and energy become necessary. For this reason, products and processes within an economy should be produced more sustainably.[143] The bio-economy strategy is linked to various goals of Agenda 2030 (SDGs, see Chapter 2.1)[144]:

143 Nationale Politikstrategie Biooekonomie – Nachwachsende Ressourcen und biotechnologische Verfahren als Basis fuer Ernaehrung, Industrie und Energie, BMEL/Referat 531, Berlin, 03/2014

144 Biooekonomierat: "Bioeconomy Policies (Part 2): Synopsis of national Strategies around the World, 2015

- nutrition security
- climate protection
- sustainable consumption and production conditions
- preservation of the most important natural resources such as drinking water, fertile soil, clean air and
- biodiversity.

The bio-economy is a component of the post-fossil economy.

The bio-economy thus touches on various policy areas such as industrial and energy policy, agricultural, food, forestry and fisheries policy, climate and environmental policy and research and development policy. The sustainable, cycle-oriented bio-economy strategy of the EU focuses on three key aspects:

- the development of new technologies and processes for the bio-economy
- market development and competitiveness in the bio-economy sectors
- close cooperation between policy makers and stakeholders.

The main objectives [145] are

- the expansion and strengthening of the bio-based sectors
- the rapid Europe-wide introduction of the bio-economy and
- the protection of ecosystems and research into the ecological bio-economy limits.

Existing biological resources can be used more sustainably than before by the bio-economy with the help of innovative processes and their fields of application can be expanded on the basis of new scientific findings.[146]

145 Bundesministerium fuer Bildung und Forschung (BMBF) Referat Biooekonomie / Bundesministerium fuer Ernaehrung und Landwirtschaft (BMEL) In Biooekonomie in Deutschland – Chancen fuer eine biobasierte und nachhaltige Zukunft, 3. Auflage, 2014

146 K. Pillen; L. Wessjohann In Jahresbericht 2018–2019 Leibniz-WissenschaftsCampus Halle – Pflanzenbasierte Biooekonomie, sedruck KG: Leipzig, 2019; S. 3–5, Pflanzenbasierte Biooekonomie – Wegbereiter der gruenen Transformation.

2.4.5 Future measures

In addition to the measures mentioned in chapters 2.4.1 – 2.4.4, the new action [147, 148] plan will focus on sectors in which most resources are used and in which there is a circular economy potential. This concerns the sectors mentioned in Chapter 2.2, such as electronics and information and communication technology. The focus here is on extending the service life of products and optimising the collection and treatment of waste. For batteries and vehicles, a new legal framework is being created to improve sustainability and strengthen the recycling management potential of batteries. New mandatory requirements will be introduced for packaging that is approved for the EU market. These include the reduction of packaging, in particular excessive packaging. For the use of plastics, new, likewise binding requirements are being created for the recycled content. These focus in particular on microplastics and on bio-based and biodegradable plastics. For textiles, a new EU strategy aims to strengthen competitiveness and innovation in the sector and strengthen the EU market for the reuse of textiles. In the area of construction and buildings, there will be a comprehensive strategy for a sustainable built environment to take account of the principle of recycling in buildings. In the area of food, there will be a new legislative initiative aimed at the reuse of disposable packaging, crockery and cutlery through reusable product in catering services.

147 Europaeische Kommission, Fuer laenger haltbare und nachhaltigere Produkte; https://ec.europa.eu/germany/news/20200311-kreislaufwirtschaft_de (Access April 30, 2020)

148 Europaeische Kommission, AEnderung unserer Produktions- und Verbrauchsmuster; https://ec.europa.eu/commission/presscorner/detail/de/ip_20_420 (Access April 2020)

2.5 Energy consumption and material efficiency / resource efficiency

2.5.1 Energy consumption and material efficiency / resource efficiency: the meaning of the terms

Energy consumption:

The term "energy consumption" is used colloquially in this context. Physically, energy in a closed system cannot be "consumed" but only "converted". The reason why the term "energy consumption" is still used is that energy is used for production processes, product applications / uses and disposal processes, i.e. it is consumed in the common sense. In colloquial language, this means the use of processed forms of energy (natural gas / oil, coal, fuels such as petrol or diesel, electricity or district heating) to carry out the above-mentioned activities.[149, 150]

Material efficiency:

In the simplest case, the term "material efficiency" first describes the ratio of material input (materials used) to product output (products obtained). For the purposes of this study, it is necessary that the term "material efficiency" also includes disposal and recycling processes. Therefore, "material efficiency "* is described by the ratio of "quantitative bonus product output" to "quantitative material input".[151] Not every product of a production process is desirable and not every material input to a production process is used in the final product. The following should therefore be taken into account:

* The definition of "product output" and "material input" only applies to the standard case of production. The now more popular term "material efficiency" is synonymous with the technically more precise term "material productivity".

149 E. Rebhan (Ed.) In Energiehandbuch – Gewinnung, Wandlung und Nutzung von Energie; Springer Verlag: Berlin 2002

150 VDI-Gesellschaft Energie und Umwelt (Ed.); VDI-Fachbereich Betriebliches Sicherheitsmanagement In VDI-Richtlinie 4661 Energiekenngroeßen: Definitionen – Begriffe – Methodik, 2014

151 H. Dyckhoff, Betriebliche Produktion – Theoretische Grundlagen einer umweltorientierten Produktionswirtschaft, 2. Auflage, Springer: Berlin, 1994

** Onus (lat.): "burden"

- The "quantitative bonus product output" corresponds to
  → the goods on the product output side (= manufactured products) minus the Onus** of the material input side such as unwanted materials, waste, etc.
- The quantitative material input corresponds to
  → the goods on the material input side such as raw materials and (scarce) resources plus the Onus of the product output side such as waste and emissions.

The material efficiency increases,

- the greater the value of the bonus goods product output (= manufactured products) minus the Onus material input (unwanted materials, waste) and
- the smaller the value of the expenditure on goods becomes material input (raw materials and (scarce) resources) plus the Onus product output (= waste, emissions)

Both are achieved by keeping the expenditure of goods material input and the onera material input and product output as low as possible. The lower the goods input and the lower the onera of the input and output sides, the higher the material efficiency.

> **A high material efficiency is given with a high value for the bonus goods product out and low values for the expenditure goods material input and the onera of the input and output side.**

In the consideration of material efficiency presented so far, energy consumption is not taken into account. The product life cycle phases "production", "use" and "disposal" are connected with energy expenditure. Therefore, through the three product phases mentioned above, material efficiency also influences the respective energy requirements.

Resource efficiency:
Consequently, "material efficiency" is closely related to the concept of "resource efficiency". In addition to material, resource efficiency takes into account the factor energy in product manufacture, product use and product disposal. Resource efficiency

serves the overarching goal of decoupling economic performance from resource use and promotes the EU's "Green Deal" initiative for climate neutrality by 2050.

Resource efficiency also takes the energy factor into account.

In general, the term "resource efficiency" describes the ratio of a certain benefit, e. g. of a product, to the use of natural resources (input) required for it. [152, 153] The following applies: the lower the required input of natural resources and the higher the benefit of the product, the greater the resource efficiency.

The term "material efficiency" can be transformed into the term "resource efficiency".

The Ecodesign Directive distinguishes between material efficiency, resource efficiency and energy efficiency.[154], [155] However, the Directive speaks of energy, materials and other resources. So the Ecodesign Directive classifies both "material" and "energy" as "resource".[156] This makes it possible to transfer the term "material efficiency" to the term "resource efficiency". In addition to the above-mentioned term "material efficiency", emissions and energy

152 J. Kosmol, J. Kanthak, F. Herrmann, M. Golde, C. Alsleben, G. Penn-Bressel, G. N. Schmitz, U. Gromke In Glossar zum Ressourcenschutz; Umweltbundesamt Dessau: Umweltbundesamt, 2012, S. 23

153 VDI-Fachbereich Umwelttechnik, VDI-Richtlinie 4800 Blatt 1 "Ressourceneffizienz – Methodische Grundlagen – Prinzipien und Strategien", VDI-Gesellschaft Energie und Umwelt (Ed.), 2016

154 Bundesministerium fuer Umwelt, Naturschutz und nukleare Sicherheit, OEkodesign-Richtlinie Art. 11 Erwaegungsgrund Nr. 10 und 13

155 F. Reimer, S. Toelle, ZUR 2013, 589 – 598, Ressourceneffizienz als Problembegriff.

156 M. Alt In Oekodesign und Kreislaufwirtschaft, Nomos Verlagsgesellschaft: Baden-Baden 2018, 1. Auflage, Kapitel 2, S. 53, Rightgrundlagen fuer produktbezogene Abfallvermeidung und das recyclinggerechte Design.

consumption are integrated and the individual efficiency components are defined as follows:

- Bonus goods product output
  → manufactured products incl. additive functions

- Onus resource input***
  → unwanted materials, waste and emissions

- Recycling share****
  → cycle-relevant material content less energy expenditure for recovery

- Expenditure of goods material input
  → raw materials to be used or (scarce) resources

- Onus product output
  → Waste, emissions, energy consumption in process cycle section

*** The above-mentioned "Onus material input" is now substituted by the "Onus resource input", which includes additional emissions.

**** A new addition is the material and/or energetic "recycling share", which is the difference between the "cycle-relevant material portion" and the "energy input for recovery". "Cycle-relevant" means that the recovery of the material portion alone is not sufficient and would be an end in itself. The recycled material must be of high quality in terms of its value giving properties (material recycling as opposed to downcycling) and must actually be reintegrated into the cycle on the basis of this requirement. The energy expenditure required for recovery must justify this recycling.

This consideration of resource efficiency is then used for the product cycle sections as a first rough qualitative estimate:

- production (Beginning of Life – BOL)
- use (Middle of Life – MOL)
- disposal (End of Life – EOL).

The summary of the individual product cycle sections can serve as a fundamental basis for decision-making on the further development of an adhesively bonded product.

- In order to achieve the goal of high resource efficiency, the highest possible bonus goods product output should be aimed for.
- The share of onus resource input should be kept as small as possible.
- The lower the energy input of the recycling share in relation to the cycle-effective material recovery, the higher the recycling share. This has a positive effect on the bonus goods product output.

- The “onus product output” has been expanded to include the energy consumption per product cycle stage. The goal for the highest possible resource efficiency is to keep both the expenditure of goods material input and the onus product output as low as possible.

The consideration of the resource efficiency of all product life cycle stages in summary can serve as a qualitative basis for decision-making in the development of adhesively bonded products.

The total resource efficiency of a product life cycle is calculated by summing up the resource efficiency per product cycle stage. With regard to products, the efficiency of the product output along the life cycle can be qualitatively examined and the “eco-return” of a product development can be estimated. Quantified statements undoubtedly require a sustainability assessment, for example on the basis of a life cycle analysis (LCA, see Chapter 2.5.2 and Chapter 3).

Lightweight construction and miniaturisation are examples of resource efficiency that should be taken into account in product design. Savings of raw materials during production, reduction of consumables and energy in the production and use phase as well as the possibility of separating and returning materials to their technical or natural cycles are further measures to optimize resource efficiency. They lead to optimized product efficiency, which results from a holistic view of resource efficiency values over the entire product life cycle.

Examples to illustrate

As a striking example for the estimation of resource efficiency, the baking of bread can be considered. The “bonus goods product output” is bread. The “Expenditure Goods Material Input” are the ingredients necessary for baking. The “Onus resource input” includes packaging materials etc. and all the emissions that are produced as well as the energy required for baking bread. To the “Onus product output” belong baking residues, waste that cannot be reused, the emissions produced during bread baking and the agents necessary for

cleaning the baking equipment. Unsold bread, for example, can be added to the compost as "recycling share".
A high degree of resource efficiency is achieved if the "bonus goods product output" can be maximised compared to the other factors. Bread baking is resource efficient if many loaves of bread are baked with little energy, little packaging material, low contamination, high sales probability and with a high recycling share of the surplus.

The comparison of two functionally identical vehicles is somewhat more in-depth, as here the product cycle phase "utilisation" can have a decisive influence on resource efficiency. Provided, for example, that the use of aluminum instead of steel reduces the vehicle weight to such an extent that the amount of energy saved during vehicle use is greater over the entire life cycle than the energy required for material production and recycling compared to steel, the aluminum-based vehicle is more resource-efficient. The "Onus resource input" would be the decisive factor in this case due to the total amount of (utilisation) energy saved.

A circular economy is to be seen in connection with resource conservation, i. e. the economical use of natural resources with the aim of preserving their quantity and function [157, 158], as well as with resource efficiency [159, 160]. The difference between "conservation" and "efficiency" is the following:

- Conservation of resources [161] is the reduction of the use of resources. This is the goal of the circular economy.[162]
- With the available resources, resource efficiency achieves the best product output (bonus goods product output) over the entire product life cycle or the same product output with

157 J. Kosmol, J. Kanthak, F. Herrmann, M. Golde, C. Alsleben, G. Penn-Bressel, G. N. Schmitz, U. Gromke In Glossar zum Ressourcenschutz; Umweltbundesamt Dessau: Umweltbundesamt, 2012, S. 25

158 https://wirtschaftslexikon.gabler.de/definition/ressourcenschonung-45471

159 Umweltbundesamt, Glossar zum Ressourcenschutz, Januar 2012, S. 23

160 E. Guenther, Ressourcenschonung – Ausfuehrliche Definition. https://wirtschaftslexikon.gabler.de/definition/effizienz-35160 (Access April 30, 2020)

161 E. Gawel In Ressourceneffizienz – Leitbild fuer das Umweltrecht / Gießener Abhandlungen zum Umweltrecht; F. Reimer (Ed.); Nomos Verlagsgesellschaft: Baden-Baden, 2016; Band 26, S. 31 – 62, Ressourceneffizienz als oekonomisches Konzept.

162 Gesetz zur Foerderung der Kreislaufwirtschaft und Sicherung der umweltvertraeglichen Bewirtschaftung von Abfaellen (Kreislaufwirtschaftsgesetz – KrWG), § 1

lower input (onus material input, expenditure goods material input, onus product output). In this context, resource efficiency is a means of conserving resources.

For the European Commission in its Roadmap to a resource-efficient Europe, resource efficiency is based on the optimisation of the input/output ratio, sustainable use of resources and minimisation of environmental impacts.

Resource efficiency is a relative, not an absolute value. Increasing resource efficiency does not necessarily lead to an absolute reduction in resource use (protection of resources or conservation of resources). If, due to an aboveaverage increase in the number of products, the economic output increases more than the efficiency increases in the use of resources, the result – in absolute terms – is an increased consumption of resources. Nevertheless, increasing resource efficiency is in principle a step in the right direction.

2.5.2 Energy consumption and material efficiency/resource efficiency: the importance of a holistic approach (Life Cycle Assessment – LCA)

"Energy consumption", "material efficiency" and "resource efficiency" must always be related to the entire product life cycle. A separate focus on individual elements of the circular economy or ecodesign distorts the basis for decision-making. Without considering the entire life cycle of the product, it does not make sense to separately optimize the "goods input material input", the "onus product output/material input" or the "recycling share"/recyclability.

The entire product life cycle must be considered.

An example from rail vehicle construction illustrates the need for a holistic approach: Compared to other vehicles, rail has a good ecological balance sheet and for this reason, the German government is focusing strongly on it as an attractive means of transport. Considerable amounts of material and energy are required to manufacture the 750-tonne railcar of an ICE of the Deutsche Bahn. However, when considering the resource efficiency of the ICE, it must be borne in mind that it has an annual mileage of approx. 500,000 km, is designed for a service life of 40 years (= 20,000,000 km) and has space for approx. 700 passengers. Here, a holistic view is taken of the construction and maintenance of the vehicles, the operation of the infrastructure, the construction and maintenance of the infrastructure and the operation of the trains. The latter, expressed in g CO_2 equivalents per passenger kilometre (pkm) or 1,000 km (tkm) across all three transport sectors (local, long-distance and freight transport), accounts for by far the largest share, while construction and maintenance of the vehicles is by far the smallest.[163] Therefore, an increased input of energy and material in the product manufacturing phase has only a small direct impact on the "onus resource input" and thus on resource efficiency. The product life cycle phase "utilisation" determines the resource efficiency and thus makes the rail vehicle superior. This superiority does not stem from the product manufacturing phase but from the product use phase[164]. Increased expenditure on energy and materials in the manufacturing phase of an ICE can even reduce the CO_2 equivalent if used as a lever for increasing efficiency in the product life cycle phase of operation. For example, measures to increase customer acceptance of the ICE (comfort, WLAN during the journey, etc.) can increase the train's capacity utilisation and thus indirectly further increase the overall resource efficiency of the ICE and further reduce the CO_2 equivalent through early, well-planned use of resources.

As well as in the railway example, but in each individual product output case, the entire environmental impact during development, production, utilisation and disposal, as well as all associated upstream and downstream processes, must be considered at an early stage. Upstream and downstream processes include, for

163 vergleiche M. Schmied; M. Mottschall In Treibhausgasemissionen durch die Schieneninfrastruktur und Schienenfahrzeuge in Deutschland (FKZ 363 01 044); Oeko-Institut: Freiburg, 2013; S. 118 / Bild 33

164 M. Mottschall, T. Bergmann In Treibhausgas-Emissionen durch Infrastruktur und Fahrzeuge des Straßen-, Schienenverkehrs sowie der Binnenschifffahrt in Deutschland / Arbeitspaket 4 des Projektes "Weiterentwicklung des Analyseinstrumentes Renewability; Umwelt-Bundesamt / Fachgebiet 3.1 Umwelt und Verkehr (Ed.), 3. korrigierte Fassung Januar 2015, S. 2

example, the production and modification of raw materials and supplies, the extraction of raw materials from the environment (e. g. ores, crude oil and their processing), the emissions into the environment (e. g. waste, CO_2 and other emissions) and the energy consumption in the development, production, utilisation and disposal of the products.

One instrument of holistic product life cycle consideration is the life cycle assessment.

One instrument for a holistic view of a product is the preparation of a life cycle assessment (LCA/DIN EN ISO 14040 – 14044).[165, 166, 167, 168, 169] The basic idea behind LCA is not to consider (and evaluate) the environmental impact of a product separately and linearly in individual phases, but to consider the entire life cycle, in this sense the sum of the product life phases.[170] It aims to identify improvement opportunities for products in a quantified manner in order to reduce the environmental impact and use of natural resources throughout the product life cycle. It is currently the most comprehensive method of assessing envi-

165 DIN EN ISO 14040:2019-11, Environmental management – Life cycle assessment – Principles and framework, Beuth-Verlag: Berlin, 2009

166 DIN EN ISO 14041:1998-11, Environmental management – Life cycle assessment – Goal and scope definition and life cycle inventory analysis, Beuth-Verlag: Berlin, 1998

167 DIN EN ISO 14042:2000-07, Environmental management – Life cycle assessment – Life cycle impact assessment, Beuth-Verlag: Berlin, 2000

168 DIN EN ISO 14043:2000-07, Environmental management – Life cycle assessment – Life cycle interpretation, Beuth-Verlag: Berlin, 2000

169 DIN EN ISO 14044:2018-05, Environmental management – Life cycle assessment – Requirements and guidelines, Beuth-Verlag: Berlin, 2018

170 Communication from the Commission to the Council and the European Parliament, Integrated Product Policy – Building on Environmental Life-Cycle Thinking, COM 2003 302 final, p. 5

ronmental impacts and can enable the environmental impact of a product to be assessed at every stage of the product life cycle.[171]

A life cycle assessment comprises four steps:

1. Defining the objective and scope of the study
The first step is to decide which product outputs are to be balanced and compared. The product outputs to be examined must have the same benefit. Using so-called "functional units", the function and benefit of products to be compared are quantified as far as possible.

2. Life Cycle Inventory
In the Life Cycle Inventory, different types of environmental impacts arising during the life cycle of a product output are quantified as far as possible, parameter by parameter, and subsumed over the entire product life cycle.

3. Impact Assessment
In the third step, the size and significance of potential environmental impacts of a product output during the product life cycle are assessed, whereby the individual results are assigned to the following impact categories:

- greenhouse effect
- direct damage to health
- direct damage to ecosystems
- resource demands
- stratospheric ozone depletion
- photochemical oxidant formation
- aquatic eutrophication
- terrestrial eutrophication
- acidification
- use of natural areas

Each impact category is characterised by one or more "impact indicators" (e. g. greenhouse effect: impact indicator CO_2-equiv-

171 J. Sanfélix, F. Mathieux, C. da la Rúia, M.-A. Wolf, K. Chomkhamsri, The International Journal of Life Cycle Assessment 2013, Vol 11, Issue 1, 273–277, The enhanced LCA Resources Directory: a tool aimed at improving Life Cycle Thinking practices.

alent). The results of the Life Cycle Inventory from Step 2 are converted into these impact indicators.

The evaluation of the importance of the individual impact categories is of central importance in Impact Assessment. To arrive at comparative statements, the different environmental impacts must be compared and ranked according to their importance.

4. Evaluation

In the final evaluation of the LCA, the results of the Life Cycle Inventory from Step 2 and Impact Assessment from Step 3 are combined. Conclusions and recommendations for policymakers, producers and other stakeholders are derived from these results.

In connection with the waste hierarchy (see Chapter 2.4.2), the Law of Life Cycle Management [172, 173] requires that the waste hierarchy measure should be chosen that best ensures the protection of man and the environment. To this end, the entire life cycle of the waste must be taken into account, in particular the expected emissions, the degree of conservation of (natural) resources, the energy to be used or obtained, the accumulation of pollutants in products, recovery waste or products obtained from them.[174] Following the idea of life cycle analysis, it is possible to break through the waste hierarchy (see chapter 2.4.2). It is more important to consider the overall environmental impact than to stick to the waste hierarchy.[175] If such a life cycle analysis proves to be advantageous for the overall balance, the deviation from the waste hierarchy is justified.

172 Gesetz zur Foerderung der Kreislaufwirtschaft und Sicherung der umweltvertraeglichen Bewirtschaftung von Abfaellen (Kreislaufwirtschaftsgesetz – KrWG), § 6 Abs. 2 S. 2

173 Gesetz zur Foerderung der Kreislaufwirtschaft und Sicherung der umweltvertraeglichen Bewirtschaftung von Abfaellen (Kreislaufwirtschaftsgesetz – KrWG), Art. 4, Abs. 2 AbfallRRL

174 Gesetz zur Foerderung der Kreislaufwirtschaft und Sicherung der umweltvertraeglichen Bewirtschaftung von Abfaellen (Kreislaufwirtschaftsgesetz – KrWG), § 6 Abs. 2 S. 3

175 F. Petersen, J. Doumet, G. Stoehr, NVwZ 2012, S. 521 – 530, Das neue Kreislaufwirtschaftsgesetz.

Deviating from the waste hierarchy can therefore be ecologically beneficial for the life cycle assessment of a product. In these cases, a deviation in one step of the product life cycle can result in significant LCA benefits in another step. This realisation of these advantages justifies the departure from the waste hierarchy, which can therefore be profitable for the LCA of a product. In these cases, a departure from the waste hierarchy in one step of the product life cycle allows significant LCA benefits in another step. This realisation of these advantages justifies the deviation from the waste hierarchy.

Deviating from the waste hierarchy can be ecologically profitable for the overall ecobalance of a product.

According to Art. 2 No. 23 of the Ecodesign Directive, which formulates the objective of environmentally sound product design along the entire life cycle of a product, the life-cycle approach builds a bridge to ecodesign [176], since according to Art. 2 No. 13 of the Ecodesign Directive, the life cycle is defined as the totality of the interlinked product existence phases. The Ecodesign Directive therefore represents an instrument of an Integrated Product Policy [177] in connection with energy-related products. It provides for environmental impacts to be taken into account throughout the entire product life cycle. The Integrated Product Policy therefore analyses the entire product life cycle, focusing on product design on the one hand, but also on consumer acceptance, adoption and utilisation of more environmentally friendly products.[178]

176 M. Alt In Oekodesign und Kreislaufwirtschaft, Nomos Verlagsgesellschaft: Baden-Baden 2018, 1. Auflage, Kapitel 4, S. 157, Konzeptionelles Zusammenwirken zwischen Oekodesign und Kreislaufwirtschaft.

177 ABIEU L 285/10 vom 31.10.2009, zuletzt geaendert durch RL 22012/27/EU, ABIEU L 315/1 vom 14.11.2012

178 Commission of the European Communities, Green Paper on Integrated Product Policy, COM 2001 68 (final) http://edz.bib.uni-mannheim.de/www-edz/pdf/kom/gruenbuch/kom-2001-0068-de.pdf (Access April 30, 2020)

The essential prerequisites for a life cycle analysis are the quality, correctness, timeliness and availability of the data on which such an analysis is based. A meaningful life cycle analysis can only be carried out if these factors are given.

2.5.3 Energy consumption and material efficiency/resource efficiency: the importance of materials

As described in chapter 1.1, new materials are necessary to meet increasing product requirement profiles. The required product properties are largely determined by their properties. With regard to "energy consumption" and "material/resource efficiency", the additional task of materials is to increase "resource efficiency" by increasing the bonus goods product output (see Chapter 2.5.1).

> **The product properties are largely determined by the material properties.**

A well-known example for the fulfilment of increasing product requirement profiles is the RegioShuttle. The RegioShuttle is a diesel-powered regional rail vehicle from Stadler Rail AG (→ **see Fig. 46, right**). The rail vehicle was launched on the market in the mid-1990s and is still in use today. Even then, it was able to meet the increased requirements for reducing energy consumption during operation. The key was the reduction of the vehicle weight by means of a material compound of glass fibre reinforced plastic (GFRP) and steel.

The "body" is a welded steel framework construction (→ **see Fig. 46, left**[179]).

The framework is a lightweight steel construction. It was able to meet the increased weight reduction requirements by using a new (lightweight) material compared to steel at the time: glass fiber reinforced plastic (GFRP). GFRP has the characteristic characteristic of fiber composite plastics (FVC) of a relatively low weight with

179 Stadler Rail AG, Bussnang, Switzerland

Fig. 46
RegioShuttle: the body (left) is a welded steel framework construction / lightweight construction with GFRP in the exterior (right)

comparatively high stiffness. In order to achieve the desired weight reduction requirement it was necessary to combine two different materials in a durable way (> 30 years!).

Figure 46 right shows the rail vehicle. In the exterior (roof segments, outer skin panels, front mask), with the exception of the buffers and the running gear (both made of steel) as well as the windows (glass), it consists solely of the lightweight construction material GFRP. With the material combination of steel/GRP and glass/GRP, it was possible to build the "RegioShuttle" 25 % lighter than comparable conventional vehicles of the same size [180].

In comparison with a welded rail vehicle of comparable size made entirely of steel at that time, the resource efficiency can be rated positively:

→ In the product cycle phase "production", the onera resource input and product output as well as the expenditure goods material input in the case of GFRP material are lower compared to steel and thus contribute to the bonus goods output. This has a positive effect on resource efficiency.
→ Due to the lightweight construction and the associated lower energy/fuel consumption, the bonus goods output in the product cycle phase "utilisation" exceeds the efficiency component expenditure goods material input and the onera resource input and product output. The latter are also reduced: The longevity of these products of more than 25 years has been proven. The vehicles' reparability is already

180 Information Stadler Rail AG, Bussnang, Switzerland

specified in their design; furthermore, to maintain their longevity, they are subject to regular, specified maintenance.

→ In the product cycle phase "disposal" the Onus product output (here: waste) increases due to the poorer recyclability of GFRP components compared to steel. At the same time, the proportion of recycling is reduced, which also contributes to a reduction in the "bonus goods output". However, this disadvantage is exceeded by the significantly reduced share of "Onus resources input" (here: energy consumption in use) with the RegioShuttle. Due to the significantly lower energy requirement in the long product cycle phase "use", this step determines resource efficiency compared to steel rail vehicles. This would be significantly heavier and the energy/fuel consumption higher, so that the resource efficiency is inferior. In addition, in the case of a rail vehicle made purely of steel, the steel cannot be recycled in an energy-free and emission-free manner, which reduces the benefit of recycling for resource efficiency.

2.5.4 Energy consumption and material efficiency / resource efficiency: the importance of joining technology

Material properties largely determine the product characteristics. Due to the increasing complexity of requirements, products usually consist of several materials. The joining technology is critical for the fulfilment of the product properties:

A material only becomes a usable material when
- a joining technology is available that is suitable for the material properties,
- this is then also used professionally and
- meets the requirements of the Product Safety Act [181].

The joining technology must not impair the material properties of the product, but it must also enable optimum exploitation of

181 Produktsicherheitsgesetz (ProdSG) – Gesetz ueber die Bereitstellung von Produkten auf dem Markt, letzte Neufassung vom 08.11.2011 (BGBl., S. 2178, ber. 2012, S. 131

material properties, including from an ecological viewpoint (see Chapters 1.2 and 2.5.1).

> **The task of joining technology is to enable the optimum use of material properties.**

The weight reduction of the RegioShuttle achieved a significant reduction in energy/fuel consumption for a service life of more than 30 years and thus an equally significant reduction in pollutant emissions (reduction of onus product output). The weight reduction resulted in an optimisation of the bonus goods product output and thus of resource efficiency compared to the old steel product. The weight reduction was only possible through the connection of the welded steel framework to the new GRP material. From an engineering point of view, the final optimisation for the resource efficiency of the RegioShuttle was achieved through the right choice of joining technology.

2.5.5 Energy consumption and material efficiency/resource efficiency: the importance of the joining technology "adhesive bonding"

The adhesive bonding technology enables the material properties to be maintained and thus their optimum utilisation to meet the requirement profile (see chapters 1.2 and 2.5.4). The RegioShuttle is a successful example of the use of adhesive bonding. In order to take advantage of the then new material GFRP, it was necessary to create a strong, material property-preserving and long-term stability joining between GFRP and steel. The adhesive bonding technology could be successfully used for this purpose:

- roof segments/with the metallic "timber framework car body
  → outer skin panels construction" adhesively bonded
- windows
  → adhesively bonded
- front mask
  → onto the structure (→ **see Fig. 47**) to fix it in place mechanically pushed on and then adhesively bonded.

Fig. 47
RegioShuttle – Use of GFRP in outdoor areas: Lightweight construction through adhesive bonding technology[94]

When joining by adhesive bonding, GFRP material properties (high stiffness with comparatively low weight) are retained! The adhesive bonding process has made it possible to make optimum use of the GFRP lightweight construction properties and to build the "RegioShuttle" 25 % lighter than comparable conventional steel vehicles.

Consequently, adhesive bonding technology makes decisive contributions that would not be possible with other joining technologies: The ecological footprint of the system is significantly smaller over the life of the vehicle. In addition, the driving comfort of the RegioShuttle is demonstrably better compared to purely welded constructions, and the manufacturing and operating costs are also lower. Even the comfort factor has an indirect positive effect on resource efficiency. The higher ride culture increases customer acceptance of the train and thus the number of passengers. This has a positive effect on the CO_2 equivalent per passenger kilometre.

In the meantime, adhesive bonding technology has established itself in almost all application areas of rail vehicle construction.

2.6 Non-detachable joining technologies – a possible misunderstanding, also for the circular economy

2.6.1 "Detachable" – "non-detachable": Basically

Product safety requirements [182] must be met in every product development. This must be observed for all requirements listed in Chapters 2.1 – 2.5 and applies to materials as well as joining technologies (see Chapter 1.2). Materials and joining technology are equally necessary for the functional and safe design of products.

> **Materials and joining technologies are equally necessary for functional and safety-compatible product design.**

Joining is the technical process (see Chapter 1.4) for producing strong, durable and safe joints between two or more materials.[183] A technical distinction is made between "detachable" [184] and "non-detachable" or "conditionally detachable" joining [185]. There

182 Gesetz ueber die Bereitstellung von Produkten auf dem Markt Produktsicherheitsgesetz – ProdSG ("Produktsicherheitsgesetz vom 8. November 2011 (BGBl. I S. 2178, 2179; 2012 I S. 131), das durch Artikel 435 der Verordnung vom 31. August 2015 (BGBl. I S. 1474) geaendert worden ist" / 08.11.2011. https://www.gesetze-im-internet.de/prodsg_2011/ProdSG.pdf (Access April 30, 2020)

183 see quotation 21

184 M. Blassing, Loesbare Verbindungen. https://www.metallbau-stahlbau.net/loesbare-verbindung (Access April 30, 2020)

185 M. Blassing, Loesbare Verbindungen. https://www.metallbau-stahlbau.net/unloesbare-verbindung (Access April 30, 2020)

is a possible misunderstanding between the common and technical terms “detachable” and “non-detachable”:

Detachable:
Detachable” joints must “hold” in use in the same way as “non-detachable” or “conditionally detachable” joints, i. e. they must be durable, strong and safe. They must not become loose in an uncontrolled manner, but should be able to be detached after use. A technically “detachable” joint allows the parts to be separated without damaging the parts to be joined or the joining element. The same joining elements can be reused to restore the joining.

Non-detachable:
The term “non-detachable” is commonly understood to mean that the joint is permanent and cannot be detached during use. Thus, according to common understanding, the joint cannot be released even after use!

However, a “non-detachable” joint can be separated in the technical sense. As a rule, however, only if the joined parts or joining elements and/or the joined components are destroyed or damaged in the process. Thus, the same joined part or joining element cannot be used to restore the joint. However, it is possible to “detach” a “non-detachable” joint for recycling purposes by damaging a joined part.

> **“Detachable” and “non-detachable” – a possible misunderstanding, not only for the circular economy.**

An example of a “detachable” joining is the classic bolt connection. The bolt is the joining element here (→ see Fig. 48[186]). The bolt – and this applies exclusively to standard bolts! – is tightened to make the joining and undone again to loosen it. The same (standard) bolt can then be tightened again. However, damage to the component is inherent in screwing and the material properties of the component are always impaired: Drilling the bolt hole

186 Adobe Stock 175519195

damages the component even before joining (→ see Fig. 7) and impairs the material properties of the component.

Typical examples of "conditional- or non-detachable" joints are welded, riveted or adhesively bonded joints (→ see Fig. 10). Both welded and riveted joints may be separated. However, during separation, the joined parts are damaged or the rivet is destroyed. In both cases, new joining aids (e.g. new weld metal or new rivets) must always be used when reconnecting the parts to be joined.

> **Even "non-detachable" joints can be separated after use – also for recycling purposes.**

2.6.2 "Detachable" – "non-detachable": adhesive bonding technology

For adhesive bonding technology, it is worth taking a more differentiated look at "non-detachability":

The adhesives used today in industry and trade are joining aids based on polymers. Compared to metals, polymers are subject to strong thermal influences. An adhesive therefore reacts more strongly to temperature than metallic joining aids such as weld metal or rivets. If the temperature falls below a certain level, the polymer becomes brittle: its strength increases and its deformability decreases. If a certain temperature is exceeded, the opposite happens: the polymer softens, i.e. its ability to deform increases, the strength of the adhesive polymer decreases simultaneously and thus the strength of the joint.

> **"Non-detachable" does not mean that the joined parts cannot be separated.**

The embrittlement of the adhesive, as well as its softening, can be used for the intentional, controlled separation of an adhesively bonded joint. This applies to high-strength industrial adhesively bonded joints with the main function of long-term stability in the

Fig. 48
Standard bolts – example

transmission of mechanical loads [187] as well as to everyday life: even the price label can be easily removed from the gift without leaving any residue. A moderate temperature application, e. g. with a hair dryer, is helpful here. If an adhesively bonded joining is reconnected, new adhesive must usually be used. A reuse of the adhesive is possible in some circumstances e. g. with hot-melt adhesives and pressure-sensitive adhesive tapes.

> **“Non-detachable” adhesively bonded joints can be separated again.**

187 H. Mason (Ed.), Composite World 2020, National Composite Centre leads dismantlable joints research, https://www.compositesworld.com/news/national-composites-centre-leads-dismantlable-joints-research (Access April 30, 2020)

2.7 First conclusions

When assessing the life cycle assessment of a product, a holistic view over the entire product life cycle is required. Picking out individual aspects leads to wrong conclusions; product safety must also always be considered. The safe "intended and foreseeable use of a product"[188] must not be subsidiary to technological development wishes or ecological objectives. In principle, this applies to all products, equally to the materials to be used and all joining technologies, including adhesive bonding.

> **Regardless of which joining technology is used, product safety must not be subordinated to ecological objectives.**

For product safety, the adhesively bonded joints must be effective and resistant to the operating environment for the duration of the planned product life. Using various examples (see Chapter 1.7), it has been shown that sufficient resistance of an adhesively bonded joint is advantageous for the LCA: aircraft fly and rail vehicles run for 30 years or more. They are regularly maintained. It has been state of the art for over 20 years for car windows to be adhesively bonded and thus become a torsion-stiffening and weight-reducing construction element. The reparability of a damaged car window is state of the art and is beyond question.

> **Adhesively bonded joints – professionally executed – are repairable.**

188 Gesetz ueber die Bereitstellung von Produkten auf dem Markt Produktsicherheitsgesetz – ProdSG ("Produktsicherheitsgesetz vom 8. November 2011 (BGBl. I S. 2178, 2179; 2012 I S. 131), das durch Artikel 435 der Verordnung vom 31. August 2015 (BGBl. I S. 1474) geaendert worden ist" / 08.11.2011. https://www.gesetze-im-internet.de/prodsg_2011/ProdSG.pdf § 3, Absatz 1 / Punkt 2 (Access April 2020)

Adhesively bonded joints can be separated because of the thermal properties described in chapter 2.6. Recyclable, separated materials are generally available for reuse. Although "adhesive bonding" is technically classified as a "non-detachable" joining technology, this joining technology is not a fundamental obstacle to recycling.

> **The adhesive bonding technology does not represent a fundamental obstacle to recycling when used correctly.**

Recycled secondary raw materials reduce the EU's dependence on primary raw materials. The use of secondary raw materials fulfils the basic idea of a circular economy and can lead to decreasing raw material costs in the EU. A major obstacle to their use and a major reason why they have so far only been used to a limited extent in the EU is their quality [189] and the EU-wide differences in quality. EU quality standards are necessary here.[190] Not every product must be "repairable"; regardless of the joining technology, replacement instead of repair may even be desirable for ecological (not economic!) reasons.

With regard to "energy consumption" and "material efficiency/resource efficiency", the bonus goods product output must be optimised. At the same time, the expenditure of goods material input and the Onera product output and resource input must be minimized. The recycling share (see chapter 2.5.1) has to be taken into account. Adhesive bonding technology can make a decisive contribution to both if used properly.

189 E. Gandert, Plastverarbeiter online, 2020, In der Rezyklat-Qualitaet liegt ein Schluessel. https://www.plastverarbeiter.de/72782/in-der-rezyklat-qualitaet-liegt-ein-schluessel/ (Access April 30, 2020)

190 Europaeisches Parlament, Plastikmuell und Recycling in der EU: Zahlen und Fakten. https://www.europarl.europa.eu/news/de/headlines/society/20181212STO21610/plastikmull-und-recycling-in-der-eu-zahlen-und-fakten (Access April 30, 2020)

> **The adhesive bonding technology – applied professionally – increases the material/resource efficiency.**

Life Cycle Assessments (LCAs, see above) enable the environmental impact of a product to be assessed holistically over all product life cycle phases. The indispensable prerequisite for a life cycle assessment is the quality, timeliness and availability of the underlying data.

> **In principle, adhesively bonded products can be used in the circular economy.**

3

Adhesive Bonding Technology: Circular Economy/Ecodesign and Life Cycle Assessment – LCA

3.1 Introduction

Adhesive bonding technology allows the sustainable production of safe and at the same time sustainable products.[191] They also enable sustainable repair solutions. These statements have been substantiated in the previous two chapters with numerous examples.

Such a qualitative statement applies to the use of inorganic adhesives in the construction industry as well as to the use of organic or organosilicon adhesives in products that are extensively used in the construction of means of transport. As a rule, you want something from a house for a lifetime.[192] A rail vehicle runs for 40 years.[193] The service life of a car is increasing.[194] The average age of cars registered in Germany on 01.01.2019 was now 9.5 years, with 40 % of cars older than 10 years.[195] However, adhesives are also used in the electronics[196] and packaging industry[197], whose

191 J. Gegner, Mat.-wiss. u. Werkstofftech. 2008, 39, 33 – 44, Klebtechnik – multifunktionales Fuegen fuer den Werkstoffeinsatz im 21. Jahrhundert.

192 Deutsches Architektenforum; Lebensdauer von Gebaeuden, 2012. https://www.deutsches-architekturforum.de/thread/10421-lebensdauer-von-gebaeuden/ (Access April 2020)

193 M. Schmied; M. Mottschall In Treibhausgasemissionen durch die Schieneninfrastruktur und Schienenfahrzeuge in Deutschland (FKZ 363 01 244 / final report); Oeko-Institut e.V., Freiburg, 2013; Kapitel 5, S. 94 / Tabelle 57, Daten und Ergebnisse fuer die Herstellung und Wartung der Fahrzeuge und Waggons.

194 B. Engel; PS Welt. 2018, Werden Autos bald fuer die Ewigkeit gebaut? https://www.welt.de/motor/article181378662/Werden-Autos-bald-fuer-die-Ewigkeit-gebaut.html (Access April 30, 2020)

195 Kraftfahrt-Bundesamt – KBA; https://www.kba.de/DE/Statistik/Fahrzeuge/Bestand/Fahrzeugalter/fahrzeugalter_node.html (Access April 30, 2020)

196 Industrieverband Klebstoffe e.V., Kleben in der Elektronik. https://www.klebstoffe.com/die-welt-des-klebens/anwendungsgebiete/elektroindustrie.html (Access April 30, 2020)

197 Industrieverband Klebstoffe e.V., Papier & Verpackung https://www.klebstoffe.com/die-welt-des-klebens/anwendungsgebiete/papier-verpackung.html (Access April 30, 2020)

products [198, 199] are nowadays designed for a much shorter service life. For them, repair solutions seem to be of less importance than in the two aforementioned domains of construction and transport.

With regard to adhesive bonding technology applications, this chapter classifies and considers an established and standardised procedure for evaluating the effects of a product on the environment in the context of sustainability – the Life Cycle Assessment (LCA).

198 D. Stoller; Die Nutzungsdauer von Elektrogeraeten sinkt und sinkt und…; INGENIEUR.de, 2016. https://www.ingenieur.de/technik/fachbereiche/elektronik/die-nutzungsdauer-elektrogeraeten-sinkt-sinkt/ (Access April 30, 2020)

199 N. Seyring; A. Kaeding-Koppers In Recyclingfaehige und nachhaltige Verpackungen; E. Sasse; M. Goeßl, Ed; IHK fuer Muenchen und Oberbayern: Muenchen, 2019; Kapitel 20, S. 9, Serviceverpackungen

3.2 Life Cycle Assessment/LCA – significance for sustainable developments

The 17 SDGs (see Chapter 2.1/Figure 38) for sustainable development shape the current expansion of sustainability management and, above all, the "measurement and control of operational sustainability performance".[200] The goal of SDG No.12 "Ensuring sustainable consumption and production patterns" is of particular relevance to companies: Sub-target 12.4 "to achieve by 2020 an environmentally sound management of chemicals and all wastes throughout their life cycle in accordance with agreed international frameworks and to substantially reduce their release into air, water and soil to minimise their adverse impacts on human health and the environment" is to be implemented before the end of this year[201]. A. Baumast[202] quotes T. Dyllick as saying that corporate sustainability is evolving: "Business as usual", previously driven by economic factors and shareholder value and seen from within the company, is being developed at an advanced stage into "Corporate Sustainability 3.0" after three central development steps. This also includes ecological and social concerns (→ see Fig. 49). These concerns extend the value added by creating a benefit for society. They align the corporate perspective from the outside inwards. An additional driving force is currently the increasing regulation of areas that have been temporarily covered by voluntary commitments. In particular, small and medium-sized enterprises (SMEs)

200 A. v. Ahsen In Betriebliche Nachhaltigkeitsleistung messen und steuern – Grundlagen und Praxisbeispiele; Verlag Eugen Ulmer: Stuttgart, 2019; S. 31–41, Einfuehrung in die Nachhaltigkeitsmessung in Unternehmen.

201 Downloadable from https://www.eda.admin.ch/agenda2030/de/home/agenda-2030/die-17-ziele-fuer-eine-nachhaltige-entwicklung/ziel-12-fuer-nachhaltige-konsum-und-produktionsmuster-sorgen.html (Access April 30, 2020.

202 A. Baumast In Betriebliche Nachhaltigkeitsleistung messen und steuern – Grundlagen und Praxisbeispiele; Verlag Eugen Ulmer, Stuttgart: 2019; S. 18–30, Geschichte und aktuelle Herausforderungen des betrieblichen Nachhaltigkeitsmanagements.

along the supply chain will also have to meet their reporting obligations by disclosing non-financial indicators. Following the guiding principle "You can't manage what you can't measure"[203], it is essential for companies to record their sustainability performance in order to determine their current status.

As already explained in Chapter 2.5.2, the Life Cycle Assessment (LCA)[204] developed since the 1970s is currently the most comprehensive method for companies to assess the environmental impact of their products at each stage of their life cycle.[205] It allows ideas to be evaluated as early as the product development phase and to identify potential improvements that help to reduce negative environmental impacts throughout the entire product life cycle.

> **A life cycle assessment allows the early evaluation of product ideas.**

Broad, comprehensive analyses that take account of the entire life cycle make a significant contribution to sustainable development, as outlined in Chapters 2.1–2.4. In addition to local, regional, national and global interwoven ecological and economic components, social components also make an essential contribution to sustainability. They form the framework for new technologies worldwide. Ultimately, sustainability is a key driver and the goal of cross-generational and responsible product development. In implementation and practice, the approaches presented[206] strive for an individual balance for each product between the wishes

203 Peter Drucker, 1909–2005

204 A. Inaba, N. Itsubo, The International Journal of Life Cycle Assessment 2018, 23, S. 2271–2275; Development of Global Scale LCIA Method – Preface.

205 European Commission; European Platform on Life Cycle Assessment. https://eplca.jrc.ec.europa.eu/ (Access April 30, 2020)

206 See chapter 2.1–2.4

and demands of different target groups, markets and players.[207]
→ see Fig. 49[208]

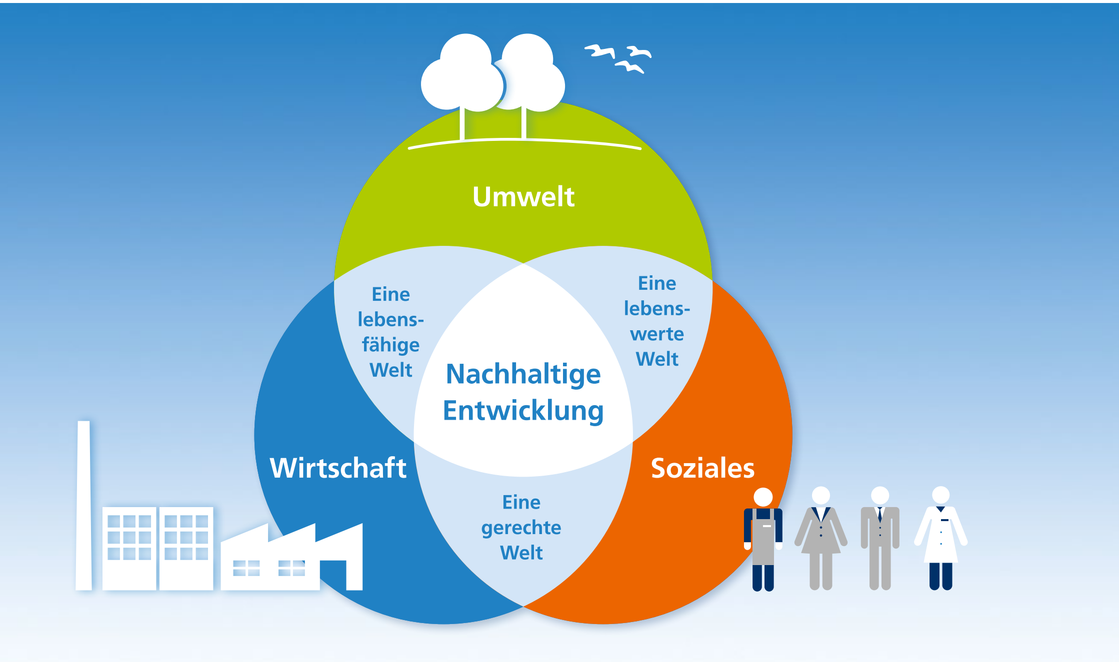


Abb. 49
Dimensionen der Nachhaltigkeit: Umwelt – Wirtschaft – Soziales

The development of adhesively bonded products is therefore also subject to general conditions. For the iterative procedure necessary for this, increasingly networked methods, virtual tools and constantly growing databases are available. These provide the yardsticks for determining the ecological, economic or social effects of a development planned in one direction or another.

207 W. Kloepffer; I. Renner; in: Environmental Management Accounting for Cleaner Production; S. Schaltegger et al. Ed.; Springer Science + Business Media B. V., 2008; Chapter 5 Life-Cycle Based Sustainability Assessment of Products

208 A. Kraemer; The Sustainable People GmbH: Hamburg. https://thesustainablepeople.com/das-drei-saeulen-modell-der-nachhaltigkeit/ (Access April 30, 2020)

In addition to accounting approaches, such as the preparation of life cycle assessments for companies or operational areas, life cycle-based methods are also used to evaluate individual products. Methods and procedures with different focuses are available for a comprehensive examination (see Figure 50) of all the sustainability facets of life cycle management within the framework of defined, for example regional or global system boundaries.[209] Swarr et al.[210] propose a summary approach to sustainability assessment based on the following three methods:

- LCC – Life Cycle Costing (also known as Life Cycle Cost Assessment – LCCA) is a cost management method that can be carried out from either the producer or product user perspective. It follows evolving rules of conduct210 and can be carried out according to various procedures (e. g. DIN EN 60300-3-3: "Application guideline life cycle costs"[211]), taking into account the product use and disposal phase as well as hidden costs.

- LCA (Life Cycle Assessment) follows the specifications of DIN EN ISO 14040[165–169] and is considered in more detail in the following subchapters.

209 A. S. Matharu, K. Lokesh In Green Chemistry Series No. 60, Green Chemistry for Surface Coatings, Inks and Adhesives: Sustainable Applications; R. Hoefer, A. S. Matharu, Z. Zhang, Hrsg.; The Royal Society of Chemistry: London, 2019; S. 1 – 17, Green Chemistry Principles and Global Drivers for Sustainability – An Introduction.

210 simplified: Lebenszyklus-Nachhaltigkeitsbewertung = LCA + LCC + SLCA; folllowing: T. E. Swarr, D. Hunkeler, W. Kloepffer, H.-L. Pesonen, A. Ciroth, A. C. Brent, R. Pagan, International Journal Life Cycle Assess 2011 , 16, S. 389–391, Environmental life-cycle costing: a code of practice"; DOI 10.1007/s11367-011-0287-5.

211 Standards series DIN EN 60300, Dependability management, Beuth-Verlag, Berlin, 2010 – 2014

- S-LCA – Social or Societal Life Cycle Assessment (S-LCA)[212] covers social, societal and socio-economic aspects (namely impacts in terms of human rights, working conditions, health and safety, cultural heritage, governance or socio-economic after-effects). It follows the specifications of DIN EN ISO 14040[165–169] and complements the ecological life cycle analysis (LCA) and life cycle costing (LCC).

One example is a study[213] published by the University of California, Berkeley, in 2012, in which LCA and LCCA were used for an automotive application. The joining technologies investigated were adhesive bonding, resistance spot welding and riveting for overlapping aluminium sheets. The study was carried out using a multi-attribute analysis to achieve the performance requirements and assessed the environmental impact and costs based on energy consumption and material throughput. A multi-criteria Pareto optimisation[214] with the aim of forsaking the economic target values at the expense of the ecological ones showed that the comparative evaluation of the joining techniques depends on the achievable stressability of the manufactured components. The achievable load-bearing capacity was determined using a material fatigue approach. For this purpose, the joints were subjected to 2 million load cycles. In the comparison, the riveting and adhesive bonding technology solutions proved to be more cost-effective, the spot welding and adhesive bonding technology solutions proved to be more environmentally friendly. With equal weighting of economic and ecological aspects, the adhesive bonding technology and spot-welding technology solutions were equal first.

212 Downloadabele from https://www.lifecycleinitiative.org/starting-life-cycle-thinking/life-cycle-approaches/social-lca/, especially Guidelines for Social Life Cycle Assessment of Products; downloadable from https://www.lifecycleinitiative.org/wp-content/uploads/2012/12/2009 – Guidelines for sLCA – EN.pdf (Access April 30, 2020)

213 J. M. Chien, K. C. McKinstry, C. Baek, A. Horvath, D. Dornfeld In Proceedings of the 19th CIRP Conference on Life Cycle Engineering; D. Dornfeld, B. Linke, Hrsg.; Leveraging Technology for a Sustainable World; Springer: Berlin, Heidelberg, 2012, S. 287–292, Multi-objective Analysis on Joining Technologies. https://doi.org/10.1007/978-3-642-29069-5_49

214 J. Weimann In Wirtschaftspolitik – Allokation und kollektive Entscheidung; Springer (4. Auflage): Berlin, 2006; Kapitel 1.2, S. 17, Die Grundposition

Fig. 50
Concepts and digital tools in life cycle management

For a life cycle based approach according to DIN EN ISO 14040 [165–169] neither the digital tools are prescribed nor is the methodical procedure defined. At a higher level of detail, this can be illustrated by several aspects. The data quality that is achieved with a naturally iterative LCA procedure can be further improved with increasing effort. This is the case, for example, when a screening LCA and a simplified LCA are followed by a complete LCA/life cycle analysis with a refined definition of objectives.[215]

As Finkbeiner et al.[216] point out, DIN EN ISO 14040 – 44 [165–169] specifies the iterative process as the basis for the preparation of a life cycle assessment study. The impetus to carry out a life cycle assessment (LCA) can result from regulatory or company-specific compliance requirements or, as in the 21st century, be policy-driven and geared towards sustainability.[217]

A LCA method should be feasible, accurate, comprehensible, meaningful and robust.

In general, each life cycle assessment (LCA) method is measured against several criteria. It should be feasible, accurate, comprehensible, stimulatingly meaningful and robust.218 In accordance with the fundamental question of defining the objectives and the scope of the LCA, two methodologically different approaches can currently be considered: [217, 218]

- the attributional LCA (ALCA) and
- the life cycle assessment (LCA) or life cycle analysis (CLCA) that considers the consequences.

The ALCA assesses the share of the global environmental Onera that is to be allocated to a product. The ALCA is char-

215 M. Stevanovic, K. Allacker, S. Vermeulen, Sustainability 2019, 11, S. 856 Development of an Approach to Assess the Life Cycle Environmental Impacts and Costs of General Hospitals through the Analysis of a Belgian Case. doi:10.3390/su11030856 .

216 M. Finkbeiner, V. Bach, A. Lehmann; "Environmental Footprint: Der Umwelt-Fußabdruck von Produkten und Dienstleistungen"; Im Auftrag des Umweltbundesamtes verfasster Abschlussbericht; ISSN 1862-4804; Dessau-Roßlau, 2018.

217 M. C. McManus, C M. Taylor, Biomass and Bioenergy 2015, 82, S. 13–26, The changing nature of life cycle assessment"; http://dx.doi.org/10.1016/j.biombioe.2015.04.024

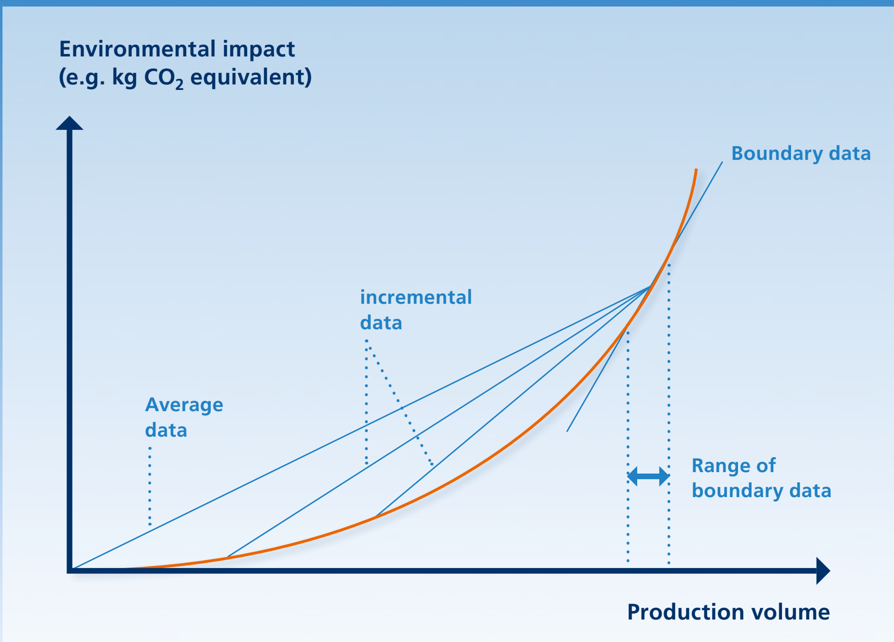
218 T. Ekvall In Sustainability Assessment at the 21st Century; M. J. Bastante-Ceca, Hrsg; IntechOpen: London, 2020; Attributional and Consequential Life Cycle Assessment; DOI: 10.5772/intechopen.78105.

acterized by comparatively narrow boundaries of the system under consideration and allows direct quantification of the impacts. The CLCA evaluates how the global environmental Onera is influenced by the manufacture and utilisation of a product. The CLCA is characterized by very broad boundaries of the system under consideration and allows projections into the future.

The two approaches differ not least in the type of data to be included and consequently to be collected or queried. While ALCA mainly uses average data in accordance with the boundaries of the production system, CLCA takes into account incremental and also marginal data (→ see Fig. 51).

For a further development of the LCA (life cycle analysis/LCA) there are currently still some tasks to be performed: [217]

Fig. 51
Display of average data, incremental data and marginal data [218]



- The integration of ALCA and CLCA experts must be increased in forums.
- The development of effective and objective digital tools should be promoted with representatives of end users.
- Transparent mechanisms are to be developed to express the (measurement) uncertainty and comparability of LCA studies.
- Data collection or investigation should fill data gaps.
- LCA methodological feedback mechanisms are to be researched and validated.

The prerequisite for a life cycle assessment are the underlying data.

In terms of a meiningful life cycle assessment (LCA), the quality, accuracy, timeliness and availability of the underlying data are an indispensable prerequisite for such a quantitative approach (see Chapter 2.5.2). For this purpose, the following data-related aspects with regard to the digital transformation in industrial production experience a high dynamic:

- With regard to data quality, the Shonan Guidance Principles for LCA databases and their data have been developed by the United Nations Environment Programme.[219]
- A representative and manageable number of social indicators must be quantitatively related to the functional unit of a product system.[207]
- The management of research data follows principles of implementing sustainable development, according to which the life

219 Global Guidance Principles for Life Cycle Assessment Databases, A basis for greener processes and products (G. Sonnemann, B. Vigon; Ed.) United Nations Environment Programme, 2011.

cycle of a product is shaped by research results and scientific findings.[220, 221]

The data on which a life cycle assessment is based should be FAIR.

The European Commission's guidelines for Horizon 2020[222], the European Union's framework programme for research and innovation, are a good example. According to these guidelines, materials research data FAIR[223]: findable, accessible, interoperable and reusable are designed. The realisation of FAIR data within the technical ecosystem is based on

- data standards
- metadata standards
- common vocabularies and
- ontologies*.

* An ontology represents a structured network of information with logical relations. It is a formally ordered and mostly linguistically defined representation that defines how general as well as specific knowledge is organised in a digitalized and formalized way and exchanged between application programs (for example "apps") and real applications. To this end, the ontology contains rules for both liability conclusions and ensuring

220 S. Deng, X. Hu In KMIR 2014 – Knowledge Maps and Information Retrieval, Proceedings of the First Workshop on Knowledge Maps and Information Retrieval (P. Mutschke, P. Mayr, A. Scharnhorst; Ed.) co-located with International Conference on Digital Libraries 2014 – ACM/IEEE Joint Conference on Digital Libraries (JCDL 2014) and International Conference on Theory and Practice of Digital Libraries (TPDL 2014) (DL 2014), London, 2014, Creating a Knowledge Map for the Research Lifecycle.

221 DIN EN ISO 14067:2019-02, Greenhouse gases – Carbon footprint of products – Requirements and guidelines for quantification, Beuth-Verlag: Berlin, 2019

222 H2020 Programme – Guidelines on FAIR Data Management in Horizon 2020 EUROPEAN COMMISSION, Directorate-General for Research & Innovation, Version 3.0, 26. Juli 2016.

223 "Turning FAIR into reality Final Report and Action Plan from the European Commission Expert Group on FAIR Data"; European Commission Expert Group on FAIR Data; 2018 Directorate-General for Research and Innovation; European Commission, 2018.

their binding nature.[224] This view is based on the statements of the European Materials Modelling Council (EMMC) with regard to the interdisciplinary ontology European Materials Modelling Ontology (EMMO), which was built as an ontology for application from the field of scientific application and which integrates physical concepts such as elementary particles, wave-particle dualism, the finiteness of space and time spans.

They help to prevent misunderstandings in the exchange of data between information seekers and information providers and allow a holistic view of products. The very numerous types of product-related data can be guessed at according to the sketch in Figure 52.

FAIR data avoid misunderstandings during data exchange and allow holistic product considerations.

This data finds its way into the basic elements of Product Lifecycle Management (PLM)[225] and allows the description of processes, methods and aspects of Information and Communication Technology (ICT), as outlined in Figure 53. The three product life cycle phases are connected with each other.

- Beginning of Life (BOL), which includes planning, design and manufacturing,
- Middle of Life (MOL), which includes distribution, utilisation and care (such as repair, maintenance and overhaul); and
- End of Life (EOL), which in the sense of reverse logistics means a return to the company with the aim of dismantling, recycling, reprocessing or disposal[225]

The time dimension of these sections is represented in the graphs by an "axis" rotating in a circle. This representation finally leads to a three-sided pyramid, whose base edges and corners each form a triad "carrying" the product.

224 With further references downloadable from https://emmc.info/emmo-info/ (Access April 30, 2020)

225 J. Stark, Product Lifecyle Management – 21st Century Paradigm for Product Realisation, Sringer-Verlag: London, 2011, DOI 10.1007/978-0-85729-546-0

Approaches based on an ontology can in future accompany sustainable, adhesively bonded products.

Chapter 5.6 uses a tripod model to illustrate how ontology-based approaches can accompany sustainable adhesively bonded products in the future. → see Fig. 52[226] and → Fig. 53[227]

The required information flow in PLM is clearly shown in Figure 54.

Since materials, machines and people are involved, the material-related, process-related and information-related levels are found side by side in PLM. Their arrangement in relation to one another, the relevant terms and the relationships between them and the exchange process are shown in Figure 55 by arrows and are recorded in the ontological representation of the product life cycle.

In Product Life Cycle Management, the levels material, process and knowledge interact.

The circle including holistic aspects closes with regard to the statements of the European Materials Modelling Council (EMMC)[228] and the interdisciplinary ontology European Materials Modelling Ontology (EMMO) developed under its leadership.

Ontologies form the bridge from information to data and knowledge.

226 J. N. Otte, D. Kiritsis M. M. Ali, R. Yang, B. Zhang, R. Rudnicki, R. Rai, B. Smith, Applied Ontology,2019, 14/2, S. 179–197, An ontological approach to representing the product life cycle.

227 S. Terzi, A. Bouras, D. Dutta, M. Garetti; Int. J. Product Lifecycle Management 2020, 4/4, S. 360–389, Product lifecycle management – From its history to its new role.

228 With further references downloadable from https://emmc.info/emmo-info/; (Access April 30, 2020)

Fig. 52
Types of product-related data (BOL: Beginning of Life / MOL: Middle of Life / EOL: End of Life)
The abbreviations not used in the text mean: Product Data Management (PDM), Computer Aided "method" (Cax), Manufacturing Process Management (MPM), (CPD), Project Portfolio Management (PPM), Computer Aided Design (CAD), Electronic Design Automation (EDA), Computer Aided Engineering (CAE), Computer Aided Manufacturing (CAM), (AEC), Computer Aided Quality Control (CAQ), Maintenance, Repair and Operations (MRO).

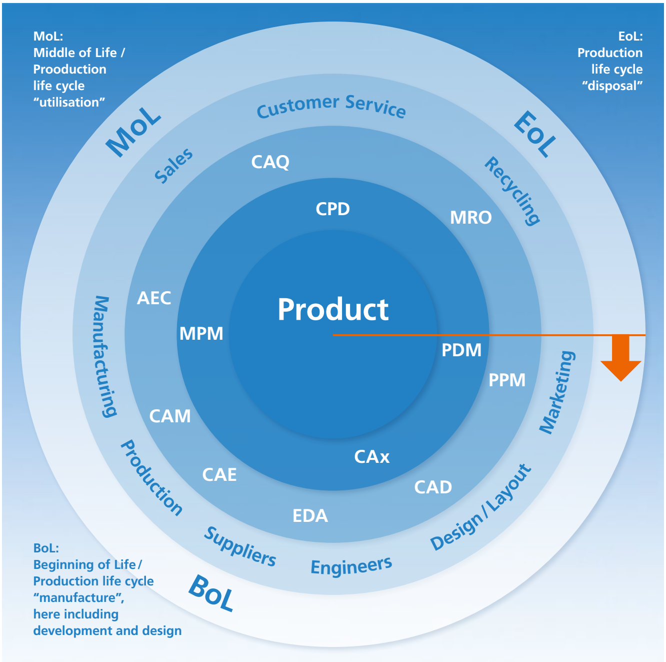
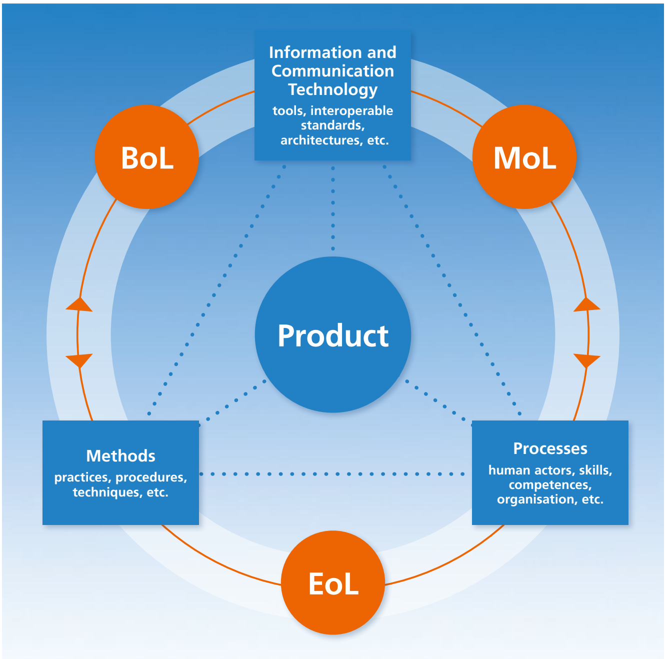


Fig. 53
Basic elements of Product Life Cycle Management (PLM)



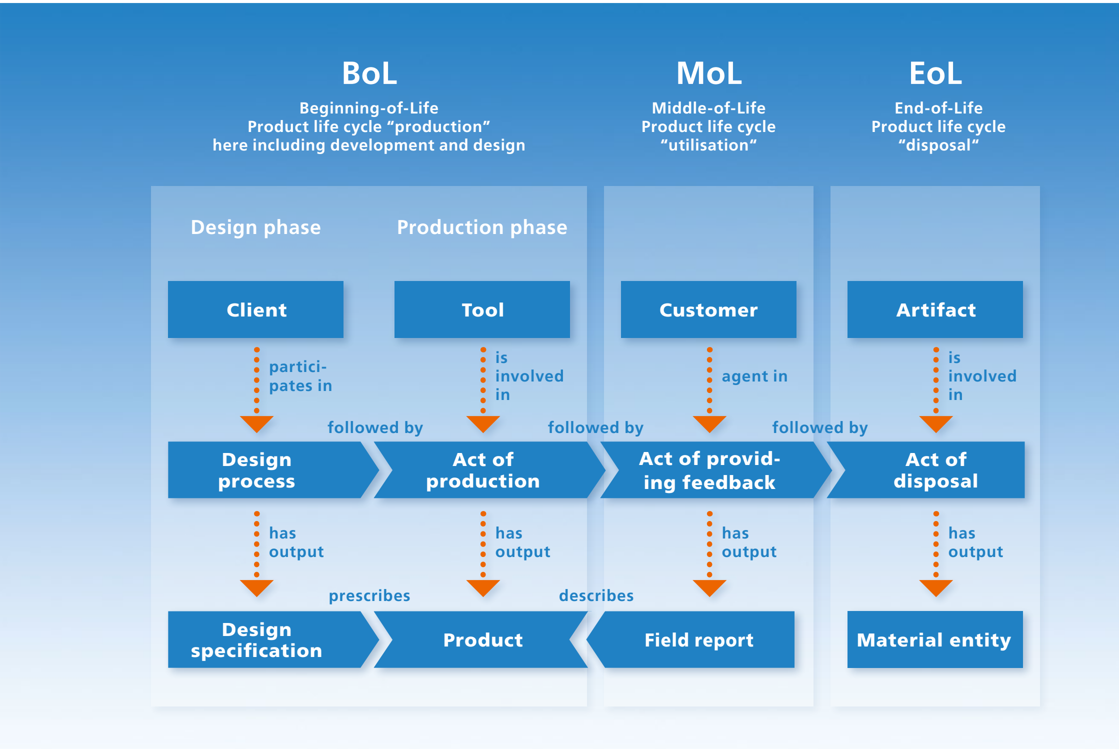
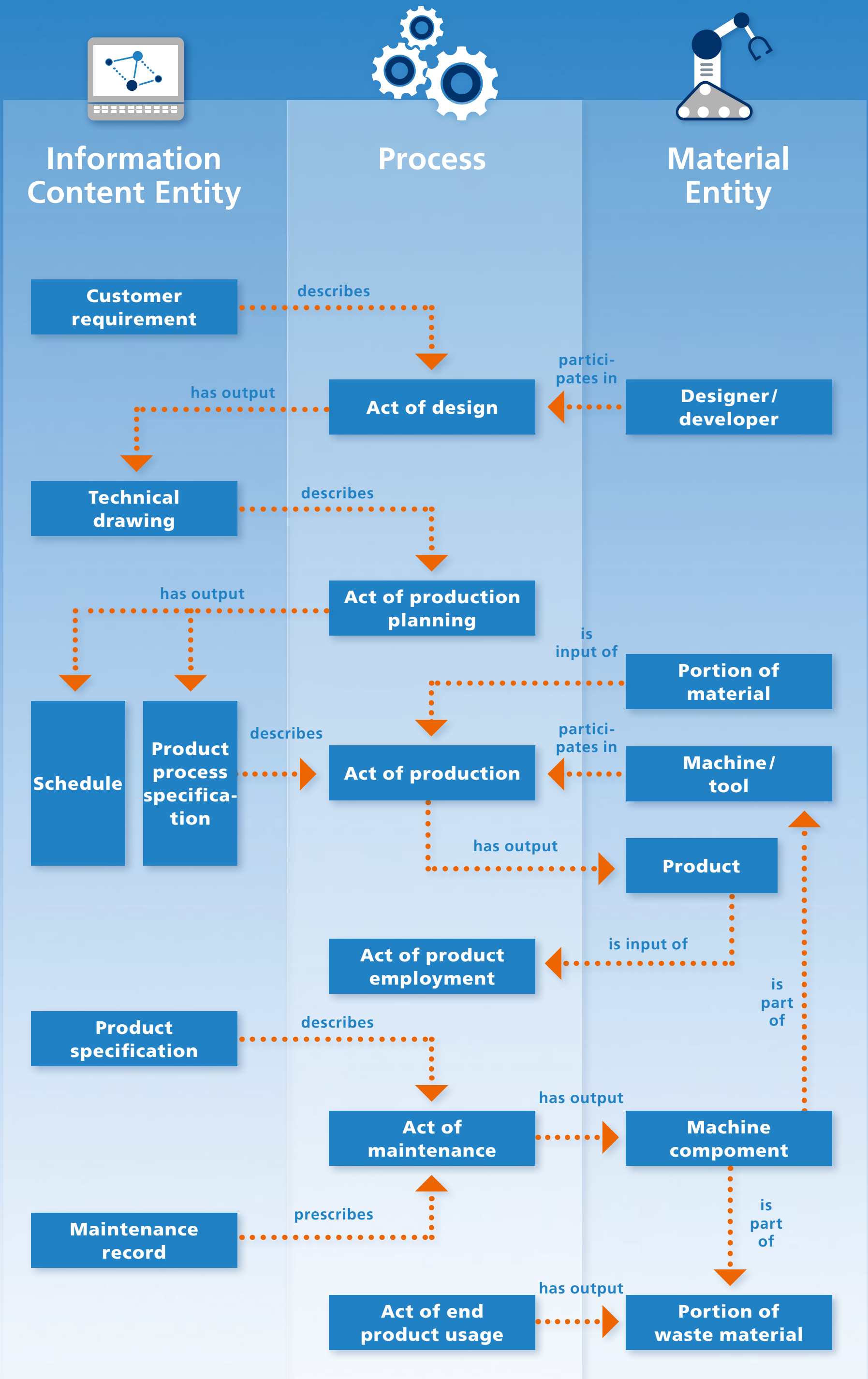


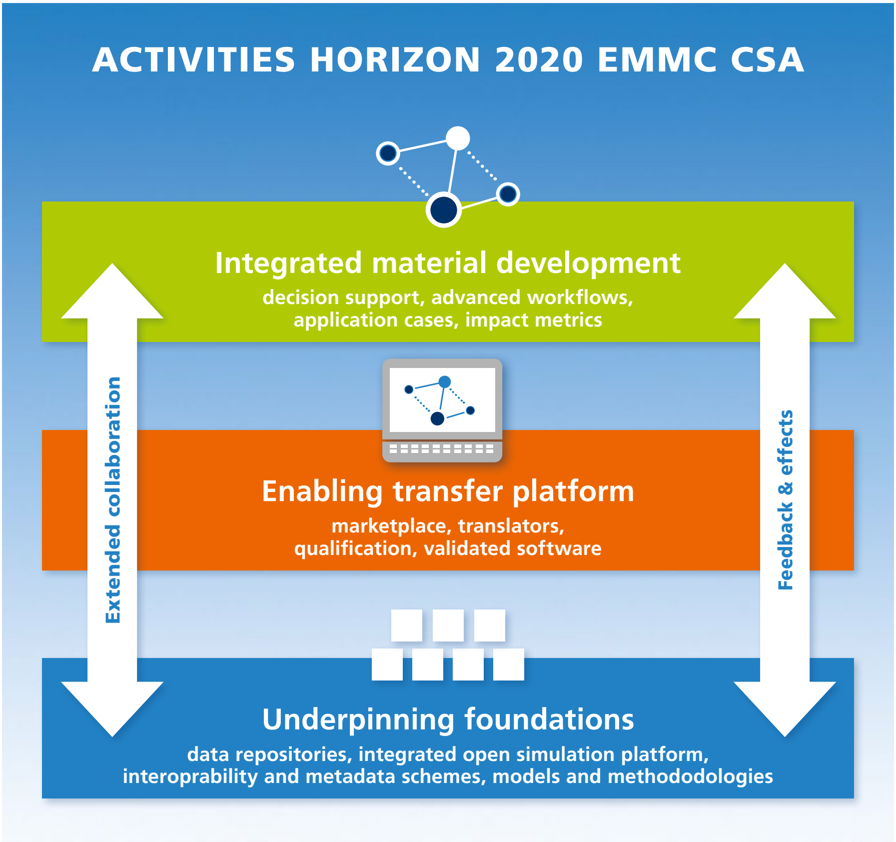
Fig. 54
Basic schematic representation of the information flow in Product Life Cycle Management (PLM) [225]

As the EMMC has pointed out, ontologies are the bridge to data and knowledge. For users in interaction with material manufacturers and industrial or institutional software owners, they offer a sustainable opportunity to accelerate material and product development by linking several models in linked workflows.[229] The objective of the EMMC as a Coordination and Support Action (CSA) within the Horizon 2020 initiative of the European Commission was explicitly to make material modelling and simulation an essential and integral part of product life

229 EMMC-CSA European Materials Modelling Council; "Report on Workshop on Interoperability in Materials Modelling"; IntOp2017, Cambridge, 7./8. November 2017; downloadable from https://emmc.info/wp-content/uploads/2018/04/EMMC-CSA_-OutcomeCambridgeFW.pdf (Access April 30, 2020)



Information Content Entity
Process
Material Entity
Customer requirement
describes
Act of design
partici-pates in
Designer/ developer
has output
Technical drawing
describes
Act of production planning
has output
is input of
Portion of material
Schedule
Product process specifica-tion
describes
Act of production
partici-pates in
Machine/ tool
has output
Product
Act of product employment
is input of
is part of
Product specification
describes
Act of maintenance
has output
Machine component
Maintenance record
prescribes
is part of
Act of end product usage
has output
Portion of waste material



cycle management.[230] An overview of the activities of this European coordination and support measure, which was completed in 2019, and of the EMMC, which continues to be visibly active

Left: Fig. 55
Detailed schematic representation of the information flow in Product Life Cycle Management (PLM) [225]

Fig. 56
Overview of the activities of the Horizon 2020 project EMMC-CSA

230 E. Ghedini, A. Hashibon, J. Friis, G. Goldbeck, G. Schmitz; "EMMO – The European Materials Modelling Ontology"; Materials Ontology Workshop, 29. June 2018, Bruessel.

Right: Fig. 57
Concept of a digital market place for products for material modelling

beyond that date, with around 1000 registered members in 2019, is shown in Figure 56. → see Fig. 56[231] and → Fig. 57[232]

Virtual marketplaces, for example, are being established for the exchange of material-related data.

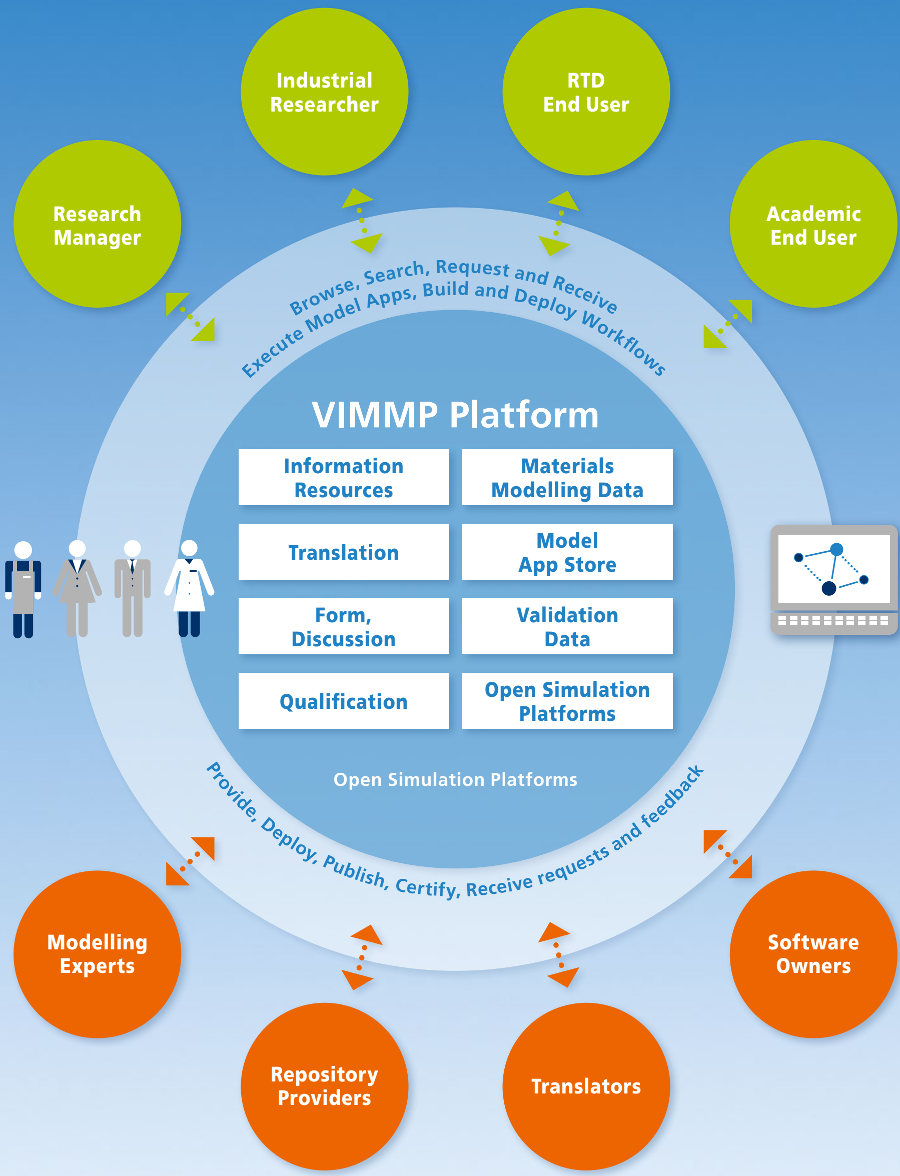
As an example, Figure 57 shows the concept of an easily accessible and user-friendly central hub, which has been developed and implemented since 2018 within the framework of the Horizon 2020 joint research project "Virtual Materials Marketplace (VIMMP)".[233] The concept is designed as a two-sided, web-based and open-source market place for the exchange of products between users or suppliers in connection with the modeling of materials. Data, methods and expertise come together in such a market place and form the basis for ideas for sustainable product development.

Data, methods and expertise exchanged on virtual marketplaces will form the basis of sustainable product development ideas in the future.

231 European Materials Modelling Council, downloadable from https://cordis.europa.eu/project/id/723867/reporting/de (Access April 30, 2020)

232 Graphics according to the homepage www.vimmp.eu . The caption reads: "VIMMP marketplace concept: serves all participants and facilitates the exchange between suppliers and consumers of products and services. The marketplace provides end-user interfaces to information, resources, discussion forum, databases and repositories, translation and training services, validated models and modelling applications. It opens up the possibility of using open simulation platforms to create and deploy workflows and run material modeling applications over cloud-based computing resources"; VIMMP "Virtual Materials Market Place" (2018-2021). Project funded by the research and innovation programme "Horizon 2020" of the European Union under Grant Agreement No. 760907.

233 Virtual Materials Market Place (VIMMP), Grant agreement ID: 760907, Funding Scheme: IA – Innovation action; zugaenglich ueber https://cordis.europa.eu/project/id/760907 sowie https://www.vimmp.eu/ (Access April 30, 2020)


Industrial Researcher
RTD End User
Research Manager
Academic End User
Browse, Search, Request and Receive
Execute Model Apps, Build and Deploy Workflows
VIMMP Platform
Information Resources
Materials Modelling Data
Translation
Model App Store
Form, Discussion
Validation Data
Qualification
Open Simulation Platforms
Open Simulation Platforms
Provide, Deploy, Publish, Certify, Receive requests and feedback
Modelling Experts
Software Owners
Repository Providers
Translators

Sustainable development therefore requires suppliers of technological concepts and technical solutions to contribute to ensuring that the price paid for a product is no higher for the environment than for consumers/end users or producers. An approach and cooperation of all representatives of all three pillars of sustainability (→ **see Fig. 49**) working together on materials development can be supported in a technologically significant way by conscious and targeted contributions to FAIR data principles and the exchange of material-based information.

One thing affects all relevant stakeholders involved in a product life cycle, i. e. developers, manufacturers and users as well as consumers: the growing awareness of the serious consequences if man-made product, material and process developments allowed the repetitive sequence of product life phases of a circular economy to become out of step with natural life cycles (→ **see Fig. 58**).

> **For adhesively bonded products, methods and digital tools will be available in increasing numbers in the future.**

In summary, numerous methods and digital tools are available for the improvement or new development of adhesively bonded products. In accordance with globally accepted values, they iteratively support developers and manufacturers on the way to sustainable development, which is also in demand on the market, by incorporating material-related data sources. Standardised life cycle-based approaches are available. In the age of digitisation, the establishment of a uniform "material language" based on ontologies as a prerequisite for a clear and rapid exchange of information accelerates the evaluation of research ideas and the material product development in the sense of a holistic view.

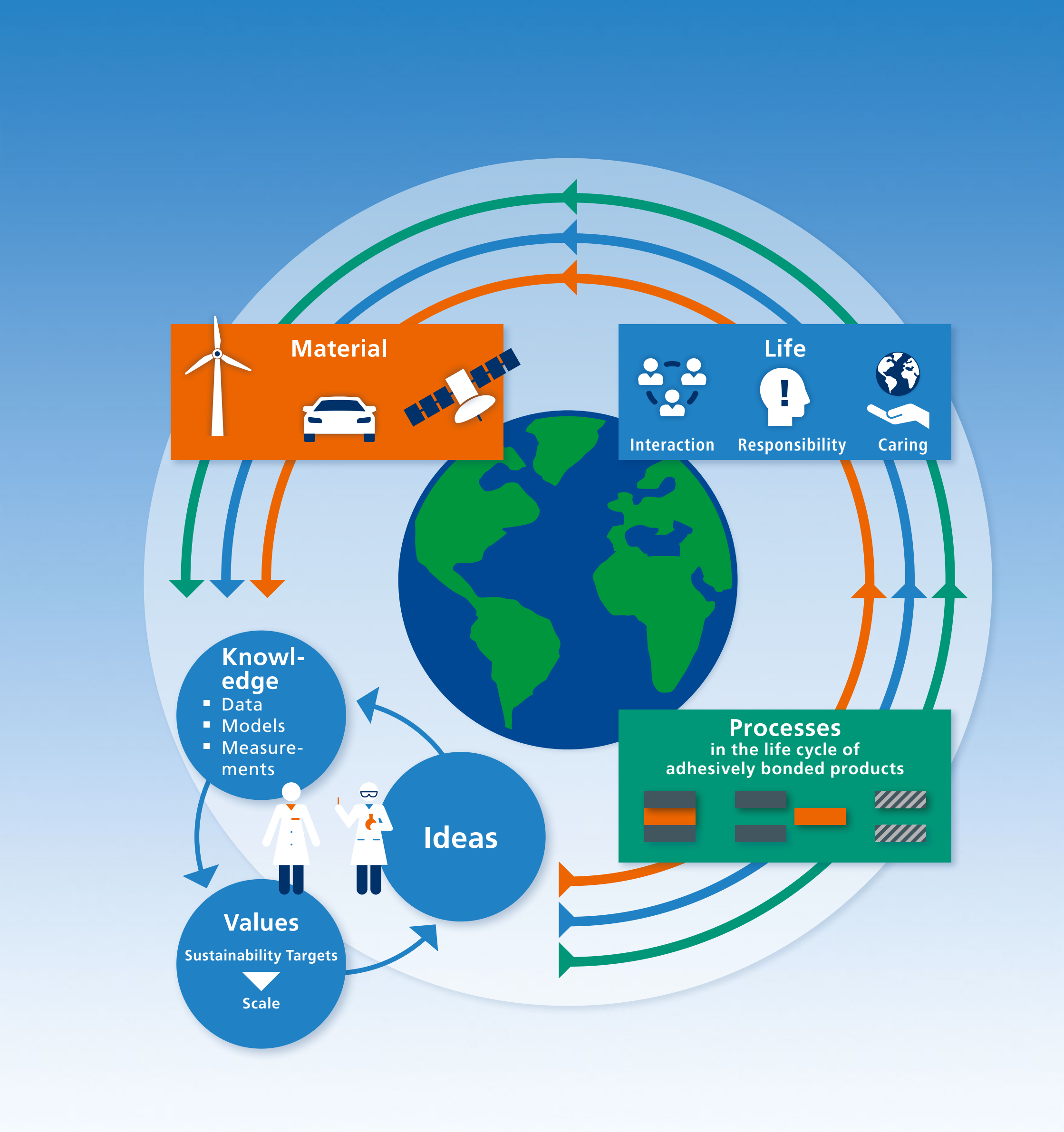


Fig. 58
Sustainable material development for imaginative adhesively bonded products

3.3
Life Cycle Assessment/LCA – data-based methods at the interface between material and environmental research

A further guiding principle for the purposes of the above considerations is to identify the most appropriate option for determining the circular economy efficiency of adhesively bonded products. A prerequisite for this determination is the implementation of FAIR data concepts. These are based on relevant material-related data, such as those generated by characterisation or modelling.

> **A determination of the effectiveness of the circular economy of adhesively bonded products requires FAIR data.**

Which relevant parameters can be obtained from these data was qualitatively considered in chapter 2.5. It should be noted here that assessing the relevance of information and the exchange of information is closely linked with the definition of its purpose. In the following, it will be seen that the methodological selection of an LCA model for the evaluation and assessment of relevant data is also influenced by its purpose or target definition.

With regard to the environmental impact of an adhesively bonded product, the Life Cycle Assessment (LCA) [165–169] provides a suitable tool for consideration. According to its basic idea, the relevant data are collected separately for the individual phases, but are evaluated as a sum of the product life phases over the entire product life cycle.[234] As already explained in Chapter 2.5,

234 Communication from the Commission to the Council and the European Parliament, Integrated Product Policy – Building on Environmental Life-Cycle Thinking, COM 2003 302 final, p. 5

a Life Cycle Assessment (LCA) covers aspects over the entire life cycle of a product, from the idea and development through the product life cycle phases "production" (including the extraction of raw materials and their treatment, energy consumption) and "utilisation" (including waste, emissions, energy consumption) to "disposal" (including waste, emissions, energy consumption). In the retrospective literature [235, 236, 237], however, examples can be found in which a certain granularity of consideration is specified by those carrying out a Life Cycle Assessment (LCA) before and during the practical implementation.

> **A life cycle assessment is suitable for considering the environmental impact of adhesively bonded products.**

In the following, a published study [235] will be considered as an example and in extracts, which prepared life cycle assessments of lead-free alternatives to lead-containing solders for the electronics industry from the product viewpoint, whereby electrically conductive adhesives were also considered. The main focus of the study is to show the dynamics of developments in the field of life cycle assessment in the first decade of the 21st century.

235 A. S. G. Andrae In Global Life Cycle Impact Assessments of Material Shifts; Springer-Verlag, London, 2010, The Example of a Lead-free Electronics Industry.

236 H. Stephan; "Bewertungsmethodik fuer Fertigungsverfahren im Karosseriebau aus Sicht des betrieblichen Umweltschutzes"; Hrsg.: Verein zur Foerderung des Instituts WAR, Wasserversorgung und Grundwasserschutz, Abwassertechnik, Abfalltechnik, Industrielle Stoffkreislaeufe, Umwelt- und Raumplanung der Technischen Universitaet Darmstadt, ISBN 978-3-932518-80-5, Darmstadt, 2007.

237 V. G. Maciel, G. Bockorny, N. Domingues, M. B. Scherer, R. B. Zortea, M. Seferin; "Comparative Life Cycle Assessment among Three Polyurethane Adhesive Technologies for the Footwear Industry"; ACS Sustainable Chem. Eng. 2017: 5, 8464–8472.

Example electronics industry

In 2010, A. S. G. Andrae published global life cycle analyses in which he dealt with the effects of replacing lead-containing solders with lead-free alternatives, whether solders or electrically conductive adhesives.235 As an introduction, the author emphasises the holistic scientific character of predictions of environmental impacts, because the complexity of environmental systems cannot be captured by analytical reduction, but rather by interdisciplinary thinking. Special attention is paid to a consequence-oriented life cycle analysis (CLCA), the inaccuracy analysis and the Japanese LIME method204 (life cycle impact assessment method based on endpoint modelling) for the assessment of environmental impacts, which is available in the year of publication. After the first two versions LIME-1 and LIME-2, which were based on Japanese environmental conditions and the environmental perception of Japanese people, the globally applicable LIME-3 method was developed in 2016, for which regionally different weighting factors were collected by means of surveys.

Software-based Decision Support Systems (DSS) for human decision makers are often used in the corporate decision-making process for operational or strategic tasks. Relevant information must be determined and processed for this purpose, whereby several dimensions must be recorded, namely technical, ecological, economic and also safety aspects. LCA systems are seen by the author as a valuable aid in screening and decision making from an environmental point of view. A. S. G. Andrae discusses the results of the study, including a link between life cycle analysis and risk assessment based on leaching tests of the materials under consideration (see above). As a product-related result, it was statistically shown that, with regard to carbon dioxide emissions, the use of silver-containing isotropically conductive adhesives (ICAs) is advantageous.

As far as methodological aspects are concerned, the author concludes, with a view to the development up to 2009, that CLCA is still at the stage of a semi-quantitative discussion approach. In conclusion, he states that for important technologies, continuous life-cycle analyses should be recommended rather than a one-off survey.

Due to its comprehensive scope, DIN EN ISO 14040 cannot provide product-specific rules as a basis for concrete life cycle-based modelling.

In spite of the outstanding importance of such product-related projects for the success of companies, in the early 2010s, other experts also considered that life-cycle management in its current form "was not yet fully developed and therefore insufficiently embedded in companies to meet the challenges of the future sufficiently[238]. The inevitably comprehensive scope of DIN EN ISO 14040[165–169] cannot provide any product group-specific rules that could provide a uniform basis for concrete life cycle-based modeling on the basis of a specific purpose. However, the uniform basis of DIN EN ISO 14040[165–169] is necessary for uniform studies with reliable comparative statements, and results obtained in uniform studies would be usable not only internally for product and process optimisation, but also externally (B2B and/or B2C).

> **However, a uniformly regulated basis is necessary for reliable comparative statements and results.**

The development over the last 15 years[217], beginning after the standardisation of the LCA with DIN EN ISO 14040[165–169], which came into force in 2006, shows that various relevant stakeholders from various initiatives have pushed forward with concretisations within the broader framework of this standard (see Figure 59). Initiated by the European Union, these include, in particular, procedures that serve to determine a footprint[239] within the framework of a life cycle perspective. Within the framework of the flagship initiative "A resource-efficient Europe"[240] of the Europe 2020 Strategy, approaches have been developed to increase resource productivity and to decouple economic growth from both resource use and environmental impacts (see Chapter 2.5). The European Commission started the development of the Product Environmental Footprint (PEF), which is not to be confused with the devel-

238 U. Raubold, Lebenszyklusmanagement in der Automobilindustrie, Gabler Verlag | Springer Fachmedien: Wiesbaden, 2011; DOI 10.1007/978-3-8349-6613-1_1.

239 https://sustainabledevelopment.un.org/sdg12 (Access April 30, 2020)

240 C. Liedtke; M. Faulstich In Ein ressourceneffizientes Europa; Ressourcenkommission am Umweltbundesamt (KRU), Hrsg.; Umweltbundesamt, 2016; S. 3–7, Ein ressourceneffizientes Europa – Ein Programm fuer Klima, Wettbewerbsfaehigkeit und Beschaeftigung

opment of approaches to determine an organisation's footprint [241] (→ see Fig. 59).

The EU launched developments in this context: Footprint initiatives.

Note

As the 2012 PEF Guidelines, in particular Annex X [242], state, in this context

- the French standard BP X30-323 [243] of 2008 [244]
- the "Ecological Footprint Standards 2009" [245] of the Global Footprint Network Standards Committee
- the comprehensive International Reference Life Cycle Data System (ILCD) manual [246] of the European Commission from 2010

241 N. Pelletier, K. Allacker, R. Pant, S. Manfredi, International Journal Life Cycle Assess 2014, 19, S. 387–404, The European Commission Organisation Environmental Footprint method: comparison with other methods, and rationales for key requirements; 387–404; DOI 10.1007/s11367-013-0609-x.

242 Product Environmental Footprint (PEF) Guide, Deliverable 2 and 4A of the Administrative Arrangement between DG Environment and the Joint Research Centre No N 070307/2009/552517, including Amendment No 1 from December 2010; Ref. Ares (2012)873782 – 17/07/2012; Annex X: Comparison of the key requirements of the PEF Guide with other methods.

243 BP X 30-323-0 "Principes généraux pour l'affichage environnemental des produits de grande consommation".

244 C. Cros, E. Fourdrin, O. Réthoré, International Journal Life Cycle Assess 2010, 15, S. 537–539, The French initiative on environmental information of mass market products; DOI 10.1007/s11367-010-0182-5 .

245 Ecological Footprint Standards 2009 (Herausgeber: J. Kitzes); Global Footprint Network, 2009, Oakland, USA: downloadable from www.footprintstandards.org .

246 European Commission – Joint Research Centre – Institute for Environment and Sustainability: International Reference Life Cycle Data System (ILCD) Handbook – General guide for Life Cycle Assessment – Detailed guidance. First edition March 2010. EUR 24708 EN. Luxembourg. Publications Office of the European Union; 2010.

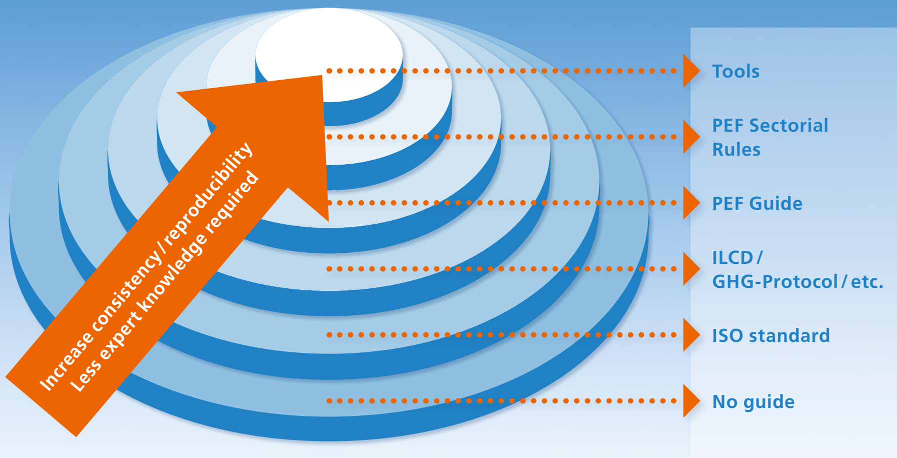


Fig. 59
Development of standards and methods to determine the Environmental footprint of organisations

- the "Product Life Cycle Accounting and Reporting Standard" of the private and transnational institution GHG Protocol [247] from 2011
- the British standard PAS 2050:2011 [248] and
- DIN EN ISO 14067:2019-02 "Greenhouse gases – Carbon footprint of products – Requirements and guidelines for quantification" [221], which came into force in 2012

should not go unmentioned.

The PCF (Product Carbon Footprint) process [256] is also important for the ongoing development of PEF in several respects, even if greenhouse gas emissions are not the only environmental impact, not only for companies but also for some products [249]. With regard to the sub-target SDG No. 12.4 (see chapter 3.2) with reference to

247 Greenhouse Gas Protocol "Product Life Cycle Accounting and Reporting Standard", World Resources Institute and World Business Council for Sustainable Development, 2011; ISBN 978-1-56973-773-6.

248 PAS 2050:2011 "Specification for the assessment of the life cycle greenhouse gas emissions of goods and services".

249 S. Dierks In Betriebliche Nachhaltigkeitsleistung messen und steuern: Grundlagen und Praxisbeispiele; A. Baumast, J. Pape, S. Weihofen, S. Wellge, Hrsg.; UTB: Stuttgart, 2019; S. 106–116, Der Product Environmental Footprint (PEF) von Kaffee bei Tchibo.

"releases to air, water and soil", the three best-known footprinting approaches in 2019 were the CO_2, water and land footprint.[250]

The CO_2, water and ecological footprints usually comprise only one environmental impact.

All footprinting approaches, which as sections of a Life Cycle Assessment (LCA) are nothing in themselves and usually limited to an environmental impact, follow a comparable approach[258], according to which the underlying calculation method is standardised and made available to the interested public. The approaches aim at "aggregation into a tangible and communicable value" and into a portrait whose symbolism is easily understood. The Footprint size symbolizes the intensity of the environmental impacts. A high degree of transparency is intended to achieve comprehensibility and acceptance; in addition, the actual approach should be clearly communicated to many users. The quantitative recording of material and energy flows is a decisive basis for the environmental performance evaluation and represents a challenge "with regard to completeness, plausibility and internal allocation"[258].

DIN EN ISO 14067:2019-02[221] is authoritative for the quantification of the emission flows attributable to gases. Its relationship to other environmental standards is shown in Figure 60. ISO EN 14067:2019-02[221] does not refer to a single greenhouse gas (GHG), but regards greenhouse gases as a gaseous "constituent of the atmosphere, both natural and anthropogenic, that absorbs and emits radiation at specific wavelengths within the spectrum of infrared radiation emitted by the earth's surface, the atmosphere and clouds"[221]. On the one hand, the gases carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6)[251], classi-

250 S. Weihofen In Betriebliche Nachhaltigkeitsleistung messen und steuern – Grundlagen und Praxisbeispiele; Verlag Eugen Ulmer: Stuttgart, 2019; S. 83–96, Carbon-, Water-, Land-Footprinting-Ansaetze.

251 "The Kyoto Protocol to the United Nations Framework Convention on Climate Change", opened for signature on 16 March 1998

fied as greenhouse gases in the Kyoto Protocol / Annex A [252], are mentioned; on the other hand, ISO EN 14067:2019-02 [221] refers to the "current assessment report of the Intergovernmental Panel on Climate Change (IPCC)" [253] of 2013. It does not include "water vapour and ozone, which are both anthropogenic and natural GHGs". The standard limits its focus "to long-lived greenhouse gases and thus excludes climate impacts caused by changes in the reflectance of the surface (albedo) and short-lived radiative forcing media (e. g. soot and aerosols)". It defines the "carbon dioxide equivalent" ("CO_2 equivalent" or "CO_2eq") as "the unit for comparing the radiative forcing* of a GHG with that of carbon dioxide".[254] The same applies to the "global warming potential "** or "GWP". As discussed in Chapter 3.2, the reference to the "current atmosphere" is noteworthy. Steadily growing scientific knowledge is relevant for the implementation and evaluation steps within a CFP study, and the standard prioritizes the following: "When "making decisions during the CFP study", preference is given to scientific knowledge (e. g. physics, chemistry, biology).

* Radiative forcing is a measure of the influence that a factor has on the change in the equilibrium of incoming and outgoing energy in the earth/atmosphere system.[255]
** Factor that indicates the radiative forcing of a greenhouse gas over a selected time horizon compared to that of carbon dioxide, expressed in CO_2 equivalents. Both the different residence times and the different infrared absorption capacity of the various greenhouse gases are taken into account.[256]

252 United Nations: The Kyoto Protocol to the United Nations Framework Convention on Climate Change; 1998; https://www.bmwi.de/Redaktion/DE/Artikel/Industrie/klimaschutz-kyoto-protokoll.html (Access April 30, 2020)

253 Intergovernmental Panel on Climate Change – IPCC; Climate Change 2013: The Physical Science Basis. https://www.ipcc.ch/report/ar5/wg1/ (Access April 30, 2020)

254 H. Hottenroth; B. Joa; M. Schmidt In Carbon Footprints fuer Produkte; H. Hottenroth; B. Joa; M. Schmidt, Hrsg.; Institute for Industrial Ecology – INEC: Pforzheim, 2013; S. 4, Treibhausgase und ihre Treibhauswirkung.

255 H. Hottenroth; B. Joa; M. Schmidt In Carbon Footprints fuer Produkte; H. Hottenroth; B. Joa; M. Schmidt, Hrsg.; Institute for Industrial Ecology – INEC: Pforzheim, 2013; S. 112, Glossary.

256 H. Hottenroth; B. Joa; M. Schmidt In Carbon Footprints fuer Produkte; H. Hottenroth; B. Joa; M. Schmidt, Hrsg.; Institute for Industrial Ecology – INEC: Pforzheim, 2013; S. 113, Glossary.

As a current research project[257] shows, CFP studies can provide valuable insights into adhesive bonding technology issues from the entire process chain.

The carbon footprint at organisational level, which is regulated in the DIN EN ISO 14067[221] standard (→ see Fig. 60), considers not only the company's own direct emissions resulting from combustion processes, but also indirect emissions caused by purchased energy and by upstream and downstream processes.[250] Further standardsation is provided by the greenhouse gas (GHG) protocol.

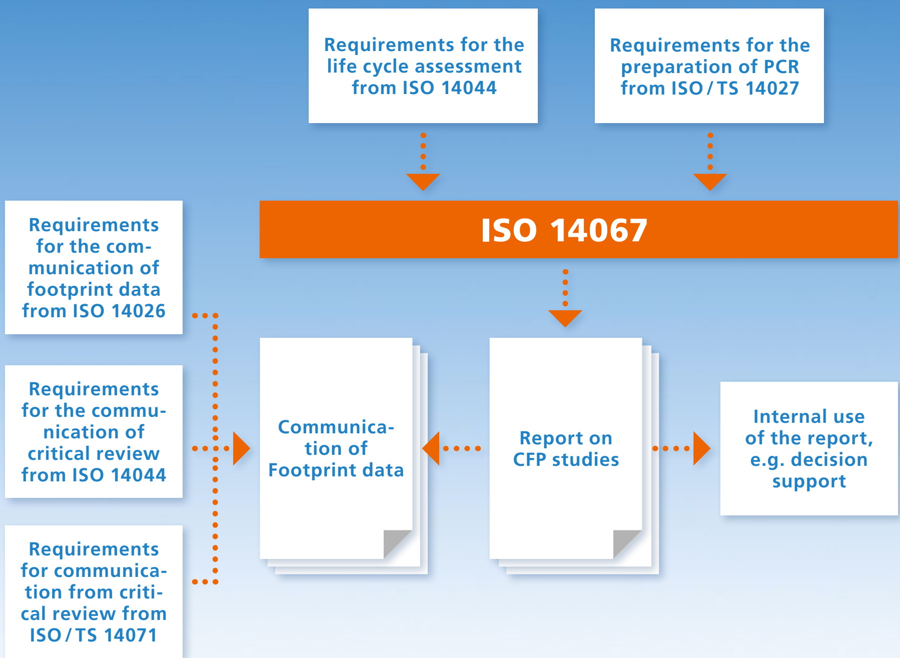
For companies, measuring the product carbon footprint is often more challenging than measuring the company-specific footprint for practical reasons. A study published in 2011, in which "44 companies asked a total of 1402 suppliers about their greenhouse gas emissions," found that "only about 20 % of companies were able" to "obtain sufficient information about the greenhouse gases in their supply chain.[200] Companies were found to be dependent on other factors to measure the sustainability performance of their products.[200] For various industrial adhesives, an estimate of typical (cradle to gate) PCF value is available in tabular form.[258]

> **The CO_2, water and ecological footprints do not allow a holistic view of environmental impacts.**

The three Footprint approaches mentioned so far (the CO_2, the water and the ecological footprint) each comprise only one environmental impact. The approaches do not allow the weighting of different environmental aspects in upstream, internal

257 S. Boehm, D. Estephan, A. Winkel, F. Ebershold, J. Hesselbach; KlebFuß – Entwicklung und Validierung einer Bewertungsmethode zur Ermittlung des CO_2-Fußabdrucks von Klebanwendungen, Vorhaben 19765 N der Forschungsvereinigung DECHEMA Gesellschaft fuer Chemische Technik und Biotechnologie e.V. und der Forschungsvereinigung Schweißen und verwandte Verfahren e.V. des DVS / AiF im Rahmen des Programms zur Foerderung der Industriellen Gemeinschaftsforschung IGF

258 Industrieverband Klebstoffe e.V. "Typical "Product Carbon Footprint" (PCF)-Values for Industrial Adhesives", Duesseldorf, Deutschland, 2014.



or downstream processes, which makes a holistic view of the environmental impacts difficult.[250] For companies, this holistic view includes, for example, not only the transport of raw materials and product containers, but also product (development) relevant business trips, the recharging of the batteries of business mobile phones or the heating of buildings.

Fig. 60
Relationship between ISO EN 14067:2018[221] and other environmental standards

In addition, the EU Commission identified obstacles to a stronger and faster diffusion of environmentally friendly products in the EU internal market[259]:

- A lack of common understanding of what makes a "green product".
- A variety of national and private initiatives using different measurement methods.

259 J. Berger In Betriebliche Nachhaltigkeitsleistung messen und steuern Grundlagen und Praxisbeispiele; Verlag Eugen Ulmer: Stuttgart, 2019; S. 96 – 106, Product Environmental Footprint (PEF).

- The unreasonable burden and considerable costs for manufacturing companies when they have to use such different methods to determine the environmental impact of their products.
- The confusion for consumers when, for example, they try to compare products based on inconsistent environmental information or an increasing variety of sustainability labels.

The Product Environmental Footprint – PEF represents a harmonisation approach in the context of the Footprint initiatives.

The product-related harmonisation approach initiated by the European Commission is represented by the "Product Environmental Footprint – PEF", i. e. the environmental footprint of products and services [214] published in April 2013. It is based on established LCA standards and the DIN EN ISO 14040/44 [165–169] series of standards, and a PEF guideline was developed by the Institute for Environment and Sustainability (IES) and the Joint Research Centre (JRC), a Directorate-General of the European Commission. The PEF has reached the transition phase in 2020 after the end of the pilot phase from 2013 to 2019.[260] The European Union expects a decision on when the environmental impact assessment for which products must be carried out according to the PEF measure from 2021 onwards in the implementation and communication phase.[261]

The PEF is described in a report commissioned by the Federal Environment Agency [214] as "a multi-criteria method for life-cycle based modelling and assessment of the environmental impacts of products and services through occurring material and energy flows as well as the associated emissions and waste

260 European Commission, Environment, "The Environmental Footprint transition phase", dowmloadable from https://ec.europa.eu/environment/eussd/smgp/ef_transition.htm (Access April 30, 2020)

261 ifu Hamburg GmbH | Institut fuer Umweltinformatik; Die Entwicklung des Product Environmental Footprint in 4 Phasen

streams". It "aims at harmonising existing methods for the LCA-based assessment of products" and follows the approach "comparability over flexibility".

The PEF makes "significantly more specifications than DIN EN ISO 14040/44": If one and the same metric is used for evaluation for a particular market, this should help to increase transparency and fair competition.[262] Although, for example, DIN EN ISO 14040/44 [165–169] specifies the iterative process as the basis for preparing a life cycle assessment study, the PEF, on the other hand, makes a binding provision for a so-called screening step in which all processes or activities are considered that are to be included in the profile. The screening step in the PEF is comparable with the iterative approach of DIN EN ISO 14040/44 [165–169], but is "only strongly recommended" in the standard.

> **The Product Environmental Footprint – PEF should contribute to transparency and fair competition when using one and the same assessment metric.**

In this way, implementation of the universally applicable and standardised methods for the assessment of environmental impact concerning different product types, which can be used universally in different domains, allows firstly a reduction in scope for interpretation, while simplifying communication with market companions or product users. Secondly, the determination of the environmental performance of products opens up time and cost-saving target guidance, which is in parallel, is a valuable indicator for further development possibilities in the manufacturing process.

The European Commission's guidelines [263] on the Product Environmental Footprint (PEF) emphasize that comparative considerations require the development of additional Product Environmental Foot-

262 "A Brief on the European Commission's Product Environmental Footprint Guide", zugaenglich ueber pre-sustainability.com (Access April 30, 2020)

263 Product Environmental Footprint (PEF) Guide, Deliverable 2 and 4A of the Administrative Arrangement between DG Environment and the Joint Research Centre No N 070307/2009/552517, including Amendment No 1 from December 2010; Ref. Ares (2012)873782 – 17/07/2012.

print Category Rules (PEFCR). The same applies to a corresponding further methodical harmonisation, specific characteristics, relevance and reproducibility for the respective product types. With regard to PEF, "the numerous existing methodological challenges first need to be solved"[216], which both concern the

- scope of the investigation (e. g. definition of the functional unit, definition of the representative product)
- modelling of the product system (e. g. the modelling of electricity)
- evaluation and interpretation (e. g. suitability of impact assessment methods and prioritisation of impact categories)

Assessments according to a SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis carried out by GS1 Germany GmbH and THEMA1 GmbH of the PEF procedure[264] are shown in Figure 61.

> **Category specific rules (Product Environmental Footprint Category Rules – PEFCR) must be developed for comparative considerations.**

This shows that the European Commission is currently making great efforts to provide consumers with reliable and concrete information on the environmental performance of products by standardizing an excessive variety of methods (→ see Fig. 62). This is done in order to prevent a possible loss of confidence in the reliability of environmental performance data. The PEF is also intended to pave the way for a method that can also be used by small and medium-sized enterprises (SMEs).

> **The Product Environmental Footprint – PEF should not only be applicable independent of company size, but should also enable adhesive users to determine further cycles in the future.**

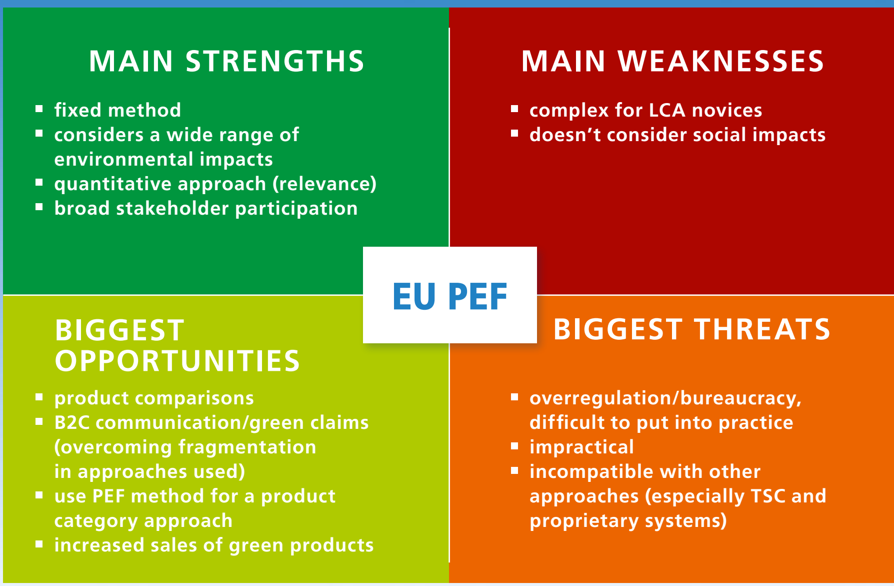
264 GS1 Solutions; "Collectively defining sustainability for product categories – An overview of global hotspot initiatives"; GS1 Germany GmbH, Koeln, Deutschland, 2013.

With regard to the areas mentioned in Chapter 3.1, i.e. construction, transport, electronics and packaging industry, it is not expected that the same measurement methodology for the Product Environmental Footprint – PEF will be used across domains. Instead, it is expected that- domain-specific regulatory requirements will be included, – for example in the course of a parallel social LCA (S-LCA, see above).

> **Adhesive data sheets would have to be supplemented in the future with information on the controlled adhesive failure mechanism.**

On the other hand, it assumed that in future, adhesives users will have options to determine the most suitable option for deter-

Fig. 61
SWOT analysis of the European Commission's PEF approach



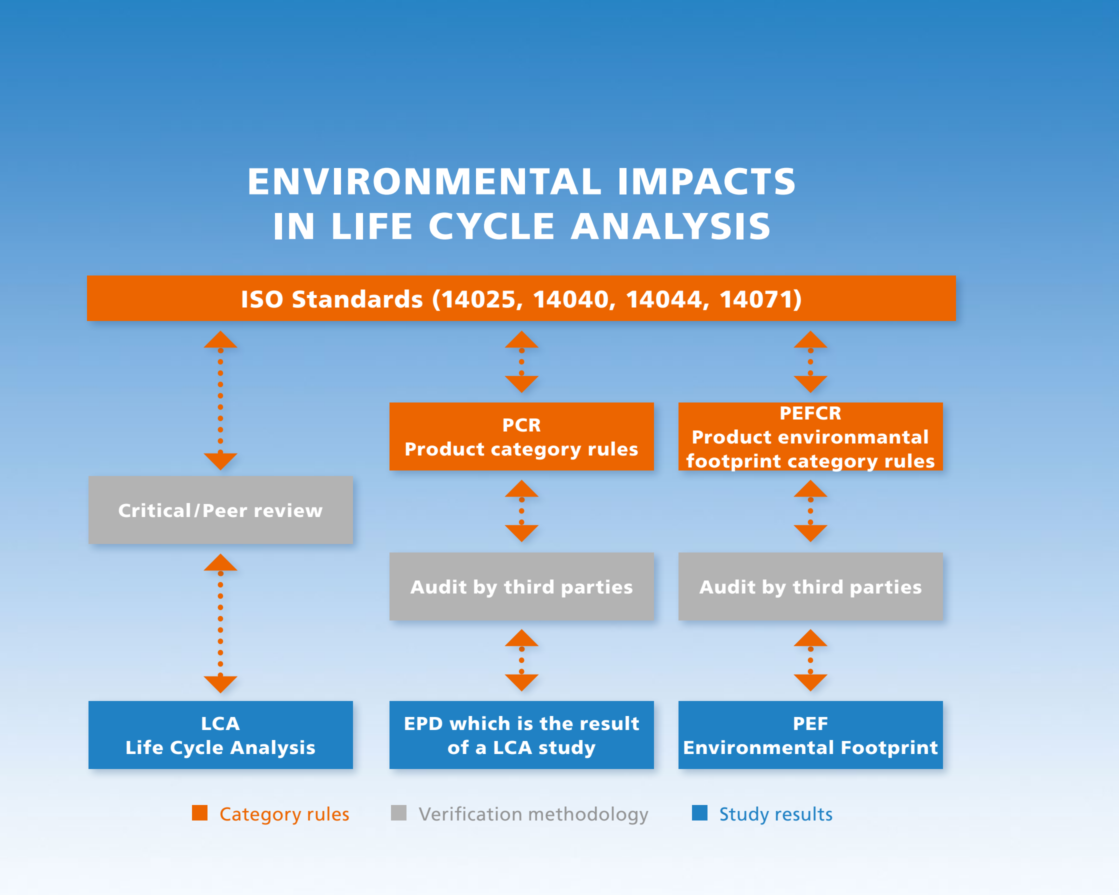


Fig. 62
Comparison of Product Environmental Footprint – PEF and ISO 14040/44

mining the circulation of adhesively bonded products internally (as has been the case up to now) but also to communicate standardized data records externally for exchange with business partners and customers.

Based on a harmonisation of methods, these will provide comprehensible information for experts as well as for non-specialists and newcomers. For example, in the future, material-related safety or technical data sheets of their adhesives issued by the adhesive manufacturers could be supplemented for adhesive users in Europe by digital, standardized data sets containing adhesive information also about the product life cycle phase "disposal" for the orderly failure mechanism of the adhesive (see Chapters 2.6, 4.1–4.4, 5.1, 5.2.6, 5.3–5.6). These then harmonise with an expected domain-specific standardised PEF procedure. When evaluating the effectiveness of the circular economy of an adhesively bonded product, the function of the adhesives manufacturer is to advise the adhesive user / product manufacturer. The involvement of the adhesive manufacturer in this function is strongly advised, although the responsible assessment is the responsibility of the adhesive user / product manufacturer, since only the latter can decide in which of their products adhesives are used, how and under which conditions.

> **The evaluation of the effectiveness of the circular economy of an adhesively bonded product is the responsibility of the adhesives user / product manufacturer, whereby the involvement of the adhesives manufacturer as a consultant is strongly recommended.**

In line with these considerations and starting from the development and manufacturing life cycle phase of a product, comparative life cycle assessments (LCA) are also found in the technical literature. These LCA's are based on system boundaries "from cradle to gate". They are used by manufacturers of adhesively bonded products for internal decision making, without being complete life cycle assessments with the claim of a holistic view. Approaches of comparative LCA are very helpful for such questions. For a consideration of the entire product life cycle, however, the LCA for the adhesively bonded products is additionally required.

Example automotive industry

With regard to an evaluation methodology for manufacturing processes in car body construction, H. Stephan started in 2007 from the point of view of operational environmental protection with the question "How can joining processes be evaluated based on the method of life cycle assessment so that the results can be processed together with the parameters customary in production planning?"[236] The main focus on the way to a practicable and user-friendly method was on the one hand the creation of the functional unit and on the other hand the definition of the system limits. The maximum tensile force of a joint in the Newton unit served as the functional unit for the evaluation method used. For this purpose, material-related data were collected with three material combinations by testing joints. Emission factors (for air impurities) were collected for welding processes on the basis of the design of experiments method. Life Cycle and Effects

Balances were drawn up for the joining processes laser beam welding, resistance spot welding, clinching and adhesive bonding. In detail, all energy requirements (per joining seam length, per number of welding spots, per number of clinching spots or per area of adhesive flange) were determined for all joining processes considered in the factory under consideration. With regard to the ratio between the lap shear strength achieved and the energy required, the adhesive bonding process produced the best results. Within the scope of the Life Cycle Inventory "for the adhesive bonding process in the automotive industry, it was not possible to fall back on any previously collected data. For this reason, new data were collected in cooperation with appropriate companies for a load-transmitting spot-weldable metal adhesive and for a reactive rubber-based adhesive/sealant. As the two adhesives are used for different purposes in car body construction, H. Stephan stated: "A direct comparison of the adhesives, in the sense of better or worse in terms of environmental impact, is therefore not appropriate. A comparison of the four joining processes investigated at a maximum tensile force of 5.5 kN according to the chosen methodology was finally carried out graphically separated according to five impact categories.[265] The considered adhesive bonding technology with the load-transferring adhesive showed the lowest greenhouse, ozone depletion, eutrophication, photochemical oxidant formation and acidification potential. This applies in particular to the last three impact categories. In the other impact category, human toxicity potential, the provision of machinery stands out in the case of the load-transferring adhesive.

Example shoe industry

In an LCA study published in 2017 by a Brazilian team of authors based on the ISO 14040 and ISO 14044 standards, three adhesive technologies based on polyurethane adhesives were compared[237]: solvent-based, aqueous and powder. For this purpose, primary data records for environmental emissions, wastewater, chemical constituents and technical specifications were determined at on-site meetings and a comparison was made of the manufacturing-relevant environmental impacts for functional units the size of one square meter according to a standard of adhesively bonded joint surface. On the basis of these considerations, the material and process developers identified possibilities for reducing environmental impacts and drew further conclusions with regard to the design of production equipment.

Like ISO 14040/44[165–169], the Product Environmental Footprint (PEF) initiated by the European Commission also sets require-

265 J. B. Guinée, M. Gorrée, R. Heihungs, G. Huppes, R. Kleijn, A. de Koning, L. van Oes, A. Wegener Sleeswijk, S. Suh, H. A. U. de Haes, H. de Bruijn, R. van Duin, M. A. J. Huijbregts, E. Lindeijer, A. A. H. Roorda, B. L. van der Ven, B. P. Weidema; "Handbook on Life Cycle Assessment Operational guide to the ISO standards"; Kluwer Academic Verlag, New York, Boston, Dordrecht, London, Moscow, 2002.

ments for the quality, type and collection of data and deals with the handling of data gaps in the life cycle-based assessment of products.[214] If one takes a closer look at data collection for the product life cycle "manufacture" of adhesively bonded products alone, it becomes clear that the data collected in this context, for example for documentation, process control or quality assurance purposes, and available to the manufacturer are already extensive and complex.

> **The Product Environmental Footprint – PEF is also based on the quality and timeliness of underlying data.**

The "special process" of adhesive bonding[266] is formally regulated by a comprehensive quality management system according to ISO 9001. Its transfer to adhesive bonding technology applications is specified in standards for the organisation of adhesive bonding technology processes.[267] This requires that the process or material-related data records generated for this purpose are based on clearly visible and clearly defined metadata records "from the cradle to the factory gate" and thus remain manageable.

The graphic shown in Figure 63 is inspired by a hierarchically staggered flat "automation pyramid". The graphic is a modified and extended three-sided building. It represents key personnel such as the adhesive bonding supervisors[268], material operands such as the parts to be joined and the adhesive bonding system, and human and machine operators such as adhesive bonders or adhesive application tools in the adhesive bonding process in one form. In addition, a time axis in the direction of the transformation of the material is integrated into the footprint. The human-ma-

266 K. Brune, Adhaesion – kleben & dichten 2015, 5, 14–16, Anwender muessen umdenken.

267 A. Groß, H. Lohse In Dichtungstechnik Jahrbuch 2016; K-F. Berger, S. Kiefer (Hrsg.); ISGATEC gmbH: Mannheim / Silber Druck oHG: Niestetal, 2015; S. 399–410, Qualitaetssicherung – die neue DIN 2304 und ihr Nutzen fuer die Praxis

268 Compare citations 40 und 71

chine interaction (also known as human-machine-interface, HMI) runs clearly across the two side surfaces of the building shown in the sketch. Environmental impacts are shown over the third building surface, which is hidden in the sketch. The communication channels to this area include, for example, those involved in occupational safety or operational environmental management in accordance with DIN EN ISO 14001 [269]. Hierarchical structures are found both in the decision-making responsibilities of the personnel and in the networks of the cyber-physical systems. These also serve to record and evaluate data collected in the process, such as quality assurance during the process, which is evaluated by the decision-makers.

From a technical point of view, adhesive bonding technology users are aware of the necessity of holistic considerations: Aspects of the product life cycle phase "development" must be taken into account as early as the product life cycle phase "utilisation". When implementing the core element "verification" of the adhesive bonding technology QA standards [270], it must be demonstrated that over the entire product life cycle "utilisation" of an adhesively bonded joint, the real stresses that occur are always less than its maximum load-bearing capacity.[271] Consequently, during the planning and design phase, significant decisions are made with a view to the entire product life cycle [272], relevant properties for the durability of the joint, which is significant in terms of utilisation, for its reparability and for the disposal phase are specified and the data for this are documented. It is important that these decisions

269 DIN EN ISO 14001:2015-11, Environmental management systems – Requirements with guidance for use, Beuth-Verlag: Berlin, 2015

270 A. Paul, DICHT!, 2017, 1, 28 – 29, DIN 2304 – das bedeutet sie in der Praxis.

271 A. Groß, H. Lohse, Konstruktion, 2016, 1, Qualitaetsanforderungen an Klebprozesse.

272 R. Ariffin, R. Ghazilla, Z. Taha, S. Yusoff, S. Hanim, A. Rashid, N. Sakundarini, International Journal Advanced Manufacturing Technolology 2014, 70, S. 1403–1413, Development of decision support system for fastener selection in product recovery oriented design; DOI 10.1007/s00170-013-5373-3.

be made in advance of the product life cycle phase "manufacture" of an adhesively bonded product. → see Fig. 62[273]

The awareness for holistic considerations of adhesively bonded products, which has long been anchored at the technical level, must be projected onto the ecological level.

From an environmental point of view, this forward thinking should be applied to Design for Environment (DfE)[274, 275]. Particularly in the case of long product life cycles, such as in the construction, aviation or rail vehicle sectors, reliable documentation and an unambiguous description of the repair and end-of-life concepts envisaged in the life cycle scenario when designing the joints proves to be indispensable. Particularly in the case of repair, maintenance or renovation, the construction industry is faced with correspondingly individual, predominantly manual and local (i. e. highly decentralised) work. Today, these works can be recorded by means of different LCA approaches, even though, according to a current overview, different studies do not uniformly accentuate different aspects.[276]

Design for Environment (DfE) must be applied to adhesively bonded products.

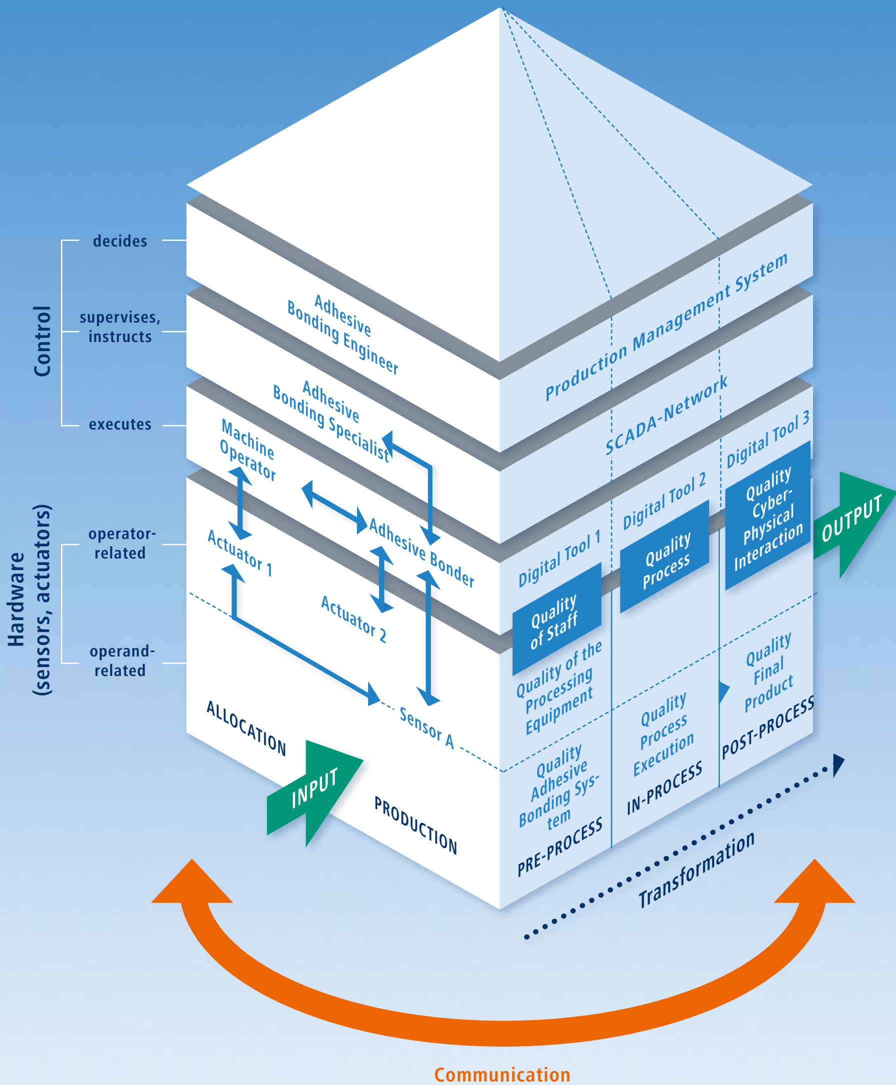
273 M. Noeske, W. Leite Cavalcanti, H. Bruening, B. Mayer, A. Stamopoulos, A. Chamos, T. Krousarlis, P. Malinowski, W. Ostachowicz, K. Tserpes, K. Brune, R. Ecault; in: Adhesive Bonding of Aircraft Composite Structures – Non Destructive Testing and Quality Assurance Concepts (Ed.: W. Leite Cavalcanti, K. Brune, M. Noeske, K. Tserpes, W. Ostachowicz, M. Schlag); Springer International Publishing, 2020; ISBN 978-3-319-92809-8.

274 T. J. O'Neill; "Life Cycle Assessment and Environmental Impact of Polymeric Products"; Rapra Review Reports, Volume 13, Report 156; Rapra Technology Limited: Shrewsbury, UK, 2003, ISBN 1-85957-364-9.

275 J. Fiksel; "Design for the Environment"; McGraw-Hill Education: New York, USA, 2011, ISBN 978-0071776226.

276 A. Vilches, A. Garcia-Martinez, B. Sanchez-Montanes; "Life cycle assessment (LCA) of building refurbishment: A literature review"; Energy and Buildings 2017, 135, S. 286–301; http://dx.doi.org/10.1016/j.enbuild.2016.11.042.

PRODUCT LIFE CYCLE PHASE „PRODUCTION“



The availability of FAIR data concepts can make a significant and transparency-increasing contribution in the course of developments in the digital transformation:

- On the one hand, it influences groundbreaking decisions of developers or manufacturers for the optimisation of the design.
- On the other hand, it makes the repair and end-of-life scenarios planned and implemented in the product design or the most probable product-related usage scenarios more precisely comprehensible for the environmentally conscious user, thus reducing the remaining uncertainties of these two product life cycles.[270]

From a technical point of view, for example, corresponding material-related aspects can be recorded online with integrated sensors (see also Chapters 5.6.3 – 5.6.6) over the entire material product life cycle.[277] From the perspective of product design, it is to be expected that the megatrends of individualisation, personalisation and "holistic orientation towards the customer" will be accompanied by market requirements that are determined before the manufacturing phase. The holistic focus on the customer makes the desire for product diversification and adaptation to individual customer requirements visible in not only the construction and automotive industries, but also in the electronics and packaging sectors[278]. Adhesive bonding technology solutions enable the necessary agile and flexible production and "end-of-life" material recycling. This applies, for example, when joining with target group-specific designed joining parts for the implementation of optical elements of the same technical core is desired within the framework of a modular product structure (see also chapters

Left: Fig. 63
Process steps in quality-assured adhesive bonding technology and interactions between people and physical or digital components

277 M. Huebner, H. Schaefer, K. Koschek, W. Lang; IEEE SENSORS October 2019, S. 1 – 4, Online monitoring of shape memory polymers with a material integrated flexible interdigital sensor; doi: 10.1109/SENSORS43011.2019.8956514.

278 B. Koelmel, T. Pfefferle, R. Bulander In Dialogmarketing Perspektiven 2018/2019, Tagungsband 13. Wissenschaftlicher interdisziplinaerer Kongress fuer Dialogmarketing (Deutscher Dialogmarketing Verband e.V., Hrsg.), Springer Fachmedien: Wiesbaden, 2019, S. 243 – 260, Mega-Trend Individualisierung: Personalisierte Produkte und Dienstleistungen am Beispiel der Verpackungsbranche; https://doi.org/10.1007/978-3-658-25583-1 (Access April 30, 2020)

5,2.6, 5.3.1–5.3.4, 5.4, 5.5). Fig. 64 shows this in the top view of a three-sided building, which, in accordance with DIN EN ISO 14040, represents "a life cycle inventory of inputs and outputs" over the entire product life phase in terms of environmental aspects.

> **Adhesive bonding technology solutions enable skillful and adapted productions as well as "End of Life" recovery.**

Here it becomes apparent that a repair, material disposal or recycling requires organisational effort. How a product is used and sent for its "end-of-life" recovery determines a large part of its environmental impact (see Fig. 65). Both can only be predicted to

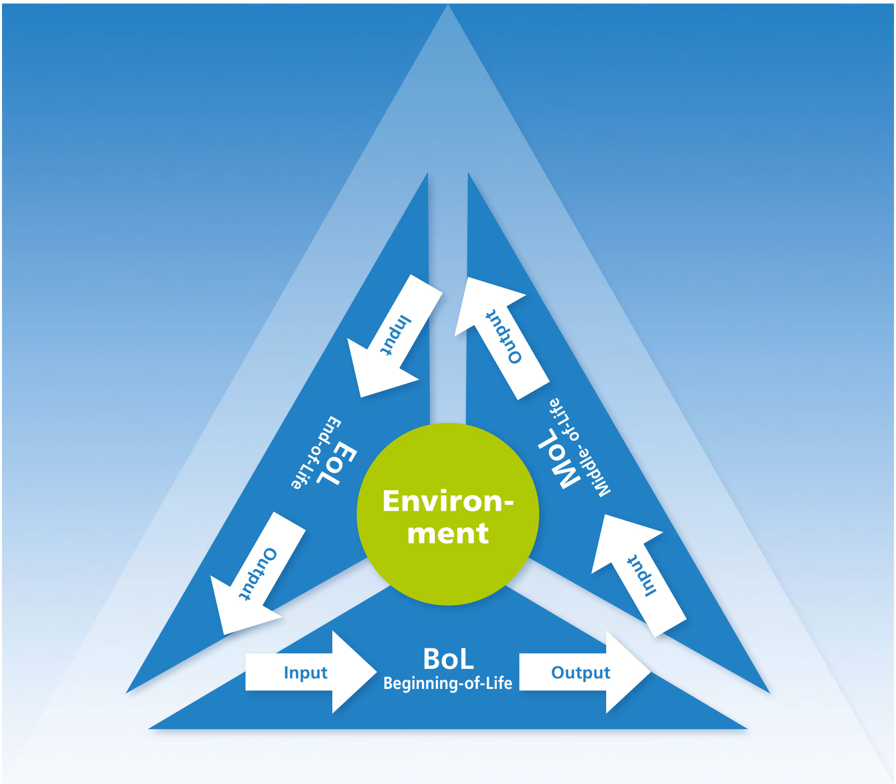
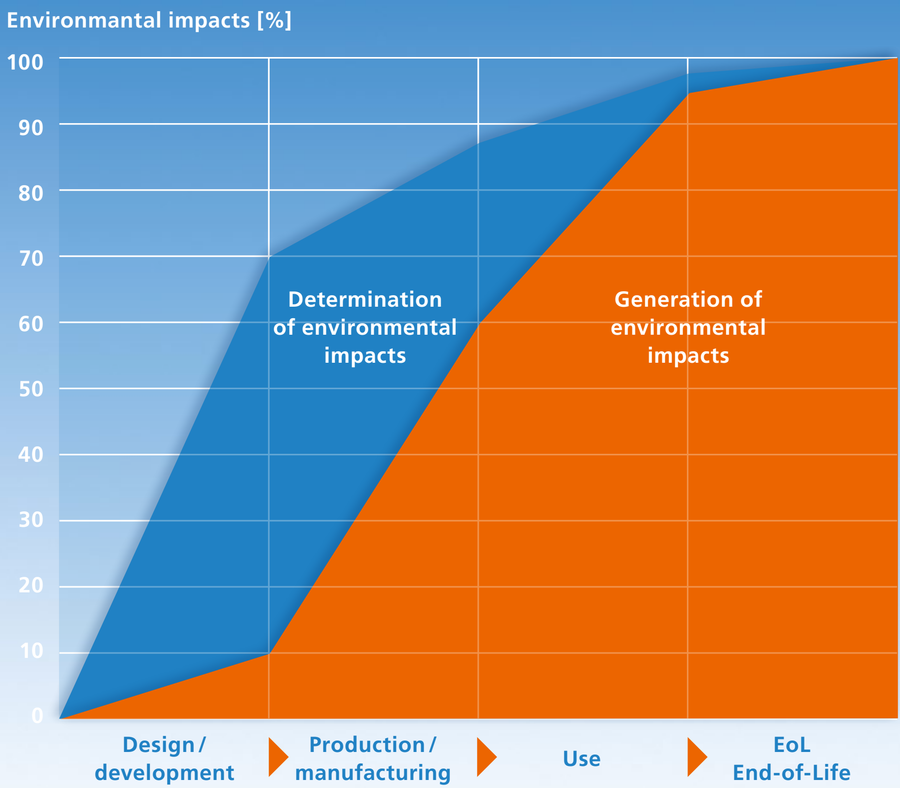


Fig. 64
Generation-spanning, environmentally conscious circular economy



a comparatively small extent in product design, as Rebitzer et al. also noted graphically.[279] This means that the end consumers of adhesively bonded products are also key stakeholders who must actively adopt this product life cycle phase for a circular economy.

Fig. 65
Determination of the environmental impact of a product along its life cycle

> **The consumer is also involved in the product life cycle phase "disposal".**

279 G. Rebitzer, T. Ekvall, R. Frischknecht, D. Hunkeler, G. Norris, T. Rydberg, W.-P. Schmidt, S. Suh, B. P. Weidema, D. W. Pennington, Environment International 30, 2004, 5, S. 701–720, Life cycle assessment Part 1: Framework, goal and scope definition, inventory analysis, and applications.

3.4 Product Environmental Footprint (PEF) and Environmental Product Declaration (EPD) – tools to identify the most appropriate option for determining the circular economy efficiency of adhesively bonded products

3.4.1 Product Environmental Footprint (PEF)

Creating a complete LCA is particularly time-consuming and costly if comparative statements are to be made on the relative environmental friendliness of two products P1 and P2. For small and medium-sized enterprises (SMEs) in particular, this represents a "major challenge".259 Even if two products P1 and P2 of two companies C1 and C2 belong to the same product group, both companies have degrees of freedom in determining their assumptions. The design of these assumptions depends on the exact respective question and objective that the companies decide on in the first LCA step when defining the objective and the scope of the study.

Comparative statements on the relative environmental friendliness of two products are complex.

Although the DIN EN ISO 14040 and 14044 series of standards lays down basic rules for the holistic consideration of all relevant environmental effects in all life cycle phases, subjective decisions remain. If there is still much consensus on which types of environmental pollution should be considered in the factual balance sheet, then a mathematically possible weighting of identified environmental aspects is "not foreseen at this stage.[259] A decision-making orientation in Germany offers recommendations from the Federal Environment Agency with regard to "order (ranking) of effect categories" from 1999[280].

The difficulty of comparable decision making using life cycle based digital tools lies in the fact that the decision path scenario is not always carried out in the same way. For example, Pareto optimisations (see Chapter 3.2) allow for multi-attribute analyses. These analyses for the comparison of two functionally identical products – e. g. of C1 for product P1 and C2 for product P2 – would offer a mathematical weighting of identified and quantitatively recorded environmental aspects.

> **The difficulty of comparative statements lies in inconsistently executed scenarios.**

However, both companies are given subjective scope for decision-making, which means that the weighting of environmental aspects would not be handled in a uniform manner. Despite uniform metrics for the individual aspects, objective comparability of the relative environmental friendliness of the products P1 and P2 on the basis of an aggregated total value would at least be considerably more difficult. The reason is that due to the above-mentioned subjective scope for decision making during the data-based decision-making process, it is likely to be optimised in different ways.

This applies eben more to the consumer. He would like to compare the products P1 and P2 and finds two well-founded, albeit differently weighted, statements from companies C1 and C2.

280 S. Schmitz, I. Paulini; "Bewertung in Oekobilanzen Methode des Umweltbundesamtes zur Normierung von Wirkungsindikatoren, Ordnung (Rangbildung) von Wirkungskategorien und zur Auswertung nach ISO 14042 und 14043 Version ´99"; Berlin, 1999; downloadable from http://www.umweltbundesamt.de (Access April 30, 2020)

The consumer wants to reliably compare two products.

Against this background, the result of an LCA study of three polyurethane-based adhesive technologies (solvent-based, aqueous and powder-based / see chapter 3.3)237 was not a ranking based on all environmental impacts achievable when used in the footwear industry. It was an identification of technological optimisation options for each of the three technologies, in itself based on the insights gained for each individual environmental impact aspect.

The Product Environmental Footprint – PEF should make comprehensible environmental comparisons possible.

In contrast, the Product Environmental Footprint – PEF is intended to enable comparative environmental statements of two functionally identical products P1 and P2 to be made in a comprehensible manner. The PEF guideline provides for the definition of product group specific accounting rules (PEF category rules, PEFCR). The target group for the PEF are "producers, manufacturers and traders in the food and non-food sector, and here in particular small and medium-sized enterprises".259 The principles and procedures from the standard DIN EN ISO 14025:2011-10 [281] contain basic rules which also apply to the establishment of the PEFCR.

Note: PEF category rules – no cold coffee with adhesives and adhesively bonded joints

As became apparent after the end of the pilot phase of the PEF, which lasted from 2013 to 2019, according to a survey by the European Commission [282], specifications were reached in about 90 % of the consortia during the limited period of the pilot projects. The white spot

281 DIN EN ISO 14025:2011-10, Environmental labels and declarations – Type III environmental declarations – Principles and procedures (ISO 14025:2006).

282 An overview is downloadable from https://ec.europa.eu/environment/eussd/smgp/ef_pilots.htm (Access April 30, 2020)

in the list of PEFCR drafts prepared within the tight time frame was, of all things, the one that would have had the goal of measuring the Footprint of a cup of coffee in a standardized way. In this case, tasks arose for the elaboration of PEFCRs, the accomplishment of which will take several years, because here in the food sector highly individually obtained, processed and consumed natural products have to be considered and several possible sub-categories have to be completely covered.249 In particular, individual consumer behaviour in coffee consumption often proves to be the proverbial reading in the coffee grounds for manufacturers of roasted coffee products.

The work of the technical secretariat responsible for defining product group-specific accounting rules (PEFCR) is still ongoing. In the example of the pilot coffee project, which involved coffee roasters, producers' associations and packaging manufacturers as well as other stakeholders, a number of "very fundamental and highly complex issues "249 were crucial. On the one hand, "the conversion to resource-efficient, environmentally friendly and socially acceptable coffee cultivation is the main challenge facing the coffee sector. In addition, according to S. Dierks, contributors to the technical secretariat promised themselves that "the project could contribute to the expansion and improvement of the existing data pools and method sets". Conversely, several challenges arose due to the diversity and sometimes lack of data availability at the source. These included the natural environment, agricultural systems or the processing up to the transport to the roasting plant; unknown customer preferences in the preparation of the coffee drink from different roasted coffee products; and the numerous possibilities in the composition of coffee specialities (mixed with milk or sweeteners). Accordingly, three approaches discussed in the technical secretariat of the PEFCR pilot project "Coffee" according to S. Dierks were:

- the compilation of a comprehensive data set on coffee cultivation and processing, whereby individual roasted coffee products can be mixed products that vary according to the harvest for taste reasons;
- a partial exclusion of the use phase in the PEF calculation and labelling, because ultimately individual customer behaviour during preparation also determines the PEF;
- the development of different sub-category rules to reflect the different preparation options.

Adhesive manufacturers are very familiar with the sources of their material suppliers and their own processes, adhesive bonders carry out adhesive bonding work in a quality assured and traceable manner. Users of adhesively bonded products make known their expectations and habits in handling the products. Nevertheless, this approach is subject to constant change, because the product producer and user are keeping up with the times.

With regard to category rules (PEFCR) for the PEF of adhesives and in particular adhesive bonding technology products, it is necessary that these rules be drawn up promptly. They make a significant contribution to the standardisation of recording of the environmental impact of products manufactured using joining technologies, joining materials and joining processes for adhesive manufacturers, adhesive users and users of adhesively bonded products. The PEFCR, which was successfully developed in the pilot phase of the PEF completed in 2019, can be found, for example, for material compounds, such as shoes, batteries and accumulators or thermal insulation, which are usually at least partially joined using adhesive bonding technology.

> **The category rules (PEFCR) for adhesively bonded products must be drawn up promptly for comprehensible environmental comparisons.**

For the following reasons, it is beneficial not to focus on the adhesive used, but on the adhesively bonded end product as a whole:

1. As a rule, the amount of adhesives in the adhesively bonded end product is low.
2. Focusing on the adhesive bonder would disregard the effects on the ecological balance sheet (see chapters 1.3, 1.5, 1.7.2, 1.10, 2.5.3 – 2.5.5, 2.7), which make adhesive bonding in the end product possible in the first place, and would falsify the assessment of the end product.
3. Available sample EPDs of adhesives and sealing materials for the construction sector support this argumentation.[283, 284]

> **The adhesive itself is not the focus of the environmental considerations of adhesively bonded products.**

283 https://ibu-epd.com/veroeffentlichte-epds (Access April 30, 2020)

284 https://www.feica.eu/our-priorities/edps (Access April 30, 2020)

Table 1 summarises the requirements for defining the most relevant contributions. This relevance consideration is carried out in the so-called "screening" during the development of the PEFCR in order to consider the relevant indicators, substances, materials etc. in the PEF analyses. With respect to the LCA, it is the adhesively bonded materials (joining partners) of the end- product under consideration for the product life cycle phase "disposal" ("End of Life"). The adhesive is not the decisive factor.

Table 1
Summary of requirements to define the most relevant contributions

Object of the assignment	**At what level must relevance be identified?**	**Threshold**
Most relevant impact category	Normalised and weighted results	Impact categories that cumulatively account for at least 80 % of the total environmental impact (without toxikological impact categories)
Most relevant life cycle phases	For each of the most relevant impact category	All life cycle stages that contribute more than 80% to this impact category
Most relevant processes	For each of the most relevant impact category	All processes that contribute more than 80 % to this impact category
Most relevant Elementary flows excluded for the pilot phase)	For each of the most relevant elementary flow and each relevant impact category	All elementary flows, that contribute more than 80 % to this impactcategory

Guidelines for the preparation of PEF categorisation rules (PEFCR) are provided by the European Commission in regularly updated versions.[285, 286]

As soon as applicable PEFCRs have been developed, the steps in a PEF study follow the procedure of a life cycle assessment.[259] Detailed explanations can be found on the websites of the Federal Environment Agency[214] or the European Commission[287], which also provides a presentation of a clearly presented PEF training course.[285]

An overview of the phases of a PEF study is shown in Figure 66. This also illustrates the cost and time saving facilitations that are possible after a preceding, coordinated and standardizing development of PEFCR. Thanks to their unique standardisation, they allow the environmental impacts of each individual product in a product category to be recorded in a comprehensible manner.

In the following, the graphically depicted steps and interrelationships are considered in more detail.

The objectives to be defined in the first step of an individual PEF study define the intentions pursued and the breadth and depth of the consideration.[286, 287] These include

- the intended applications of the study (e. g. provision of product information to a customer)
- the reasons for implementation (e. g. preparation of a response to a customer enquiry)

285 European Commission, PEFCR Guidance document, – Guidance for the development of Product Environmental Footprint Category Rules (PEFCRs), version 6.3, December 2017; downloadable from https://eplca.jrc.ec.europa.eu/permalink/PEFCR_guidance_v6.3-2.pdf (Access April 30, 2020)

286 Training on Product Environmental Footprint European Commission, Brussels, 13 and 14 January 2014; downloadable from https://ec.europa.eu/environment/eussd/smgp/pdf/PEF-training.pdf (Access April 30, 2020)

287 Product Environmental Footprint (PEF) Guide, Deliverable 2 and 4A of the Administrative Arrangement between DG Environment and the Joint Research Centre No N 070307/2009/552517, including Amendment No 1 from December 2010; Ref. Ares (2012) 873782 – 17/07/2012 .

- the target audience (e. g. an external and technically skilled target group in the context of business relations between companies)
- the decision whether to publish the study
- the commissioner of the study
- a possibly desired review of the study (e. g. by external experts).

The PEFCRs relevant for this stage specify the requirements for testing a PEF study.

In each PEF study, a product category is defined for an adhesively bonded product under investigation. This makes it clear which other products, possibly with different compositions, can be considered comparable and by the consumer as an alternative to this product.[214] Product classification is carried out in the relevant PEFCR study framework using the NACE/CPA[214] code (Statistical Classification of Products by Activity (CPA). The categories of products refer to the economic activities defined in the Statistical Classification of Economic Activities in the European Community (NACE). This PEFCR framework defines the representative product and the PEFCRs specify the unit(s) of analysis to be covered for each product category and their level of detail.

> **The PEF approach compares adhesively bonded products with the average environmental impact of the assigned product category.**

The PEF approach therefore compares the environmental impacts of a specific product, for example adhesively bonded, with the average environmental impacts of the associated product category, regardless of the joining method. The products under consideration are outlined with a product model in such a way that this comparison can be achieved in relation to a category-typical reference point (benchmark) of an ecologically average product within the scope of the investigations. It can be assumed that the average environmental impacts of the product category are essentially embodied by the environmental impacts of the product with the highest market share. The result of the PEF study would be, for example, the comparative statement that product P1 is more environmentally friendly than the average product.

> **Possible PEF result: Product P1 is more environmentally friendly than the average product.**

In the second step of the PEF study of an individual product, the scope and application area of the study, the system to be evaluated and the analytical specifications required for it are defined. In case of a function-based approach, as also regulated in DIN EN ISO 14025 [281], the functional unit and the reference flow are defined. Four aspects are defined to derive the former:

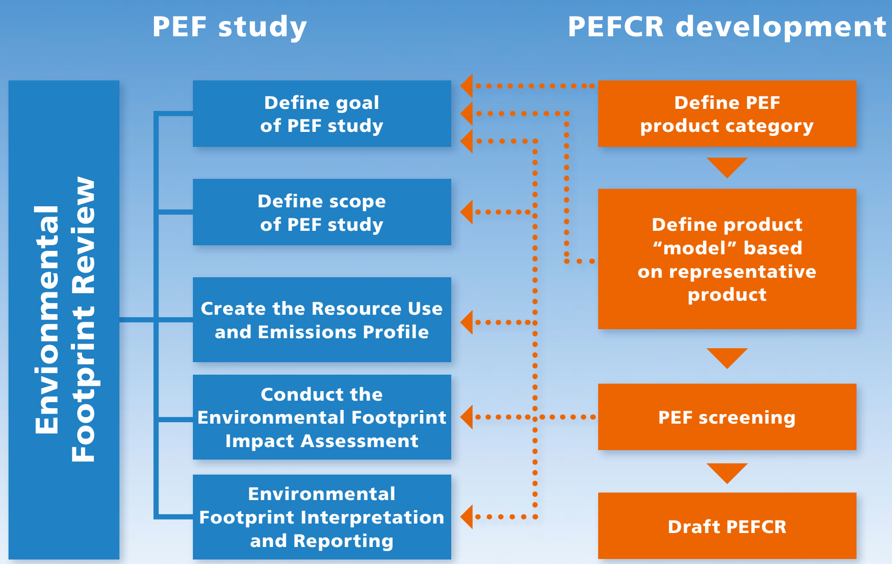
- Which function and use should the investigation unit perform (what)?
- What is the scope of function and use (how much)?
- What quality is expected of the examination unit (how good)?
- What resistance and durability should the product have (how long)?

Note

In the illustrative PEF-Training [286], exactly one mattress of average size is given as an example, which is to be used daily for more than ten years and is to remain dimensionally stable. A quantitative description of product performance is often a challenge, but comparative qualitative descriptions are easier. For example, a mattress should make it "comfortable" to lie on, or a detergent should make laundry "clean".

Secondly, as far as the reference flow is concerned, this is the quantity of product that must be available to fulfil the functional unit [214], i. e. in the examples considered 11 kg spring mattress or 75 millilitres of liquid detergent with the packaging used.

In establishing the resource use and emission profile, quantifying the life cycle inventory in the third step of a PEF study, data is collected and the material flows are recorded as input and output for all life cycle phases.[268]



For the impact assessment that follows in the fourth step, environment-related impact categories listed in Table 2 with associated impact indicators are used.[216] In addition, "additional environmental information" may be relevant, such as the impact on biodiversity, which cannot yet be quantified using recognised life cycle-based impact categories.[268] The PEFCRs drawn up for the respective product category make it possible here to focus uniformly on the most important environmental impacts during the most relevant life cycle phases[286], whose selection and weighting do not tend to influence the result of the investigation.[268]

The PEFCRs, which are designed specifically for each product category, enable a focus on the most important environmental impacts during the decisive product life cycle phases.

Fig. 66
Phases of a PEF study[286]:

- **Definition of the objectives**
- **Definition of the scope of the investigation**
- **Preparation of resource use and emission profile (life cycle inventory)**
- **Impact assessment**
- **Evaluation and reporting and their relation to the previous, one-off and coordinated development of PEFCR**

Table 2
Environmental impact categories and associated impact indicators for impact assessment in a PEF study

Impact category	Impact indicator
Climate change (total, biogenic, land use and transformation)	Increase of infrared radiation
Stratospheric ozone depletion	Ozone depletion potential
Human toxicity, carcinogenic and non-carcinogenic	Comparative Toxic Unit for humans
Eco-toxicity, fresh water	Comparative Toxic Unit for ecosystems
Fine dust	Effects on human health, ratio of particulate matter intake
Ionising radiation	Human exposure efficiency related to U^{235}
Photochemical ozone formation	Increase in trophospheric ozone
Acidification, terrestrial	Cumulative exceedances with regard to acidifying effects
Eutrophication, terrestrial	Cumulative exceedances with regard to eutrophication
Eutrophication, aquatic	Percentage of phosphorus nutrients entering the fresh water compartment
Eutrophication, aquatic	Proportion of nitrogen nutrients entering the marine compartment
Land use	Soil quality index[288], biotic production, erosion resistance, mechanical filtration, groundwater recharge, changes in soil organic matter

288 V. De Laurentiis, M. Secchi, U. Bos, R. Horn, A. Laurent, S. Sala, Journal of Cleaner Production 2019, 215, S. 63–74, Soil quality index: Exploring options for a comprehensive assessment of land use impacts in LCA; https://doi.org/10.1016/j.jclepro.2018.12.238 .

Impact category	Impact indicator
Water consumption	Potential restrictions for future users, water use related to local water scarcity
Resource use, minerals and metals	Abiotic resource depletion ($ADP_{ultimative\ reserves}$ or $ADP_{reserve\ base}$)
Resource use, fossil	Abiotic resource depletion (ADP_{fossil}) Abiotic resource depletion ($ADP_{reserve\ base}$)

Characterisation models are required and stored so that any impact indicator that quantitatively describes the environmental footprint can be specified as the result of a PEF study. These are calculation models which are used to convert the Life Cycle Inventory results into the common unit of the impact indicator. They must be developed in the following way that they are robust in practical application.[268] In the PEFCRs, the essential impact factors are then to be discussed, defined and considered in a subsequent study.

A version of the 2018285 circular footprint formula (CFF) for products is a combination of material, energy and disposal contributions, as shown in Figure 67. A corresponding approach was introduced in chapter 2.5. In the modular version of this formula, CFF-M for short, the onera occurring during product manufacture is listed first, which are taken into account when looking from the cradle to the factory gate. The parameters used are considered below.

First of all, reference should be made to the modular version of this formula, CFF-M for short, in Figure 68, in which the onera occurring during product manufacture are listed at the top, which are taken into account when looking from the “cradle to the factory gate”.

MATERIAL

$$(1-R_1)E_V+R_1\times\left(AE_{recycled}+(1-A)E_V\times\frac{Q_{Sin}}{Q_P}\right)+(1-A)R_2\times\left(E_{recyclingEOL}-E^*_V\times\frac{Q_{Sout}}{Q_P}\right)$$

ENERGY

$$(1-B)\,R_3\times(E_{ER}-LHV\times X_{ER,heat}\times E_{SE,heat}-LHV\times X_{ER,elec}\times E_{SE,elec})$$

DISPOSAL

$$(1-R_2-R_3)\times E_D$$

Fig. 67
The circular footprint formula (CFF) [285]

The additional information is then summarised by the End-of-Life (EoL) life cycle phase. These include contributions to onera and benefits from the input or output of secondary materials, energy recovery and disposal (see also chapter 2.5.1).

In the cyclical Footprint formula, two dimensionless allocation factors appear: A from a value range between 0.2 and 0.8 and B, which should have the default setting "zero" ("0") in PEF studies. The other parameters are described in Table 3.

Production Burdens $(1-R_1)E_V+R_1\times E_{recycled}$ **Cradle-to-gate**

Burdens and benefits related to secondary materials input

$$-(1-A)R_1\times\left(E_{recycled}-E_V\times\frac{Q_{Sin}}{Q_P}\right)$$

Burdens and benefits related to secondary materials output

$$(1-A)R_2\times\left(E_{recycledEoL}-E^*_V\times\frac{Q_{Sout}}{Q_P}\right)$$

Enegy recovery

$$(1-B)R_3\times\left(E_{ER}-LHV\times X_{ER,heat}\times E_{SE,heat}-LHV\times X_{ER,elec}\times E_{SE,elec}\right)$$

Disposal

$$(1-R_2-R_3)\times E_D$$

Fig. 68
Modular form of the cyclical footprint formula (CFF-M)[285]

Table 3
Parameters in the cyclical footprint formula

Parameter	Description
A	Allocation factor for onera and benefit when comparing two life cycles with the aim of reflecting market conditions; usually $0.2 \leq A \leq 0.8$
B	Allocation factor for energy recovery processes; default setting $B = 0$
Qs_{in}	quality of incoming waste material, i. e. the quality of recycled material at the point of substitution
Qs_{out}	quality of the outgoing waste material, i. e. quality of the recyclable material at the point of substitution
Q_p	quality of the basic material, i. e. quality of the raw material
R_1	Percentage of material in production input that is reused from a previous system
R_2	Percentage of product material that is recycled (or reused) in a subsequent system; R2 should take into account inefficiencies in collection and recycling (or reuse) processes. R2 should be measured at the exit of the recovery facility.
R_3	Proportion of product material used for energy recovery in the EoL phase
$E_{recycled}$ (E_{rec})	specific emissions and resources consumed per functional unit resulting from the recycling process of the recycled material, including collection, sorting and transport processes
$E_{recyclingEoL}$ (E_{recEoL})	specific emissions and resources consumed per functional unit resulting from the recycling process in the EoL phase, including collection, sorting and transport processes
E_v	specific emissions and resources consumed per functional unit resulting from the introduction and pre-treatment of virgin material

Parameter	Description
E_{*v}	specific emissions and resources consumed per functional unit resulting from the input and pre-treatment of virgin material assumed to be substituted by recyclable material
E_{ER}	specific emissions and resources consumed per functional unit resulting from the energy recovery process (e. g. incineration with energy recovery, landfill with energy recovery).
$E_{SE,heat}$ and $E_{SE,elec}$	emissions and resources consumed per functional unit that would have resulted from the specific substituted energy source, for heat and electricity
ED	specific emissions and resources consumed per functional unit resulting from the disposal of residues in the EoL phase of the analysed product, without energy recovery
$X_{ER,heat}$ and $X_{ER,elec}$	Efficiency of the energy recovery process for heat and electricity
LHV	lower heating value of the product material used for energy recovery

The complexity of the environmental footprint (PEF) illustrates – also for adhesively bonded products – the importance of developing digital tools.

The complexity of determining the PEF (product environmental footprint), which is revealed in these calculation rules, once again makes it clear how much impetus the progress in the development of digital tools is experiencing and will continue to receive with increasing dynamism in the future. Responsible corporate action is supported by clear, standardized procedures for determining product environmental impacts. On the basis of available and well-founded information, these actions can be communicated to people who see themselves increasingly less as consumers and more and more as equally responsible stakeholders, using comprehensible parameters. After all, regional and global markets are being driven by increasingly networked and thinking people.

Standardised, traceable procedures for determining the environmental impact of adhesively bonded products support responsible corporate action.

3.4.2 Environmental Product Declaration (EPD)

An Environmental Product Declaration (EPD) is a Type III eco-label (→ see Fig. 69) that provides and communicates environmental information about the product life cycle in a neutral way.[289] On a quantified basis, such an EPD documents environment-related information about the product life cycle. It allows comparisons between functionally identical products or so-called "declared units", e.g. per kg. It is based on independently verified and DIN EN ISO 14040 [281]-compliant data from life cycle assessments, life cycle inventories or information modules. In view of the different EPD programmes186[290] in use around the world, users or consumers can compare products in terms of their environmental impact if their LCAs are based on the same Product Category Rules (PCRs). These rules contain specific guidelines and requirements for the development of a life cycle assessment. Environmental indicators for different impact categories along the product life cycle are generated parameter by parameter and included in the EPDs together with other environmental information. The European plastics industry association (PlasticsEurope)[291] and the Federation of the European adhesive bonder and sealant industry

289 D. Fischer, greenBUILDING 2017, Sonderausgabe BAU, S. 18 – 21, Umweltkennzeichnungen – eine Typfrage!. https://www.greenbuilding-magazin.de/fileadmin/user_upload/greenBUILDING/BAU2017/gB_BAU17_018.pdf (Access April 30, 2020)

290 M. D. Bovea, V. Ibáñez-Forés, I. Agustí-Juan; "7 – Environmental product declaration (EPD) labelling of construction and building materials"; in: Eco-efficient Construction and Building Materials Life Cycle Assessment (LCA), Eco-Labelling and Case Studies, Woodhead Publishing Series in Civil and Structural Engineering; Woodhead Publishing, 2014, Pages 125 – 150; https://doi.org/10.1533/9780857097729.1.125

291 PlasticsEurope, Brussels / Frankfurt /London / Milan / Paris, Life Cycle Thinking, https://www.plasticseurope.org/en/resources/eco-profiles (Access April 30, 2020)

(FEICA)[292] have developed EPD methodologies on this basis.[293]
→ see Fig. 69[294]

Environmental Product Declarations (EPDs) document quantified environmental information about the product life cycle and enable comparisons between functionally identical products or so-called “declared units”.

Model EPDs for adhesives inevitably focus on the adhesive itself.

Where relevant, a typical EPD contains information on the environmental impact of an adhesive and, ultimately, of an adhesively bonded product in terms of impact categories such as global warming, ozone depletion, water pollution, ozone formation and greenhouse gas emissions. EPDs help adhesive manufacturers, adhesive users and users of adhesively bonded products to understand the sustainability-related properties and environmental impacts of a product more thoroughly. Developers are provided with criteria for environmentally conscious material selection. Manufacturers can communicate the environmental performance of their products in a reliable and transparent way. Users can compare adhesively bonded products with the environmental specifications required of them, making it easier to make a purchase decision.

The amount of adhesive in an adhesively bonded product is usually rather low.

292 FEICA; Brussels https://www.feica.eu (Access April 30, 2020)

293 FEICA, Brussels, https://www.feica.eu/our-priorities/edps (Access April 30, 2020)

294 J. Laso, M. Margallo, P. Fullana, A. Bala, C. Gazulla, A. Irabien, R. Aldaco, MethodX 2017, 4, S. 143–152, Aiding eco-labelling and its implementation: Environmental Impact Assessment Methodology to define Product Category Rules for canned anchovies.

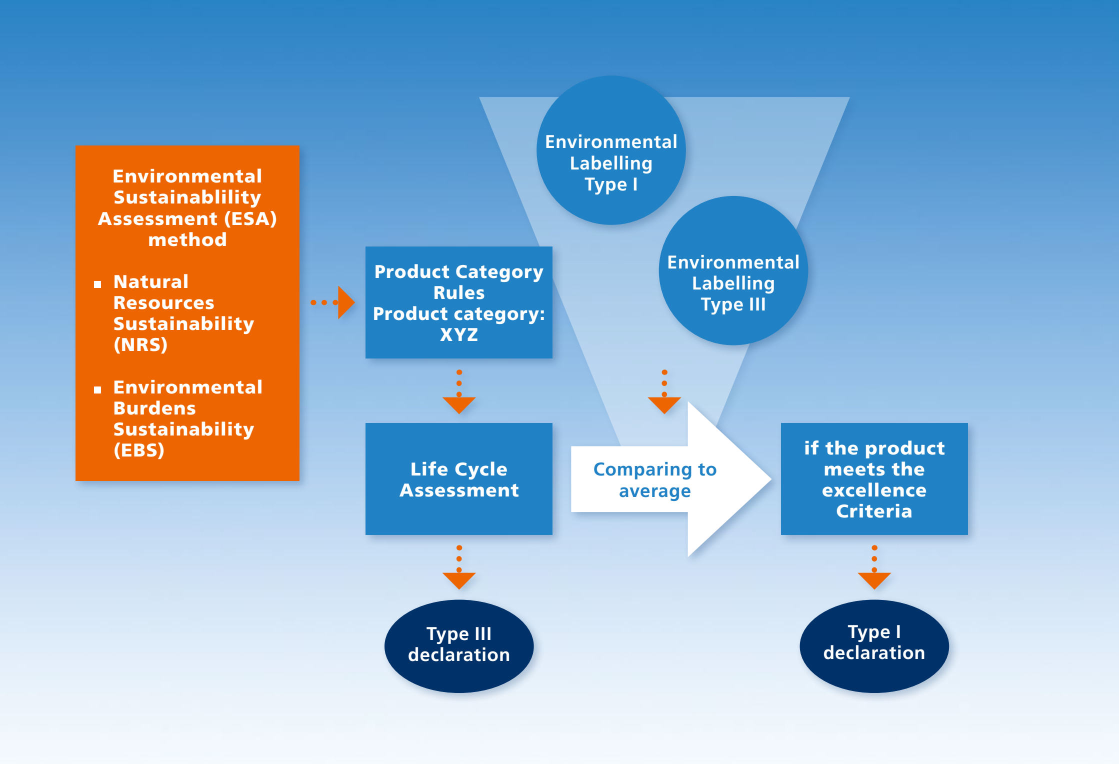


Fig. 69
Combination of Type I and Type III eco-labels using the Environmental Impact Assessment (ESA) method to define Product Category Rules (PCRs)

For the various industrial sectors (see Chapter 3.1) sustainability criteria have been or are being introduced which must be met on the basis of sound environmental data. For building products and the construction sector, basic rules for the preparation of EPDs are laid down in DIN EN 15804.[295] It is of course possible for an adhesive manufacturer to prepare and publish an EPD on this basis with a corresponding effort. This is also done in individual cases.[296] The present Model EPDs[297] for construction adhesives and coatings are a pragmatic response to the necessary effort and inflexibility involved. In contrast to the Standard EPDs, which would have to be developed for each individual adhesive product, which would be disproportionate with 33,000 different adhesives (see Chapter 1.8), and to Average EPDs, which are unsuitable for adhesives because the chemical composition is very different, even within an adhesive

295 DIN EN ISO 15804:2014-07, Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products, Beuth Verlag: Berlin, 2014

296 https://ibu-epd.com/veroeffentlichte-epds (Access April 30, 2020)

297 https://www.feica.eu/our-priorities/edps (Access April 30, 2020)

class, such Model EPDs are suitable for adhesives. These Model EPDs have been developed in a cradle to gate approach based on product category rules298, for example for reactive resin products. On this basis, FEICA published Model EPDs for several product categories. 299 Model EPDs do not specifically cover individual products in detail; instead, a worst case scenario is considered for an entire product category. In the case of house construction or renovation, environmental impacts determined based on this scenario are included in the LCA of a building as a contribution to the LCA of all building products and materials used.

> **The development of Standard EPDs for each adhesive would be disproportionate given the variety of adhesive products and the low adhesive content in the adhesively bonded product.**

Example construction industry: [300]

The environmental friendliness, resource conservation or sustainability of certain products or materials depends largely on the buildings in which they are used. An igloo is typically built manually using only snow as a building material. Snow is natural, environmentally friendly and fully recyclable. Therefore, snow as a building material and the igloo are ecologically sustainable. However, this only applies under certain conditions. If an igloo were to be built in other climate zones, the production and import of the building material snow would require a great deal of energy and the igloo would melt after a short time if the snow is not cooled or permanently replaced.

This highly simplified example clearly shows why building products are not end products and why their impact on the environment depends largely on how, where and for what they are used. Therefore, at first glance, environmentally friendly building materials are no guarantee of sustainability. This is the reason for EPDs: they contain the data needed to calculate and assess environmental impacts in a specific case. EPDs in this context are based on life cycle assessments for building products. They sum up and analyse the environmental impacts of a specific product over its life cycle from raw material extraction to the ready-to-install product (cradle-to-gate) and also include processes and factors

298 https://www.ul.com/offerings/product-category-rules-pcrs

299 FEICA, Published European Core Model EPDs for adhesives and sealants, https://www.feica.eu/our-priorities/edps (Access April 30, 2020)

300 Institut Bauen und Umwelt – IBU, https://ibu-epd.com/was-ist-eine-epd (Access April 30, 2020)

related to the product, such as packaging and transport. Increasingly, other phases of the product life cycle are also taken into account, such as the product life cycle phases “utilisation” and “disposal”. LCA’s do not provide a single key figure or evaluation, but rather depict a large number of different environmental influences such as greenhouse gas emissions, the influence of acid rain, smog formation, consumption of fossil resources and water or the recycling share individually. This information on largely all environmental impacts enables sustainable solutions to be found. Essentially, the life cycle assessment of a building consists of the life cycle assessments of all building products and materials used and the energy consumption during the product life cycle phase “utilisation”. The environmental impacts of a complete building can be viewed and calculated holistically from the extraction and production of the materials, through the construction and product life cycle phase “utilisation”, to the product life cycle phase “disposal” (deconstruction of the building).

From an ecological point of view, calculating the building ecobalance during its planning phase enables the comparison of different materials and concepts and building optimisation. As the example “igloo” shows, the direct comparison of different building products and their life cycle assessments is usually not very useful. In building LCA’s, however, their comparison is an essential basis for the planning of sustainable buildings. For this reason, LCA’s are mandatory in some certification systems for sustainable buildings (e. g. the German Sustainable Building Council).[301]

Due to their optimised energy efficiency, modern buildings consume less energy in the product life cycle phase “utilisation”, which leads to an overall lower overall energy demand. This leads to a shift in the percentage of energy used in the product life cycle phases “utilisation” and “production” in the total energy requirement and thus also in the environmental impact of the building. In the case of a “zero-energy building”, the product life cycle phase “manufacture” would account for the total environmental impacts.

Life cycle planning in the construction industry can be supported by utilisation of the buildingSMART ontology[302], which combines the building information model, environmental data, data from the geographic information systems (GIS) and product information from a material database in an interlinked and sophisticated way, as shown in Figure 70.

301 Deutsche Gesellschaft fuer Nachhaltiges Bauen (DGNB), https://www.dgnb.de/de/verein/system (Access April 30, 2020)

302 H. Bell, L. Brørkhaug In ECPPM 2006: European Conference on Product and Process Modelling 2006: eWork and eBusiness in Architecture, Engineering and Construction Valencia, Spain, September 13 – 15, 2006; Manuel Martinez, Raimar Scherer. Hrsg.; CRC Press: Boca Raton, (Florida (USA), A buildingSMART ontology”.

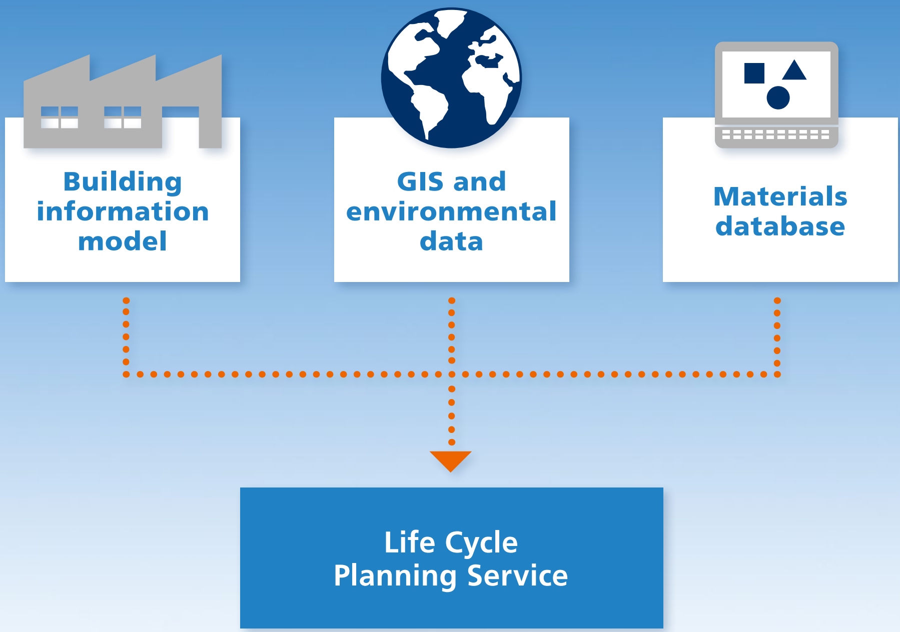


Fig. 70
Contributions to life cycle planning in the buildingSMART ontology

3.4.3 Comparison: Product Environmental Footprint (PEF) and Environmental Product Declaration (EPD)

EPDs in general are generally only suitable for a direct product comparison due to different data compression levels (granularities) if they have been prepared according to the PCRs of the same program operator. The above examples refer exclusively to adhesive classes for the construction industry. This system makes sense in this context, because the manufacturer of adhesives for the construction sector cannot know how and where exactly the house is built in which his adhesive is used. He can therefore only make statements about his material, which is part of the supply chain from the perspective of house construction.

> **EPDs are usually only suitable for direct product comparison.**

There are several different approaches to producing EPDs. For this reason, the GWP values of different EPD considerations are not comparable.[303] The approaches for the construction sector represent a special case for the functional unit chosen by IBU299. This accepted and verified system consists of established category rules (CR) that define the impact categories to be considered. This consideration is done individually for each impact category. The selection of the category rules is based on ISO 14025 (see Chapter 3.4.1) in the same way as the PEFCR, and from the user's point of view, agreement on a uniform procedure and harmonisation is necessary here. This should avoid, for example, inconsistencies in the case of several PCRs for the same product category or confusion among product users in the case of "similar-but-different" methods[304, 305, 306, 307].

The decisive factor in all cases is the FAIRe availability, accessibility and interoperability of the underlying data sets, which are discussed in Chapter 5.6.4 as the digital environmental twin. Whether these are then communicated in the sense of an eco-label, by a set of characteristics (as in an LCA or an EPD) or by an aggregated characteristic value to technically less interested users, is ultimately a question of the progressive awareness raising among material users. Model EPDs, which do not underestimate

303 F. Pacheco Torgal, L. F. Cabeza, J. Labrincha, A. Giuntini de Magalhaes; Eco-efficient Construction and Building Materials: Life Cycle Assessment (LCA), Eco-Labelling and Case Studies; Woodhead Publishing Series in Civil and Structural Engineering; Woodhead Publishing: Cambridge (UK), 2014; ISBN 0857097725, 9780857097729

304 N. Minkov, L. Schneider, A. Lehmann, M. Finkbeiner, Journal of Cleaner Production 2015, 94, S. 235–246, Type III Environmental Declaration Programmes and harmonisation of product category rules: status quo and practical challenges.

305 A. Del Borghi, L. Moreschi, M. Gallo, International Journal Life Cycle Assess 2019; Communication through ecolabels: how discrepancies between the EU PEF and EPD schemes could affect outcome consistency; https://doi.org/10.1007/s11367-019-01609-7 (Access April 30, 2020)

306 V. Durão, J. Dinis Silvestre, R. Mateus, J. de Brito, Resources, Conservation & Recycling 2020, 156, Assessment and communication of the environmental performance of construction products in Europe: Comparison between PEF and EN 15804 compliant EPD schemes; 104703.

307 E DIN EN 15804/A2:2018-04, Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products, Beuth Verlag, Berlin, 2018

the environmental impacts of products in view of the worst-case scenarios, allow manufacturers, for plausible reasons, to take a streamlined look at each individual product with its corresponding diversified requirements.

> **The view beyond the adhesive to the adhesively bonded product is mandatory.**

An extended view beyond the adhesive to the bonded product is necessary, since the joining technology adhesive bonding fulfils further environmentally relevant functions beyond simply joining parts to be joined (see Chapters 1.5, 1.7.2, 1.10, 2.5.2–2.5.4, 2.7) and thus makes a decisive contribution to the circular economy and ecological balance.

Example: transport construction

In rail vehicle construction, manufacturers[308, 309, 310, 311, 312] make environmental product declarations available for their products manufactured using adhesive bonding technology, in which the product life cycle properties of adhesives are taken into account. The same applies to the automotive industry. The Volvo S80 1998 was the first car to receive an EPD.[313] Since 1998, the manufacturer has published an EPD

308 Environmental Product Declaration AZUR; Bombardier Transport, St-Bruno, QC, Canada, 2015.

309 Environmental Product Declaration DT5, Bombardier ALSTOM; https://www.alstom.com/sites/alstom.com/files/2018/07/12/alstom_dt5_metro_hamburg_-_environmental_product_declaration_-_aug_2013 (Access April 30, 2020)

310 Coradia Polyvalent Environmental Product Declaration, , ALSTOM, https://www.alstom.com/sites/alstom.com/files/2018/07/14/m-csr-18-Environmental Product Declaration – Coradia Polyvalent (Access April 30, 2020)

311 Inspiro, Siemens Mobility, https://assets.new.siemens.com/siemens/assets/api/uuid:87d8b8c66bd41961a415b2fa8318bca0f80458df/version:1492092654/metro-inspiro-environment-declaration-en.pdf (Access April 30, 2020)

312 Life Cycle Analysis of Stadler Eurodual Locomotive Valencia, Stadler Rail, https://www.ik-ingenieria.com/en/life-cycle-assessment-lca/project-life-cycle-analysis-eurodual-locomotive-stadler-valencia (Access April 30, 2020)

313 Volvo Car Germany GmbH, https://www.volvocars.com/de/volvo/innovationen/forschung-und-entwicklung (Access April 30, 2020)

for each new car model, the information of which is based on an LCA and supplemented with information on environmental management systems and recycling.[314] The declarations have been verified by third parties and comply with the ISO 14040, ISO 14031, ISO 14021 and ISO 14001 standards, focusing on the three aspects of the product life cycle: "manufacture", "utilisation" and "disposal".[315] The aspects of material use in production, greenhouse gas emissions in use, and the labeling and reuse of plastics in recycling are particularly material-related. Dealers and suppliers are also involved in environmental management. EPDs are also available for this manufacturer's trucks, the quality of which depends largely on the quality of the input data, for example with regard to the material resources used or intended for repairs. The environmental impacts indicated are, for example, effects relating to greenhouse gas emissions/global warming, ozone layer depletion or acidification potential[316]. EPD data can be used to obtain data for the PCF, for example.[317]

Other car manufacturers are making environmental certificates available for their products, which also take into account the product life cycle properties of adhesives.[318] For example, Mercedes-Benz publishes product-related environmental information in accordance with EN ISO 14020 and EN ISO 14021, which includes adhesive-related information in the context of the relevant process polymers.[319]

314 E. Dahlqvist, A. Wendel, "LCA Working Procedures when Developing Environmental Product Declarations for Cars from Volvo," SAE Technical Paper 2001-01-3731, 2001, https://doi.org/10.4271/2001-01-3731.

315 Paul Niewenhuis, Peter Wells; The Automotive Industry and the Environment; Woodhead Publishing in environmental management; CRC Press, 2003; ISBN 0849320720, 9780849320729

316 European Commission DG Environment; Evaluation of Environmental Product Declaration Schemes; Final Report – Annex X: Examples of EPDs under the different schemes; September 2002.

317 X. Li, Possibilities for Volvo Trucks to Provide Carbon Footprint Information Derived from Environmental Product Declarations, Chalmers Technische Universitaet, Goeteburg, Schweden, 2009; ISSN No. 1404-8167.

318 Oeko-TREND-Zertifikat fuer vier BMW Group Modell emit vorbildlicher CO_2-Reduktion, BMW Group, https://www.press.bmwgroup.com/deutschland/article/detail/T0004475DE/oeko-trend-zertifikat-fuer-vier-bmw-group-modelle-mit-vorbildlicher-co2-reduktion?language=de (Access April 30, 2020)

319 Mercedes-Benz Modelle mit Umweltzertifikat, Daimler AG, https://www.daimler.com/nachhaltigkeit/umweltzertifikate (Access April 30, 2020)

In the future, adhesively bonded products will therefore have to be taken into account in all phases of their product life cycle, which is currently not yet the case in the EPDs of all those involved in the supply and disposal chains → see Fig. 71[320] (e. g. in the sense of a reverse logistic procedure[319, 321, 322]. Here the PEF would offer the advantage that the data sets collected in the LCA could be included in it (→ see Fig. 72).

> **In future, the entire adhesively bonded product and its entire product life cycle must be considered comprehensively.**

320 M. A. Sellitto, Journal of Cleaner Production 2018, 187, S. 923–931, Reverse logistics activities in three companies of the process industry.

321 C. Hans, K. A. Hribernik, K.-D. Thoben, International Journal of Product Lifecycle Management 2010, 4, S. 338–359, Improving Reverse Logistics Processes Using Item-level Product Lifecycle Management. https://doi.org/10.1504/IJPLM.2010.036488

322 J. Daaboul, J. Le Duigou, D. Penciuc, B. Eynard, Journal of Remanufacturing 2014, 4 (1), S. 1–15, Reverse logistics network design: a holistic life cycle approach.

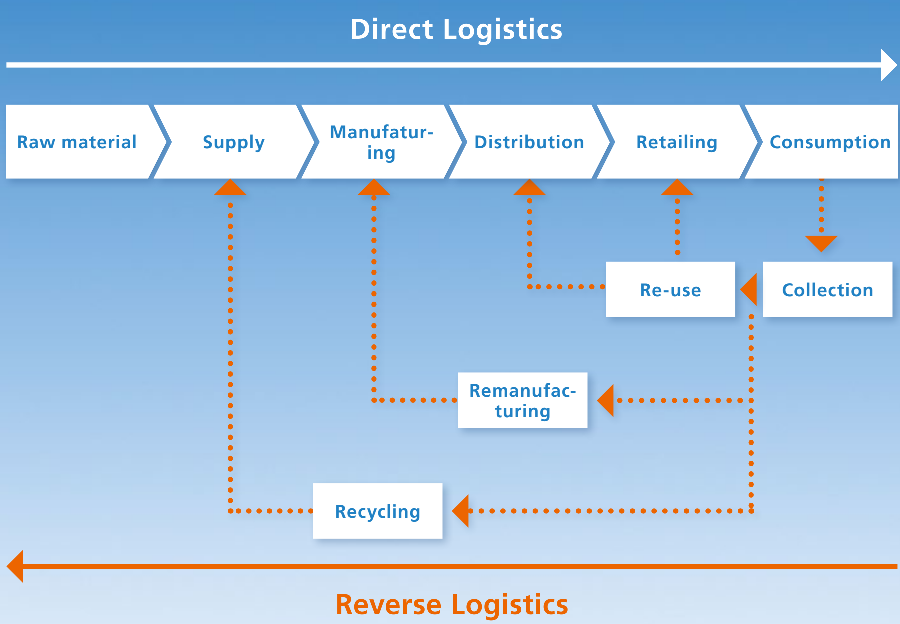


Fig. 71
Representation of material flows in return logistics at the end of product life

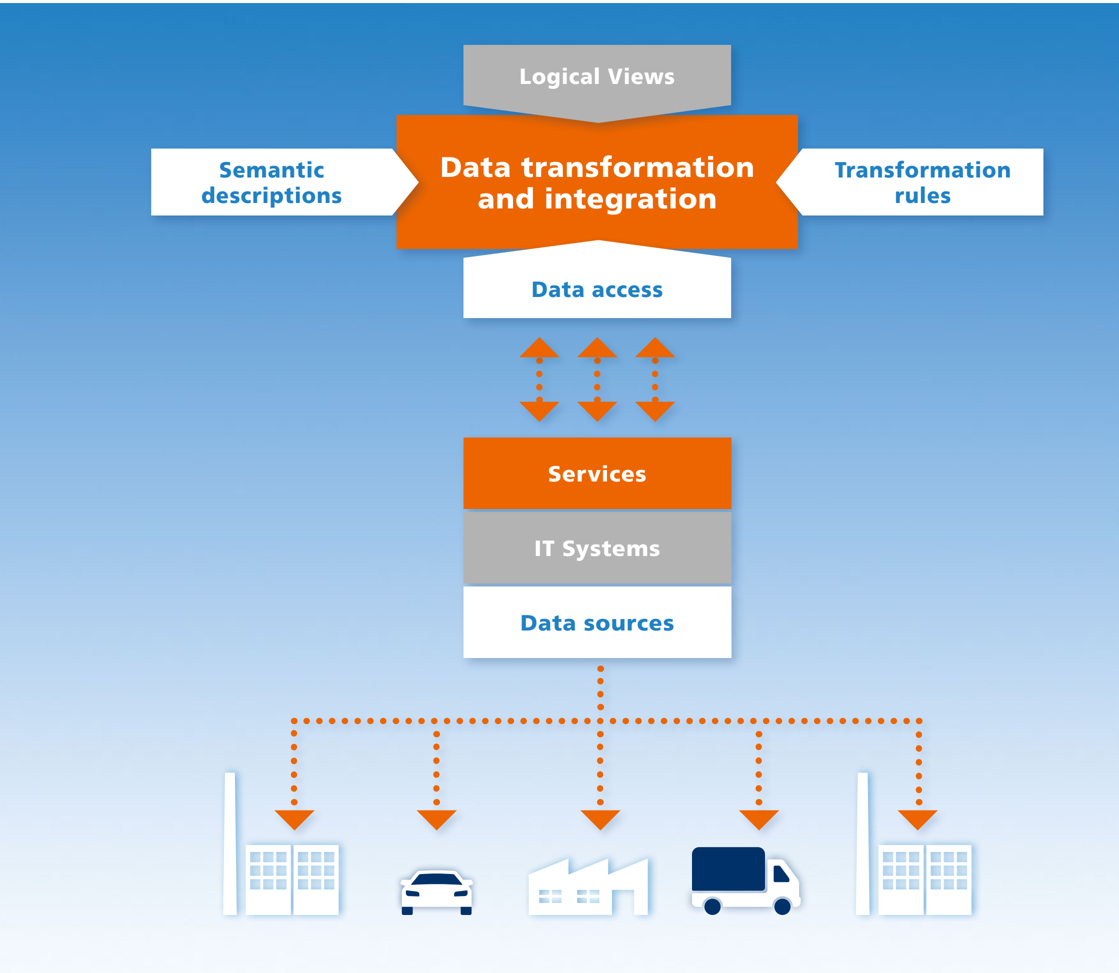


Fig. 72
Representation of the integrated data flow in the Product Life Cycle Management[320]

3.5 Sustainable business models thanks to the effectiveness of the circular economy of adhesively bonded products

Currently, business models that take into account changed market-relevant conditions are increasingly being recognised as a research topic. The results of such research work will continue to promote the circular economy efficiency of adhesively bonded products of the 21st century in the sense of a sustainable business idea. As shown in Figure 73, the perspective ranges from Sustainable Business Models (SBM)[323, 324] to closed-loop business models[325]. This shows the importance of this task and the diversity of the design potential. From a long-term perspective, new, sustainable business models for a circular economy include the proactive management of a wide range of interest groups (multi-stakeholder management) and the creation of monetary and non-monetary value.[325]

New business models include sustainability and monetary and non-monetary values.

323 S. Schaltegger, E. G. Hansen, F. Luedeke-Freund, Organisation & Environment 2016, 29(1), 3–10, Business Models for Sustainability: Origins, Present Research, and Future Avenues; DOI: 10.1177/1086026615599806.

324 N. Dentchev, Romana Rauter, L. Johannsdottir, Y. Snihur, M. Rosano, R. Baumgartner, T. Nyberg, X. Tang, B. van Hoof, J. Jonker, Journal of Cleaner Production 2018, 194, 695–703, Embracing the variety of sustainable business models: A prolific field of research and a future research agenda. https://doi.org/10.1016/j.jclepro.2018.05.156 .

325 M. Geissdoerfer, D. Vladimirova, S. Evans; Journal of Cleaner Production 2018, 198, 401–416, Sustainable business model innovation: A review; https://doi.org/10.1016/j.jclepro.2018.06.240.

At the same time, as shown in Figure 74, value networks are growing up. The decisive factor, also for adhesively bonded products, is the creation of sustainable utility values in economic, social and ecological terms.[326]

A sustainable business model helps a company to describe, analyse, manage and communicate in three ways: firstly, in terms of its value proposition to its customers and all other stakeholders; secondly, in the way it creates that value; and thirdly, in the way it gains economic value while preserving or recreating natural, social and economic capital beyond its organisational boundaries.322

> **Economic, social and ecological aspects are also decisive for adhesively bonded products.**

Based on empirical studies of practical example cases, the new perspectives range from theoretically and knowledge-based conceptual new approaches and focal points to the use of new ontologies for describing and structuring business models and the identification of multiple win-win potentials. The complexity of future decisions for a sustainable business success of adhesively bonded products is reflected in the multifaceted nature of new calculation models and the ontologies on which they are based. For example, the framework for a company's decisions is determined by the social and legal definition of its boundary conditions, is filled by systems within the company and is significantly influenced by the environment or ecosystem in which the company is embedded.[327] The decisive factor here is not so much the static structure of the framework and the system building blocks, but rather their mutual relationships and their dynamic developments.

326 S. Evans, D. Vladimirova, M. Holgado, K. Van Fossen, M. Yang, E. A. Silva, C. Y. Barlow, Business Strategy and the Environment 2017, 26, 597–608, Business Model Innovation for Sustainability: Towards a Unified Perspective for Creation of Sustainable Business Models; DOI: 10.1002/bse.1939.

327 A. Upward; P. Jones, Organisation & Environment 2016, 29(1), 97–123, An Ontology for Strongly Sustainable Business Models: Defining an Enterprise Framework Compatible with Natural and Social Science; DOI: 10.1177/1086026615592933.

The players involved in holistically designed, manufactured and handled adhesive bonding technology products are aware that adhesive manufacturers and recyclers, as part of the adhesive application ecosystem, must network even more closely with the adhesive user in order to master the design tasks. Within the framework of a multi-stakeholder management of each network partner, a product-oriented, joint and holistic approach along the life cycle of adhesively bonded products can develop. The decision-makers in research & development, adhesive production and adhesive application have a creative scope for the further development of their business models in the expected further development and gradual change of social, political or technical framework conditions and markets. This will increasingly be characterized by thinking, exchange and action in networks.

> **In the future, adhesive manufacturers and recyclers will have to network even more closely with the adhesive users.**

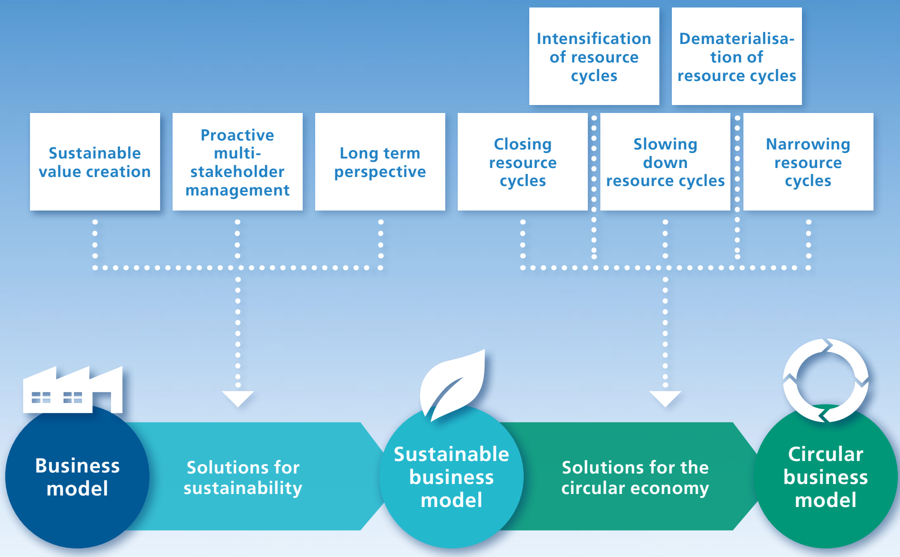
Note

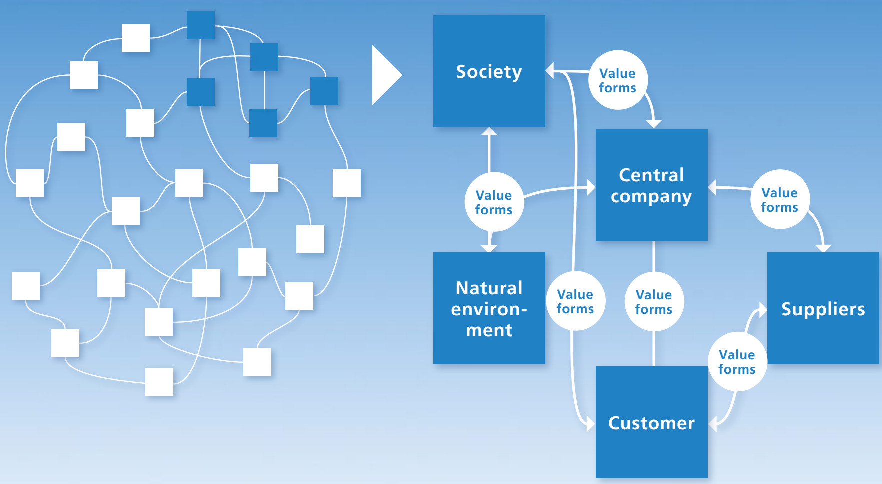
The interplay of several drivers on the way to the development of sustainable technologies in Europe is illustrated by the example of smart grids. Particularly in the case of renewable energies, smart grids serve to manage the coordination between the fluctuating supply of electrical energy and the demand, which fluctuates equally in terms of time and location. On the one hand, the balancing of electricity flows is basically a similar challenge as the control of material flows. On the other hand, it is obvious that a guaranteed availability of electrical energy that is also cheaper and comes from renewable sources will have a direct and profound impact on both the life cycle assessment and the cost balance of material products. The beginning and end of life can be redesigned using this energy. The sketch shown in Figure 75, which provides a view of processes in future material-based networks, was inspired by processes in decision-maker networks in which changes are currently being driven forward on the European energy market. Attentive observation of these driving forces has an illuminating effect on the development prospects for adhesive bonding technology products.

Right, top: Fig. 73
Future development towards sustainable and cycle-orientated business models[325]

Right, bottom: Fig. 74
Future development towards sustainable value networks[326]

Today it is clearly foreseeable that the legal framework conditions for material flows will also change towards a cycle orientation in an intelligent network (→ see Fig. 75). It is becoming increasingly


Intensification of resource cycles
Dematerialisa-tion of resource cycles
Sustainable value creation
Proactive multi-stakeholder management
Long term perspective
Closing resource cycles
Slowing down resource cycles
Narrowing resource cycles
Business model
Solutions for sustainability
Sustainable business model
Solutions for the circular economy
Circular business model


Society
Value forms
Central company
Value forms
Value forms
Natural environ-ment
Value forms
Value forms
Suppliers
Value forms
Customer

apparent that, given the global positioning of EU policy, significant changes will take place in the medium term.

Business models for adhesively bonded products will increasingly be shaped by thinking, exchanging and acting in networks.

Adhesives manufacturers are preparing for new challenges posed by the circular economy by intensive communication within the respective value chains, especially with customers and recyclers. Technical innovations or changes in the business model are to be initiated.[328] The ability in terms of technical flexibility, adaptability and innovation has already been proven in the past with many new requirements. Examples of this with regard to constantly increasing regulatory requirements are the reduction or replacement of certain substances (e. g. from the group of solvents, plasticisers, monomers and biocides). → see Fig. 75[329]

Adhesive manufacturers have already demonstrated their flexibility, willingness to adapt and innovative ability in the past.

Society and politics are formulating new sector-specific framework conditions for sustainability and the circular economy, for example. These are to be aligned holistically and not focused on individual aspects (see Chapter 2.5.1 – 2.5.5). Adhesives development in research & development and in the adhesives industry has the potential to develop and offer technically suitable solutions within given legislative and ecological boundary conditions, which lead to measurably optimised solutions in a Life Cycle Assessment

328 M. Bulmahn, Nachrichten aus der Chemie (May) 2020, 68, 42, Verklebt und ausgewaschen.

329 M. E. Biresselioglu, M. Nilsen, M. H. Demir, J. Røyrvik, G. Koksvik, Journal of Cleaner Production 2018, 198, 417 – 429, Examining the barriers and motivators affecting European decisionmakers in the development of smart and green energy technologies; https://doi.org/10.1016/j.jclepro.2018.06.308.

(LCA) over the product life cycles "production", "utilisation" and "disposal" of adhesively bonded products.

> **Research & Development and the adhesives industry have the potential to develop suitable solutions with an impact on the ecological balance sheet.**

The task of the adhesives industry is to meet new requirements, especially with regard to the circular economy, with suitable solutions for the specific industry. The necessary adaptability and efficiency of adhesive bonding technology and adhesive development to design adhesively bonded joints that are compatible with the ecological balance sheet has already been demonstrated by the key personnel involved in research & development and the adhesives industry with many examples (see chapters 1.7.2, 2.5.3–2.5.5, 2.6–2.7, 4.2–4.6).

> **The efficiency of adhesive bonding technology and adhesive development is already proven today.**

FORMAL SOCIAL UNIT

THE EU

- Clear Definition of Smart Energy Technology
- Consider member states individually and adopt suitable action
- Consider resources of each country when developing policies
- Transparent unternational/EU standards
- Provide generic and common actions to all the schemes (EU-28)
- Update of communication directives on environmental issues
- Governance and organisational structure

↕

MEMBER STATES

- Policies and regulations
- Consider interoperability of Smart Material Networks
- Encourage new technologies
- Specify policy for specific technology
- Consider the view of new and small actors
- Consistent and long-term
- Avoid ad-hoc policies
- Encourage eco-friendly behaviour
- Market regulation
- Consider household behavioural patterns
- Incencitives, taxes, subsidies
- Resource provision, support
- Rights of recourse for installations
- Measure to reduce uncertainty/risks for industries
- Improve infrastructure to supprt environment-friendly behaviour

↕

REGIONAL

- Strengthen local neworks
- Common vision, level of activity
- Types of organisations
- Develop trust and community acceptance
- Clarify confusions, provide information
- Involve the public and local communities
- Improve communication
- Word choice, examine opposition, expression
- Plan over various periods
- Highlight benefits in smart technology
- Fosters social justice, well-being
- Climate change mitigation
- Increase environmental awareness
- Use of voluntary agreements as a policy measure
- Facilitate quick and efficient negotiations betwenn infrastructure developers and local groups
- Active marketing strategies
- Information communicated should be locally relevant
- Consider the demographics in policy development

UNIT FOR COLLECTIVE DECISION MAKING

INDIVIDUALS

RESEARCHY / ACADEMY

- Institutional embeddednes of systems
- Resource efficiency solutions and oppotunities
- Analysis of the market, policies and regulations
- Interaction of system and individuals
- Reduce the research gaps

INDUSTRY

- Industry role of prosumer
- Increase focus on end-users
- Awareness of user-system interaction
- Look beyond short-term financial criteria
- Identify challenges and develop an approach based on company size, activity, sector and ownership structures
- Improve energy service, trust and information to end-users

INDIVIDUALS

- Research on how systems become instituionally embedded
- Indentify solutions and possibilities for resource efficiency
- Analysis oft he market, policies, regulations in various levels
- Understanding the interaction of system and individuals
- Reduce research gap

LOCAL COMMUNITY

- Community involvement
- Community acceptance
- Cooperative networks
- Benefit-sharing methods
- Awareness and knowledge
- Materials and environment
- CO_2-neutrality
- Local resource initiatives

Fig. 75
Outlook on future political development towards sustainable smart material networks (along the lines of smart electricity networks)

4

Adhesive bonding technology and its function as a partner for fulfilling requirements within the framework of “circular economy” and “ecodesign”

4.1 Adhesive bonding technology and ecodesign: no contradiction

As already described in chapter 1, adhesives can be found in almost all products. Also in nature, adhesive bonding is the preferred joining technology. In order to achieve the greatest possible product safety, technical adhesively bonded joints are designed for high durability. In many places, they may be oversized due to this safety concept. This is because the actual utilisation of products by the respective user may differ from the actually intended utilisation in real life, and thus the loads that occur are difficult to predict. In addition, from an ecological point of view, the service life of a product should be as long as possible, even if newer product generations, for example, have a higher energy efficiency, since new production often requires a greater input of energy and materials. The substitution of the still fully functional "old product" by that of the newer generation does not lead to any ecological savings effect when viewed holistically.

For product safety reasons, technical adhesively bonded joints are designed for high durability.

However, in terms of the circular economy, disassembly is also necessary at a given point in time to separate different materials and reuse them at the highest possible value-added stage. This applies equally to all joining technologies between different materials.

This chapter deals with the apparent contradiction between longevity, safety and durability on the one hand and separability on the other. One can also speak here of the "controlled longevity" of a product. What is meant by this is that one has control over the integrity of the joint for a given, predictable period of time and can then detach it in a controlled manner. Although all adhesively bonded joints can already be released at the end of a product's life (see chapter 2.6), previous adhesively bonded joints were rarely designed for the above-mentioned "controlled longevity" approach, which combines the control of product integrity with the control of material separation.

> **The "controlled longevity" of an adhesively bonded product combines the control of product integrity with the control of material separation.**

The status of this concept is explained in this chapter. At the same time, it will be shown what research is needed to improve the products of industry, trade and daily life both with the help of adhesive bonding technology from an ecological and an economic point of view.

4.2
Detachable adhesively bonded joints

The possible contradiction of the common view of “detachable” and “non-detachable” joints has already been pointed out in chapter 2.6. Even non-detachable joints can be separated in principle. The extent to which the materials of products can be separated according to type under consideration of ecological and economic boundary conditions depends primarily on the material purity of the products. This is also largely independent of the type of joining technology. However, questions of sorting logistics will not be addressed in this study.

Even non-detachable joining can be separated.

If a mixture of different end-of-life products is present, shredding with subsequent separation of the fragments is practically the only possibility of separation. However, the quality of the recycled material is correspondingly low.

If, on the other hand, similar products are available in large quantities, they can be automatically disassembled and sorted according to type. In principle, a disassembly line could be set up for each product. From today’s point of view, this extreme solution makes sense only for a few products due to the high development effort and requires consideration of the dismantling at the product design stage.

The targeted detachment of an adhesively bonded joint is a prerequisite for repair and dismantling as well as for recycling. Even though this is still a rare industrial practice, there is some scientific literature on the “debonding” of adhesively bonded joints. Many of the approaches cannot be considered for broad application per se due to high resource consumption, the need to use hazardous components in the adhesive or in the separation process. Similarly, the performance of the adhesively bonded joint is a possible exclusion criterion.

Targeted debonding is a prerequisite for repair, dismantling and recycling.

The following is an overview in which such "no go" criteria play no role. The study is primarily based on a recently published review article.[330] Statements that are not quoted elsewhere refer to this; these are combined with the authors' own practical experience. Since the early 1990s, scientists at the Fraunhofer IFAM have been repeatedly dealing with questions of repair and recycling of adhesively bonded products. This has always been uncritical under the conditions of the respective spirit of the time and was not considered a real issue in politics and society. Publications dealt with adhesively bonded electronics[331] and adhesively bonded products in general.[332]

The detachment of an adhesively bonded joint is caused by an external trigger that does not occur during normal use of the adhesively bonded joint and therefore does not affect the safe use of the adhesively bonded product. If necessary, two triggers are combined to prevent unintentional detachment in any case. This is shown schematically in Figure 76.

The universal but unspecific triggers are mechanical load and heat. These can be used to detach all adhesively bonded joints. Other triggers, which usually do not require an adhesive adapted

330 N. Schuewer, R. Vendamme In Green Chemistry Series No. 60, Green Chemistry for Surface Coatings, Inks and Adhesives: Sustainable Applications, R. Hoefer, A. Singh Matharu, Z. Zhang, Eds., RSC, London 2019, Chapter 13, 310–338, Debondable Adhesive Systems; https://doi.org/10.1039/9781788012997-00310.

331 A. Hartwig, R. Lueschen, F. Kriebel, T. Seidowski, O.-D. Hennemann, In Proc. Adhesives in Electronics 94, Berlin, Nov. 2–4, 1994, Comparison of soldered and adhesively bonded joints from the ecological point of view.

332 A. Hartwig, O.-D. Hennemann in VDI Berichte 1072 Fuegen im Vergleich – Feinbleche, VDI Verlag Duesseldorf 1993, S. 225–235, Recycling geklebter Materialverbunde.

specifically to them, are water and other media such as solvents, although detachment may take a long time. If necessary, superheated water in an autoclave or steam pot can be very helpful here. However, there are also adhesives that use very specific triggers, such as light with specific wavelengths, an applied electrical voltage or heating with microwaves or high-frequency fields. The effectiveness of the individual triggers depends largely on the composition of the adhesives.

> **The detachment of an adhesively bonded joint is realized via a trigger that does not occur in the product life cycle phase "utilisation".**

Other frequently cited concepts refer to weak or reversible chemical bonds built into the adhesive, so that they lose their strength at lower temperatures. At the same time, however, this is usually associated with lower thermal durability or a more pronounced tendency of the adhesively bonded joint to deform mechanically (especially creep, i. e. irreversible deformation under mechanical stress). For economic and ecological reasons, this can also be achieved in a simpler way, so that such concepts have so far been of academic interest. → **see Fig. 76**

Just as in the case of unintentional failure, the breakage of the adhesively bonded joint occurs either adhesively (i. e. between the part to be joined and the adhesive) or cohesively (i. e. in the adhesive) when the joint is deliberately detached.In order to prevent the surfaces from being soiled with old adhesive, which need not be a problem in the special case of replacing a windscreen, for example, the targeted loosening of the adhesively bonded joint is generally aimed at breaking the adhesion, i. e. the release of the adhesive from the surface of the part to be joined. Since the strength of the adhesive, and thus that of the adhesively bonded joint, can be controlled much better than the respective adhesion level, the mechanical design of an adhesively bonded joint has so far been based on safety reasons, with the aim of a cohesive fracture: the solidified adhesive tears and remains adhesively attached to the joined parts. "Rebonding" after detaching, i. e. rejoining using the same adhesive is almost never possible. As the current state of the

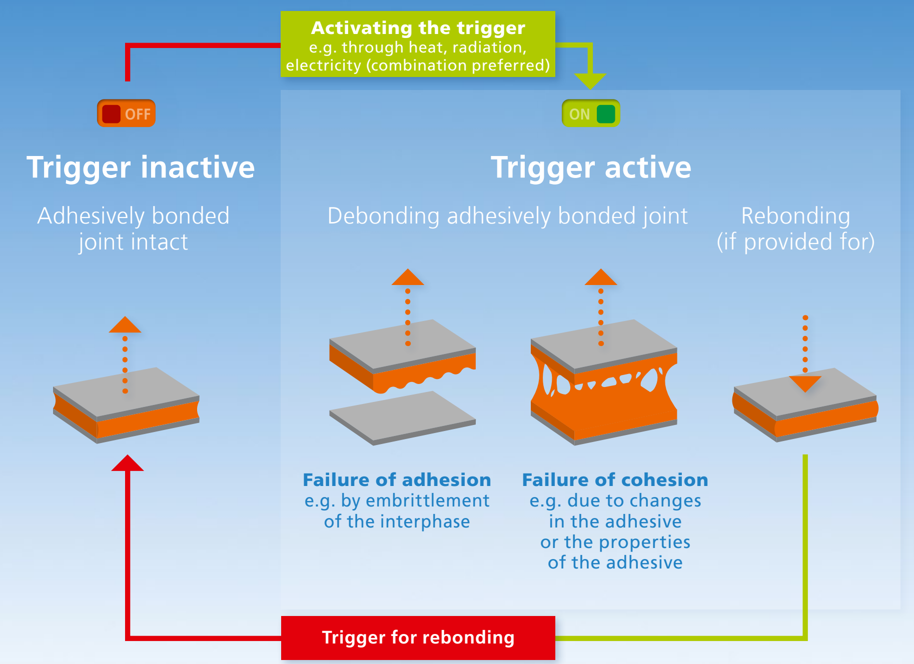


Fig. 76
Debonding due to a trigger leads to adhesive or cohesive detachment of the adhesively bonded joint. In rare cases, rebonding can be performed due to another trigger.

adhesive is unknown, this is not advisable for the usual technical products for the safety reasons mentioned above alone.

> **For product safety reasons, a controlled cohesive failure during separation of adhesively bonded products is sought.**

In this context, it should be noted that the amount of adhesive used is usually very small (see Chapter 3.4.1), so that material recycling of the adhesive itself would hardly have any ecological impact. A rebonding could be realized with hot melt adhesives, for example. If, for example, there were machines running that functioned with adhesive bonding technology, very frequent debonding and rebonding would be necessary for them to function efficiently. However, this is an exception and belongs in the realm of science fiction, at least today.

> **A material recycling of the adhesive itself would have no ecological impact.**

In nature, on the other hand, there are countless adhesively bonded joints for the most diverse purposes. These can be permanent or reversible. The adhesion of barnacles or mussels under water belongs to the first group. Joints of this kind, as in technology, can only be undone mechanically in a destructive way, and part of the adhesive remains on the substrate. The targeted detaching of permanently bonded joints with a specific debonding trigger does not occur in nature. In contrast, there are countless examples of reversible adhesively bonded joints in nature. These serve for example to catch prey or to walk on vertical surfaces or even overhead. Reversible adhesion can be achieved dry by van der Waals interactions, for example when the geckos move around or, as in the case of prey caught with the frog's tongue or sundew, by secretions.

As a rule, secretions also play a role in the locomotion of numerous insects. Very often, the adhesives are viscoelastic liquids [333], the composition of which is only known in very few cases. Often fats, fatty acids and carbohydrates are present, but occasionally proteins have also been detected.[334] Since the adhesives are a combination of polar, non-polar and amphiphilic substances, it can be assumed that the adhesives are often emul-

333 O. Betz, M. Frenzel, M. Steiner, M. Vogt, M. Kleemeier, A. Hartwig, B. Sampalla, F. Rupp, M. Boley, C. Schmitt, Biol. Open 2017, 6, 589–601, Adhesion and friction of the smooth attachment system of the cockroach Gromphadorhina portentosa and the influence of the application of fluid adhesives; doi: 10.1242/bio.024620.

334 O. Betz, A. Maurer, A. N. Verheyden, C. Schmitt, T. Kowalik, J. Braun, I. Grunwald, A. Hartwig, M. Neuenfeldt, Mol. Biol. 2016, 25, 541–549, First protein and peptide characterisation of the tarsal adhesive secretions in the desert locust, Schistocerca gregaria, and the Madagscar hissing cockroach, Gromphadorhina portentosa; doi: 10.1111/imb.12241.

sions with specific rheological behaviour.[335] During an analysis of adhesion and delamination during locomotion of the Madagascar fox cockroach it was found that due to the fluids and morphological structure of the tarsi ("feet"), a high shear strength is present as long as the tarsi are resting on the substrate, and if necessary, pressed down throughout a longer stay. However, as soon as the tare is unrolled in the next step, peeling forces are exerted which allow the joint to be undone practically without force.[336]

> **With adhesively bonded joints in nature, the detachment mechanism is already integrated.**

From a technical point of view, the detachment mechanism has thus already been taken into account in the design, and the viscoelastic adhesive supports it. It can be assumed that this is a general principle. In the form of the so-called Gecko® tape, the principle could also be technically reproduced, but without a fluid adhesive, which is also not found in the Gecko. The tape is made of elastic silicone and has a high density of micro-scale nubs (→ **see Fig. 77**[337]). It has a high shear strength, but peeling removes it little effort.

In recent years, a great deal of work has been published on polymers that change their structure when triggered from outside, especially when they degrade or lose their cross-linked character. In some of these studies, it was also investigated to what extent such reactions are suitable for reversible adhesively bonded joints. Schüwer and Vendamme cite numerous examples of this.330 One

335 M. W. Speidel, M. Kleemeier, A. Hartwig, K. Rischka, A. Ellermann, R. Daniels, O. Betz, Beilstein J. Nanotechnol. 2017, 8, 45–63, Structural and tribometric characterisation of biomimetically inspired synthetic "insect adhesives"; doi:10.3762/bjnano.8.6.

336 O. Betz, K. Albert, M. Boley, M. Frenzel, H. Gerhardt, I. Grunwald, A. Hartwig, M. Kleemeier, A. Maurer, M. Neuenfeldt, K. Rischka, B. Sampalla, C. Schmitt, M. Speidel, M. Steiner, N. Verheyden, M. Vogt, Mitt. Dtsch. Ges. Allg. Angew. Ent. 2018, 21, 159–164, Struktur und Funktion des tarsalen Haftsystems der Madagaskar-Fauchschabe Grompardorhina portentosa (Blattodea).

337 Gecko®-Tape: Company Gottlieb Binder / Figure Fraunhofer IFAM

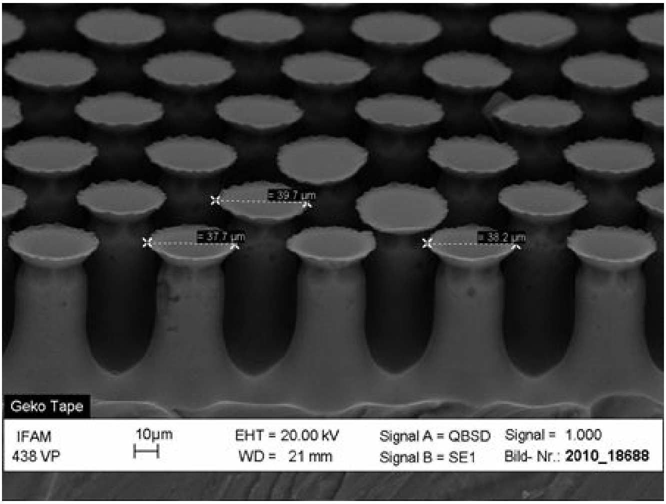


Fig. 77
Electron microscope image of the microstructure of Gecko®-Tape

possible trigger is irradiation with light. Here it must be limited that on the one hand the parts to be joined must be transparent for the necessary wavelength, on the other hand the respective light must be excluded during use to ensure the safety and longevity of the product. The weakening of the adhesively bonded joint is caused in particular by embrittlement of the adhesive or structural degradation.

There are also examples where instead of the adhesive itself, only a photodegradable primer layer, i. e. a kind of "precoat", which primarily improves the adhesion of the adhesive, is removed. The irradiation times described for the photodegradation of this layer range from a few minutes to many hours. For special repairs, a few minutes may still be acceptable, but longer times are not acceptable for practical applications. Together with the required special chemical composition of the adhesives, the aforementioned necessary transparency of the joined parts and the necessary durability under ambient conditions, it is easy to estimate that photochemical debonding for recycling and repair will not be used for mass products.

> **Different triggers can be used to detach adhesively bonded joints.**

Heat is a universally applicable trigger for debonding. Above a certain temperature, every adhesive softens, combined with a decrease in strength (see Chapter 2.6). The glass transition temperature is reached and, in the case of semi-crystalline adhesives, the melting temperature. Whether this trigger is already sufficient for disassembly depends on the individual case. Thermal decomposition usually occurs at even higher temperatures and eventually leads to failure of the adhesively bonded joint.

If an adhesive system deliberately incorporates bonds that are already split at comparatively low temperatures, this also inevitably leads to a reduced temperature resistance of the adhesively bonded joint. Nevertheless, harsh conditions are often still required for debonding. For example, Hashigara reports a 15 to 60-minute thermal treatment at 260 °C for debonding an adhesive designed for this purpose.[338]

There are also works in which carriers made of shape memory polymers[339] (SMP) are provided with adhesive layers. When a certain temperature is exceeded, these tapes deform and the joint is detached. However, only joints with a low strength level can be realized with this method, since the deformation force of an SMP is not sufficient to loosen higher strength adhesively bonded joints. Similarly, adhesion forces, again shown primarily for pressure-sensitive adhesives, can be significantly reduced by adding melting additives. Joints made with thermoplastic adhesives can also be released with less force above their melting temperature.

A frequently pursued idea for detaching adhesively bonded joints is the addition of substances that release large quantities of gas when heated. This ranges from normal blowing agents to microencapsulated liquids that evaporate and expanded graphite. Due to the expansion of the adhesive when heated, the adhesively bonded joint is virtually broken open. However, the typical required temperatures are in the range of 200 °C. This significantly

338 T. Higashihara, M. C. Fu, T. Uno, M. Ueda, J. Polym. Sci. A: Polym. Chem. 2016, 54, 1153 – 1158, Synthesis and characterisation of polycyanurates as dismantlable adhesives; https://doi.org/10.1002/pola.27955.

339 https://www.chemie.de/lexikon/Formged%C3%A4chtnis-Polymer.html (Access April 30, 2020)

limits the applicability, especially since most adhesives degrade at this temperature anyway.

For adhesives with reversible bonds, i. e. those that open at higher temperatures and close again at lower temperatures, the so-called Diels-Alder reactions dominate.[340] Besides a very limited raw material base, numerous side reactions that do not allow the opening again are the main disadvantages of these reactions. Reviews of the state of the literature on reversibly cross-linked polymers, as they can serve as a basis for high-modulus adhesives, have recently been published, so for special chemical systems reference is made to these reviews.[341, 342]

Koschek developed reversibly cross-linked materials based on other principles at Fraunhofer IFAM. These are, for example, benzoxazines, a typical base for high-temperature adhesives, which can be split with the aid of thiols.[343] However, this is disadvantageous for adhesively bonded joints, as an added medium must penetrate the adhesively bonded joint, which always takes an unacceptable amount of time for repair or recycling. Koschek et al. recently presented systems that can be detached by a combination of heat and water vapour.[344] The recovered components can be used again. Up to now, these polymers have been used as matrix resins for fibre composites, but can also be used for adhesives.

340 O. Diels, K. Alder, Justus Liebigs Ann. Chem. 1928, 460, 98–122, Synthesen in der hydroaromatischen Reihe; https://doi.org/10.1002/jlac.19284600106.

341 C. J. Kloxin, C. N. Bowman, Chem. Soc. Rev. 2013, 42, 7161 – 7173, Covalent adaptable networks: smart, reconfigurable and responsive network systems; DOI: 10.1039/C3CS60046G.

342 R. J. Wojtecki, M. A. Meador, S. J. Rowan, Nat. Mat. 2011, 10, 14 – 27, Using the dynamic bond to access macroscopically responsive structurally dynamic polymers; https://doi.org/10.1038/nmat2891.

343 T. Urbaniak, M. Soto, M. Liebeke, K. Koschek, J. Org. Chem. 2017, 82, 4050 – 4055, Insight into the Mechanism of Reversible Ring-Opening of 1,3-Benzoxazine with Thiols; https://doi.org/10.1021/acs.joc.6b02727.

344 T. Urbaniak, K. Koschek, Polym. Chem., eingereicht, Reversible Crosslinking of Thermoplastic Polyesterpolyols with a Bifunctional Vicinal Tricarbonyl Compound to Thermosetting Materials.

Intense cooling makes adhesives hard and brittle (see chapter 2.6.), so that the joints will break under mechanical impact. This requires very low temperatures; the use of liquid nitrogen is typical. This is not energy efficient as cooling is not limited to the adhesively bonded joint, thus it is a solution limited to special cases. This also applies to the use of solvents for debonding, as diffusion into the adhesively bonded joint is very slow.

Furthermore, there are methods to heat the adhesively bonded joints in isolation by electromagnetic radiation. For this purpose, the adhesive is modified with particles that absorb the electromagnetic radiation and thus heat up. For example, soot can be heated specifically by microwaves, and high frequency in the range of several hundred kilohertz to the megahertz range is suitable for heating adhesives with magnetic and superparamagnetic particles. Work at the Fraunhofer IFAM has shown that in many cases the adhesively bonded joint can be selectively heated to such an extent that adhesives cure with these energy sources. For disassembly, much higher temperatures are usually required, and these are much more difficult to achieve because the heat is transferred to the surrounding parts to be joined, which negates the advantage of selective heating of the adhesively bonded joint.

In contrast, an applied electrical voltage could be used very successfully for dismantling. Here, however, it is essential that the parts to be joined are electrically conductive, i. e. that they are metals. In the overview article of Schüwer [330] some approaches to solving this problem are listed and voltages between 48 and 100 V are required for a few minutes to reduce the adhesive strength of the joint by up to 90 %. Through a combination of slight heating (65 °C) and a voltage of 48 V (maximum voltage for operation without protective measures), Fraunhofer IFAM achieved almost powerless debonding within a few seconds.[345] This principle can be transferred to other applications and adhesives besides the proven hot melt adhesives, which has already been done in part in industrial formulations. It remains to be noted, however, that this separation principle must also be taken into account in the

345 J. Kolbe, M. Stuve, Adhaesion – kleben & dichten 2006, 50, 16 – 19, Die loesbare Klebverbindung wird Wirklichkeit, https://doi.org/10.1007/BF03243670

design and that the necessity of complex contacting only justifies it for the removal of valuable components or the replacement of components that have to be changed frequently. The latter could be battery packs in mobile phones modified with metallic bonding pads, for example.

Even pressure-sensitive adhesives can be adjusted so that they are relatively easy to remove. However, the low strength levels associated with this joint do not permit applications with safety-relevant requirements. If, however, a double-sided adhesive tape can be deformed rubber-elastically and has a so-called "handle" for pulling out of the adhesively bonded joint, it is possible to achieve pressure-sensitive adhesive joints that are at the same time easy to release and have strength levels acceptable for many applications (e. g. Powerstrips® from Tesa).

In principle, paste-like adhesives that cure to form an elastomer can also be used in a similar way for detachable adhesively bonded joints. A "handle", which is outside the adhesively bonded joint, must be applied here. This was demonstrated a few years ago for removable headlamp lenses.[346, 347]

The Schüwer review also lists some adhesives that have been specially developed for debonding.[330] These work according to the release mechanisms described above and are often designed for applications in electronics. There is also an example of painless removal of plasters.

> **Adhesives specially developed for debonding are already being used in specific areas.**

Overall, it can be seen that there is already a wide variety of possibilities for detaching adhesively bonded joints using adhesives specifically designed for this purpose. However, many of the princi-

346 EP 1 108771 A2, Loesbare Klebstoffe zum Verbinden von Substraten, 21.11.2000

347 S. Schmidt, Adhaesion – kleben & dichten 2002, 5, 14 – 19, Recycling-gerecht dank loesbarer Klebverbindungen.

ples described in the literature will not find their way into practice due to the necessity of using toxic raw materials, their price or their slow speed of action.

However, other ways of detaching adhesively bonded joints are already being used in commercial products. In order to be able to detach the joint, however, it is necessary to know which detachable adhesive was used and how to handle it. This will only be applicable for special products, which are collected for repair and recycling. This latter requirement will hardly be applicable to all industrial products, regardless of the joining technology used. There may be opportunities to achieve this for higher-value products by using a digital twin or other methods of digitisation.

Therefore, the following are examples where adhesively bonded joints can already be detached for repair or recycling using current technology. In principle, this is possible for all joints, but should already be considered in the design and selection of adhesives.

4.3 Adhesive bonding technology and repair

Many repairs in the private, craft and industrial sector would be unthinkable without adhesive bonding. It is probably the most frequently used joining method in the field of repair. Although adhesive bonding technology is then typically used by untrained persons and is not tested for the particular joining, it often works surprisingly very well and reliably. In this way, adhesive bonding ensures that articles in daily use can often be reused for years after a defect, which is a significant contribution to the conservation of resources. Nearly every craftsman has certain adhesives always at hand (often one-component moisture-curing adhesives), and the number of different adhesives is also increasing in the private sector. Adhesives for non-industrial applications in particular are increasingly being designed so that their application is robust and therefore less prone to error. Most of these repairs are carried out spontaneously based on the damage found. The safety requirements in these cases are usually low.

> **Probably adhesive bonding is the most commonly used repair method.**

On the other hand, safety-relevant components are repaired using adhesive bonding technology according to precisely worked out repair instructions. These include in particular fibre composites, for example in aircraft construction or wind turbines. In the event of damage, e. g. due to rockfall or hail, part of the material is cut out, tapered and then an exactly fitting repair patch is adhesively bonded. After that, the components can be loaded to the same extent as before the damage.

However, the fundamental question is how products with adhesively bonded joints can be repaired. As shown above, in principle, any adhesively bonded joint can be separated, and in most cases, the cured adhesive provides a good base for rebonding. The separation must normally be carried out locally without damaging the rest of the product. Unless special separation mechanisms are installed, separation is mechanical, often at elevated temperature. This is explained by the following two examples, where a similar repair is carried out repeatly in the same way. There are detailed descriptions of how and with which equipment and adhesives the repair is to be carried out. Already at the design stage, the basic consideration of the repair and its implementation in valid regulations is useful if similar repairs occur persistently. In the case of individual damage, on the other hand, a suitable solution must be worked out with creativity and manual skill. In both cases, a personnel qualification in adhesive bonding technology should be provided.

Example 1: Repair of windscreens in means of transport
For several decades now, windscreens, and subsequently also other windows, have been adhesively bonded into cars and other means of transport. Elastic thick-film adhesives are used for this purpose, which, among other things, compensate for body tolerances. The fact that the windows are joined to the bodywork in a load-transmitting manner makes them a structural element of the entire vehicle. As a result, the bodywork becomes safer and at the same time, considerable material can be saved. Sheet thicknesses can be reduced and lighter constructions can be used, saving energy in the construction and operation of the vehicles.

The removal of the windowa has already been taken into account in the design and is carried out by cutting the “thick” adhesively bonded joint with a cutting wire. After removing the window, the remaining adhesive can be removed with a vibrating spatula, for example, and then the new window can be adhesively bonded in place. This repair is carried out in all garages according to specified procedures. The same applies to the repair of minor damage to the windows themselves. Special light-curing adhesives have been developed for this purpose, which can penetrate particularly well into the fine cracks of a damaged area. As a result, the windows only need to be completely replaced in the event of major damage, which in turn saves a considerable amount of resources.

Example 2: Repair of display screens of mobile phones

The display screens of mobile phones are also often damaged, so that they have to be replaced. Unless the manufacturer deliberately prevents this by choosing unsuitable designs or adhesives, the windows can usually be replaced. Repair kits are available for this purpose, which function in a similar way to car windows, except that additional heating, for example with a household hair dryer, is often required to detach the adhesively bonded joint. A repair is also possible by skilled laymen, but the procedure is not yet as established as for car windows, but nevertheless already common practice.

4.4
Adhesive bonding technology and recycling

In principle, all adhesively bonded joints can also be removed for recycling. If possible, however, this should already be taken into account during product design, which is still very rarely the case today.

> **The detachability of an adhesively bonded joint must already be taken into account in product design.**

Generally, the more alike the products to be recycled, the more targeted the dismantling for recycling can be. In this case, automated lines for dismantling can also be set up. It must be made aware that this involves a similar joint cost as the assembly of the products. This too is independent of the joining technology used. In the case of a limited number of products, the dismantling line can also detect which product is currently present and how it is to be dismantled. As a rule, a combination of local heat and mechanical force should be used for debonding. The latter is preferred in the form of peeling forces, to which adhesively bonded joints are more sensitive and significantly less durable than other types of force application.

Today, adhesively bonded joints are often used in combination with other joining methods such as spot welds, bolts or rivets, etc. The additional joining points serve on the one hand as assembly aids and prevent the components from slipping off when the adhesive is not yet solidified in the adhesively bonded joint and on the other hand as crack stoppers when unintentional peeling forces act on the adhesively bonded joint. In the case of combined joining, such as adhesive bonding in combination with spot welding, rivets or screws, the adhesive ensures the long-term and safe transmission of force and the durability of the joint. The other joining technologies mentioned above are to be regarded as auxiliary joining technologies in this context. They prevent targeted dismantling; this also applies to bolts as an auxiliary joining technique. Research should be carried out to find out how they can be dispensed with in future without compromising the safety and reliability of the products.

> **In the future, research should be conducted into how adhesive bonding technology can dispense with supporting assembly aids or the like.**

In the case of a diverse mixture of products, it is only possible to separate the materials after shredding, as no information is available on the materials used, designs and joining techniques of the different products. This is established state of the art. Preliminary disassembly of individual components, such as batteries, windows or larger plastic parts, can be useful. Plastic components from heterogeneous product mixtures can only be reused at a low quality level after separation.

Usually the adhesives – as well as lacquers and various impurities – remain on the separated materials or form part of the light fraction. This is not critical for materials that undergo a hot recycling process, such as metals or glass. In the case of plastics, on the other hand, the adhesives lead to a loss of quality. However, since heterogeneous product mixtures always contain aged mixed plastics, including adhering adhesives and lacquers, which are no longer recyclable, this too is not critical. In the case of current raw material recycling or thermal recycling, this should not be a further problem.

In the following, the separation of raw materials for recycling is shown using three different products as examples. These are largely adhesively bonded and were deliberately selected from three very different product groups, namely

- Example 1: Cars
- Example 2: Mobile phones
- Example 3: Soft packaging.

Example 1 – Recycling of cars:
Nowadays, cars are first partially assembled after the operating materials have been removed, in order to separate large plastic parts, the cables (since copper is considered a particularly valuable raw material, which also interferes with the recycling of steel and aluminium) and the windows. Especially for the windows, the adhesively bonded joints are also detached for this purpose. As explained above, the "thick" adhesively bonded joints are cut with a specially designed wire. The adhesive residues and plastic parts of the glass windows decompose thermally during glass recycling and therefore do not interfere with the process.

If the proportion of cars with a high proportion of plastic in the body increases (e. g. panelling of body frames with fibre composite plastic), it will be necessary to remove these before the subsequent process steps. In the interests of lightweight construction, but without compromising safety, and thus resource-saving vehicles in production and operation, joints will have to be achieved primarily by adhesive bonding (see Chapter 1.3). The disassembly can be carried out here in a similar way to the glass windows. This is severely limited by auxiliary fasteners (such as bolts or rivets) which are required in production or in the event of a crash as crack stoppers for safe operation. In these cases, the parts would be torn off by a high, specifically applied force. If utilisation of these parts as spare parts is desired, the auxiliary attachments must be removed beforehand with relatively high effort (e. g. drilling out).

The remaining car body, which consists largely of steel and aluminium, is shredded and then separated into fractions using long-established and proven processes. Residues of adhesives and varnishes are still on the metal, but do not interfere there due to the high temperatures during metal recycling. The greater portion is found in the light fraction, together with other plastics that remain in small proportions in the car body. From today's perspective, these can only be used for energy generation using themal techniques. In the future, however, it is conceivable that recycling this fraction as raw material by breaking it down together with other plastic waste into low-molecular basic materials will be possible.

The illustration shows that cars can largely be dismantled into their components. This is only slightly affected by adhesively bonded joints, although there is a clear need for improvement. Adhesively bonded joints can already be separated to a large extent, but this should improve significantly if disassembly is taken into account in the design of the vehicle. There is a great need for research in this area, whereby the development of adhesives must also be taken into account.

Example 2 – Recycling of mobile phones:

Mobile phones, including smartphones, are generally considered non-repairable and only recyclable at a low value chain. The reason often given is that the devices are adhesives play a major role in assembling the phone. It is certainly possible that the manufacturer is able to make the reprocessing of these products more difficult in this way, as well as their non-reparability by not providing spare parts. However, neither of these are technical necessities.

Systematic dismantling and recycling of the individual components can be automated and requires the devices to be collected in an economical manner. Apple has developed a process with which iPhones can be completely dismantled, regardless of the joining technology used.[348] The dismantling robot is called Liam. This is coupled with a buy-back system when buying a new device.[349] As early as 2018, the recycling robot Liam was replaced by the successor system Daisy. Daisy is able to recognise the different iPhones and can disassemble 200 smartphones per hour.[350] In 2019, a second line was built to increase capacity, so that up to 2.4 million units per year can now be dismantled.[351] This is independent of whether the components are bolted, clipped or adhesively bonded.

348 https://www.youtube.com/watch?v=AYshVbcEmUc (Access April 30, 2020)

349 http://apple.co/1SdvFbJ (Access April 30, 2020)

350 https://www.youtube.com/watch?v=2Bu-gl7v-P8 (Access April 30, 2020)

351 https://www.crn.de/telekommunikation/apple-baut-iphone-recycling-aus.119757.html (Access April 30, 2020)

However, there are also semi-automatic processes for the disassembly of mobile phones. This is partly aimed at recycling components, but also at repair in the professional sector. The iPhone X is intended to serve as an example for the procedure of disassembly with a special tool set and is available as a video.[352] Most dismantling instructions aim at repair, i. e. the highest possible level of recycling. Repair instructions are available on the Internet for almost every type of telephone, so that even experienced laypersons can carry out many repairs, including loosening the respective adhesively bonded joints, independently. This shows that disassembly is possible, regardless of whether the device, individual components or just the materials are reused later.

There are also more comprehensive manufacturer-independent concepts for recycling mobile phones. One was developed in 2019 as part of a student competition organised by the Society of Process and Chemical Engineering in the Association of German Engineers (VDI). . Smartphones that are easy to recycle are automatically sorted out and then, among other things, specifically dismantled in workshops for the disabled in order to recycle individual components. Especially with increasing quantities, types for which automatic dismantling is established could be dismantled in dismantling processes, as described above by way of example. Equipment that is still usable could also be ejected and repaired, if a market for this is established (conceptual additions by the authors).

In the case of smartphones that are difficult to dismantle, which have been sealed beyond the point of need and where disassembly was not taken into account in the design, as well as rare types, the plan is to shred them and separate the recyclable materials in a multi-stage process. In the first step, the material is separated into a metal, glass and plastic fraction. The precious metals are then separated in a biotechnological process using cyanogen-forming bacteria, and aluminium and tungsten (as well as other heavy metals) are then separated in metallurgical processes.[353]

352 https://de.ifixit.com/Teardown/iPhone+X+Teardown/98975 (Access April 30, 2020)

353 N. N., CITplus 2019, 22, S. 11, Das chemPhone wird recycelt; www.vdi.de/chemplant (Access April 30, 2020)

Example 3 – Recycling of soft packaging:
Soft packaging, in particular also known under the trade name Tetra Pak®, is often considered non-recyclable due to the composite of paper (approx. 75 %), plastic (approx. 20 %, polyethylene, PE) and aluminium (approx. 5 %). Manual dismantling is practically impossible, if only because of the small thickness of the plastic and metal layers.

However, industrial processes have been developed in which separation is possible and is carried out to a high degree.[354] The process starts, similar to paper recycling, by mechanically treating the cartons together with water in a so-called pulper. In this process, the paper fibres are released and are processed into corrugated board, for example. The proportion of polyethylene (PE) and aluminium is separated and is used today as raw material in the cement industry, for example. In the future, however, this residual fraction could also be recycled as raw material by cracking the polyethylene (PE) into basic raw materials in appropriate plants. The resulting aluminium-rich fraction could be melted down and recycled as metal.

There is also the question of a more targeted separation process. This could work, for example, via the melting of the polyethylene (PE) in the mixed fraction from which the aluminium is filtered out. There is still a great need for research in this area. However, the task seems to be technically solvable, and the question arises as to when this will make economic and ecological sense.

354 https://www.tetrapak.com/de/clevereverpackung/recycling , https://www.youtube.com/watch?v=cAf8lY9IyaA (Access April 30, 2020)

4.5 Adhesive bonding technology and resource efficiency

Adhesive bonding technology is a key technology for manufacturing products more efficiently than with other methods or, if necessary, for enabling new designs and products in the first place. This has already been explained in detail in Chapter 1. All materials can be joined universally, and power is transmitted over a large area instead of at specific points, e. g. when riveting or bolting. Because their material properties are retained, thinner semi-finished products and lighter materials can be used without compromising the safety of the product. This leads to a saving of material and thus also energy in the production of the products. In addition, adhesive bonding is a key technology for lightweight construction, which leads to a reduction in energy consumption during operation.

> **Adhesive bonding is a key technology for lightweight construction.**

The longevity of products can also be significantly increased by the use of adhesive bonding. For example, the adhesive can be used to electrically insulate metals from each other and thus prevent contact corrosion. Due to a lighter design, the mechanical load during operation is also lower, resulting in a lower cumulative load during continuous operation. Overall, this has the effect of extending a material utilisation cycle for the circular economy and consequently, when viewed over several cycles, minimizing the proportion of waste or materials ("Onus resource input" or "expenditure goods material input"/see Chapter 2.5) that can only be reused at a low value-added stage. The material savings achieved by adhesive bonding will be explained using food packaging and a vehicle as examples of very different products.

Adhesive bonding can increase the longevity of products.

Food packaging

The usual food packaging consists of multilayer compounds, whereby each layer is assigned a specific function. Although the layers are not adhesively bonded in the actual sense, good adhesion between the layers is still necessary. If necessary, this is realized with adhesion promoter layers (so-called tie-layers) during the coextrusion of the multi-layer films; the base film, for example, consists of polyethylene. This can be produced at low cost and can bear the mechanical loads, so that damage to the packaging, which would result in the food no longer being saleable and thus being waste, does not occur. A layer of polyvinyl alcohol acts as a permeation barrier, especially to reduce the penetration of oxygen into the package. Metal or thin layers of glass also prevent permeation, especially to prevent the loss of aromas and the diffusion of undesirable substances. Cover layers of other polymers in turn ensure that the packaging can be hermetically sealed to prevent microbiological spoilage and retain the aromas in the food.

The multilayer films thus ensure that the food packaged with them can be safely consumed over a given time. In principle, this could also be achieved by a homogeneous material, which is a compromise between the different functional materials of the joint. However, this would require considerably thicker packaging and cans would be used instead of foil packaging. This would result in a considerable increase in the need for packaging material, which would be in considerable conflict with the need to use materials as sparingly as possible.

Vehicle

In vehicles, adhesive bonding is the key technology for lightweight construction. This includes not only the possibility of using new structural materials with lower density and lower weight of the components and products made from them. In particular, it also allows a reduction in sheet thickness for conventional steel construction. For conventional steels, which are weldable, adhesive bonding is an alternative joining method and is used, usually in combination with spot welding as a quick fixing and crack stopper, with flat instead of punctiform or linear force transmission. By doubling up, which prevents the sheet metal from fluttering, etc., adhesive bonding allows the use of thinner sheets.

In principle, even thinner plates can be used for modern high-strength and ultra-high-strength steels.[355] Their microstructure is responsible for their high strength. However, these steels cannot be welded sensibly, as the inner (micro) structure of the steel is destroyed when the steel melts, making the weld seam the weakest point of the component. Consequently, such sheets can only be used in means of transport if they are adhesively bonded.[356] Reducing the thickness of the sheet metal saves a lot of material and thus also energy for its production, primarily in the construction of the vehicles, and then secondarily due to the lower vehicle weight also during operation.

In addition, without adhesive bonding, all alternative energy sources are unthinkable, unlike conventional energy production by combustion power plants or nuclear power stations. In the case of alternative energy sources, this begins with the sealing of solar cells and the construction of solar modules and extends to the joining of the rotor blades of wind turbines (see Chapter 1.7.2). Here, up to about 1 t of adhesive is required to join the two half-shells of a rotor blade. These products are sufficiently longevity and lightweight only by using adhesive bonding, which when joining the two rotor blade half-shells provides the required material properties of the FRP rotor blades. The latter is also joined by lower material consumption and, at least when the parts are moved, higher energy yields. Here too, adhesive bonding leads to a high level of resource efficiency and is the key to modern systems for alternative energy generation.

355 T. Heller, H.-J. Kaiser, A. Kern, H.-J. Tschersich, ATZ – Automobiltechnische Zeitschrift 1998, 100, 664–668, Moderne hochfeste Staehle im Nutzfahrzeug- und Mobilkranbau.

356 A. Lutz, D. Symietz, Adhaesion – kleben & dichten 2008 (10), 52, 14–18, Gleiche Strukturfestigkeit trotz duennerer Bleche, Kleben von hochfestem Stahl.

The development of alternative energy sources is not conceivable without adhesive bonding.

The adhesive bonding technology is also indispensable for the storage and conversion of alternative energies. In addition to lightweight construction aspects – high material and energy efficiency due to low weight – adhesive bonding is the key to the production-ready and longevity of batteries and fuel cells. Electric mobility, for example, would be inconceivable without adhesive bonding. In an exemplary enumeration, this starts with the construction of the magnetic cores for the electric motors from electro-packaging sheets, continues with the sealing of the battery cells and ends with the heat management of the batteries with thermally conductive adhesives.[357] The same applies to fuel cells. These not only have to be hermetically sealed and mounted as modules, but the bipolar plates must also be joined together. Here it could be shown that this is particularly efficient through electrically conductive adhesive bonding.[358] Sealing is a particular challenge, regardless of whether hydrogen or methanol is used as fuel, as both are highly permeable.

Electric mobility is unthinkable without adhesive bonding.

The few examples show that adhesive bonding makes an outstanding contribution to making products lighter, thus saving material and energy during “manufacture” and “utilisation”. Likewise, all technologies for alternative energy generation, storage and conversion are directly dependent on the successful use of adhesive bonding. Reliable energy generation on a large scale with alternative technologies is impossible without adhesive

357 F. Kerstan, Adhaesion – kleben & dichten 2019 (12), 63, 4–5, Zukunftsweisende Rolle der Klebstoffe fuer emissionsarme Mobilitaetskonzepte.

358 K. Dilger, E. Stammen, M. Weber, S. Brokamp, P. Beckhaus, A. Heinzel, Adhaesion – kleben & dichten 2014 (7–8), 58, 36–41, Vereinfachte Montage von Brennstoffzellen – Bipolarplatten elektrisch leitfaehig kleben.

bonding. This makes adhesive bonding an integral part of a successful energy turnaround.

> **Adhesive bonding is an integral part of the energy turnaround.**

4.6 Utilisation of renewable raw materials in adhesives

Renewable raw materials are one way of significantly improving the CO_2 balance of a product, since the CO_2 released during product degradation is bound again in the form of natural raw materials via photosynthesis. However, it is critical to see that the renewable raw materials that are easy to use (e. g. vegetable oils, starch) are in competition with food production. This applies either directly or indirectly, because the available arable land is not available for both at the same time. In terms of the overall balance of the national economy, the aim should also be to close the cycle of renewable raw materials at the highest possible level, i. e. to recycle biopolymers, for example, and not just to rely on the final degradation product CO_2 being bound again. As a result, composting biodegradable polymers is only of limited use, since microbiological degradation produces the same end products carbon dioxide and water as incineration, but with the difference that the energy bound in the material is not used.

In this context, however, the terminology should also be mentioned. Biobased and biodegradable are often equated. This is not the case! There are biodegradable and non-biodegradable bio-based polymers as well as synthetic polymers.

Adhesives based on renewable raw materials have been used by people for many thousands of years. Birch pitch is probably the oldest adhesive and was already used in the Stone Age to attach barrier spikes. In all early cultures, numerous objects were made with natural adhesives. Outstanding examples are the Egyptian longbows, which were produced by a complex lamination process. This is still not known in detail and cannot be reproduced. It was a contribution to the stabilisation and spread of Egyptian culture in antiquity and one of many examples of how adhesive bonding technology had a significant influence on cultural history (and still does today).

Adhesives based on renewable raw materials have been used for a long time.

Also in later times, numerous adhesives were developed on the basis of renewable raw materials and are partly used practically unchanged until today. Examples are glutin glues such as bone glue and fish glue from slaughterhouse waste – mainly used for gluing wood – or starch paste, which was often used for gluing paper or cardboard and is still used as a label adhesive or in the form of Stein-Hall adhesives for the production of corrugated cardboard and other cardboard products. Since the invention of synthetic polymers 100 years ago, more and more new synthetic adhesives have been added. Most of today's common classes of adhesives were discovered in the middle of the 20th century and have been permanently developed further. Overall, the importance of adhesive bonding as a joining technology increased rapidly, but at the same time the use of renewable raw materials declined steadily. It should be noted that even today very important adhesives such as cellulose-based wallpaper adhesives and starch-based adhesives for the production of cardboard products are still produced in large quantities on the basis of renewable raw materials. The question arises as to why there is a decline in the use of renewable raw materials and how one can sensibly counteract it.

As explained in more detail above, the use of new adhesives in recent decades has made it possible to:

- make products more durable and safer
- produce using smaller quantities of material (e.g. use of thinner sheet metal in automobiles, miniaturisation)
- produce more economically
- give products a more attractive design or
- make new products possible in the first place.

This study discusses numerous examples and clearly shows that the overall balance of ecological aspects due to adhesive bonding is positive.

Through adhesive bonding, the overall ecological balance of adhesively bonded products is generally positive.

This is emphasised through the example of an adhesively bonded car body. Adhesive bonding enables forces transfer not only at points but also over the entire surface. This allows the use of thinner sheets of metal or alternative materials with lower weight, which may also consist of renewable raw materials; the further details will not be discussed again here. Additional mechanical stabilisation is achieved by defined shapes of the sheet metal components and, if necessary, local doubling, which is only effective with adhesive bonding. The possibility of constructing the body using significantly thinner steel sheets saves material and thus energy in the product life cycle "manufacture." This leads to lower energy requirements in the product life cycle "utilisation" of the vehicle. However, it is still not possible to provide suitable adhesives based on renewable raw materials. As is the case with many other reactive adhesives, a great deal of research remains to be carried out.

To come back to the question of the reasons for the decline in the share of renewable raw materials raised above: Modern adhesives are designed to manufacture complex products with high safety and high productivity. This is usually not possible with the much earlier adhesives made from renewable raw materials. The question arises as to how novel adhesives can be developed because of renewable raw materials without too many synthesis steps, in which bio-based carbon in the products is reduced and energy is required.

Known adhesives based on renewable raw materials can therefore not be used in car body construction or many other applications. There are also examples where bio-based adhesives have been directly replaced by synthetic ones for good reasons. Wood adhesives were produced over a very long period of time with glutin glue*. This has been almost completely replaced by white glue based on polyvinyl acetate. There are many reasons for this: First of all, the traditional glue must be applied hot. In traditional joineries, there was a glue pot on the oven for this purpose. Hot application can be difficult, especially on larger surfaces, and when kept warm for a long time, the glue can easily scorch or the amount of water it contains cannot be kept constant. In addition, microbiological decomposition occurs easily in the unprocessed state and in adhesively bonded wood products. In addition, the water resistance of adhesively bonded joints is only limited. It is significantly better with white glue and can be increased even further by additives, the so-called hardeners. Glues modified in this way are designated D3 or D4 and meet the highest requirements for water resistance of wood adhesives. So in the medium term, the question is not really one of using glutin glue* again, but of what an adhesive based on renewable raw materials must look like in order to be at least equal to white glue.

* Glutin glue, also known as bone glue, is produced from slaughterhouse waste. Gelatine is a food-grade form of glutin glue.[359]

> **Research is still needed to further develop the properties of adhesives based on renewable raw materials.**

However, many substances can be obtained chemically identically from renewable materials. The polyvinyl acetate of white glue is a good example of this.[360] The vinyl acetate required as starting material is produced on an industrial scale in the gas phase from acetic acid and ethylene under oxidizing conditions. Raw fossil materials are used in the process for ethylene and acetic acid that predominates today, but the raw materials can be obtained in principle from relatively easily from biomass, e. g. ethylene from bioethanol and acetic acid as a by-product of the wood processing industry.

As already described, various adhesives are based on renewable raw materials. This also applies in particular to those that are produced in large volumes, such as wallpaper paste based on

359 https://www.chemie.de/lexikon/Glutinleim.html (Access April 30, 2020)

360 https://www.farbeundlack.de/Markt-Branche/Unternehmen-und-Maerkte/Wacker-erhaelt-Zertifizierung-von-Bindemitteln-auf-Basis-nachwachsender-Rohstoffe (Access April 30, 2020)

cellulose derivatives or starch-based adhesives for the production of corrugated board and other cardboard products. In addition, carbohydrate derivatives in particular are used as additives; also in synthetic adhesives. Cellulose derivatives are often used as thickeners and rheological additives. Vegetable oils are another class of renewable raw materials with increasing use. Castor oil is widely used in polyurethanes including polyurethane adhesives and is becoming increasingly popular. The question arises, however, to what extent the available quantities can be further increased, since their cultivation is only possible in large monocultures in tropical regions. This should be seen against the background that castor oil is a very interesting raw material for numerous applications due to its chemical structure. It is the only vegetable oil with hydroxyl groups and double bonds available in large quantities. This allows many subsequent reactions to be carried out, which is not the case with the more easily available fats and oils. Thus, ricinus oil is also used for the production of polyamides based on renewable raw materials (e. g. Vestamid® Terra [361]). It should be noted that high-quality hot-melt adhesives can also consist of polyamides, so that castor oil could be the basis for this.

Vegetable oils with unsaturated or polyunsaturated fatty acids can be converted in many ways into substances that can potentially be used as adhesive raw materials. Since most animal fats – the main exception being fish oils – contain only a small proportion of unsaturated fatty acids, they are much less suitable as raw material for technical applications than vegetable fats. Due to the long flexible hydrocarbon chain of the oils, it is difficult to obtain solid polymers from these modified oils. Modifications have to be made here in order to develop hard-tough materials that would also be suitable as higher-modulus adhesives. These developments are still in their infancy. Essentially, it must be possible to specifically adjust the morphology of the cured adhesives, although the required tough-elasticising additives are currently only available in isolated cases on the basis of renewable raw materials.

The oils themselves have been modified in many ways in recent years. Some of the methods used for this purpose are significantly

361 https://www.vestamid.com/product/vestamid/en/products-services/VESTAMID-terra/ (Access April 30, 2020)

older than 50 years, and some of the reactions are still industrially established. However, many things have been forgotten. In other cases, better methods will have to be developed, including new structural variants of existing fat modifications, in order to cover the property profiles required for modern high-performance adhesives. In the simplest case, polyunsaturated oils can be used in unmodified form. They harden by reaction with atmospheric oxygen in the form of oxidative drying, if appropriate metallic catalysts (siccatives) are present. The main areas of application are newspaper printing inks, oil paints, wood preservation oils and putty. The latter in particular is an adhesive bonding and sealing agent with excellent resistance to ageing. Compared to the synthetic materials that replaced it, however, processing is significantly more difficult and curing takes a very long time.

In particular, polyunsaturated vegetable oils can be converted with maleic anhydride, which is not yet available on the basis of renewable raw materials. This is called maleisation and plant based anhydrides are obtained, which are in principle applicable for the curing of epoxy resins.[362] A polymerisation of the maleinised oils with polyols is also possible. However, as with most other oil-based adhesive raw materials, the mechanical properties that can be achieved still need to be improved according to the current state of development. The double bonds of unsaturated oils can also be epoxidized. The epoxides formed in this process are intermediate stages of our fat metabolism and can be used for numerous other reactions. Epoxidized soybean oil in particular is produced in large quantities and used as a plasticizer, for example. No chemical reaction takes place. For the use in adhesives, it is advantageous to use oils with a higher proportion of double bonds in order to achieve a higher cross-linking density during curing. Curing can be done with anhydrides, including the bio-based ones just described, or by cationic polymerisation; amines, on the other hand, are not very suitable for curing. In a recently completed project, it was shown that the incorporation of novel polylactic acid-based polyols significantly increased the toughness of cationically curing epoxidized

362 V. Fombuena, R. Petrucci, F. Dominici, A. Jordá-Vilaplana, N. Montanes, L. Torre, Polymers 2019, 11, 301 – 319, Maleinised Linseed Oil as Epoxy Resin Hardener for Composites with High Bio Content Obtained from Linen Byproducts; doi: 10.3390/polym11020301.

oils.[363] The mechanical properties also improved significantly with the epoxy content of the oils. Adhesives made almost entirely from renewable raw materials could be presented, which led to high adhesive strengths with plastics and metals as substrates.

The epoxidized oils also serve the synthesis of secondary raw materials. Hydrolysis produces oil-based polyols, which can be used for the formation of polyurethanes. When the epoxidized oils are reacted with acrylic acid, multifunctional acrylic acid esters are formed, which can be used to produce photocuring adhesives and coatings. However, just as with the previous types of raw materials, it is difficult to achieve mechanical properties equivalent to those of synthetic adhesives. There is no reason why this cannot be achieved, but it requires appropriate research efforts.

Numerous substances potentially suitable as adhesive raw materials or for the synthesis of adhesive raw materials are now produced biotechnologically. These differ structurally from the substances commonly used today. As a result, it is still largely unknown how raw materials for adhesives, and consequently the adhesives formulated from them, should be chemically structured in order to achieve the best possible property profile from an adhesive bonding technology point of view. Examples of such raw materials available in principle are itaconic acid, lactic acid, polyhydroxybutyrate, isosorbite, succinic acid and sorbitol.

The renewable raw materials mentioned so far can be used in many different ways. The level of added value varies greatly – from utilisation as food to the production of biogas. The utilisation for adhesives is certainly in the middle range. It would be more advantageous to use real waste materials, i. e. materials for which today only landfill or incineration is possible. These substances are very rare in agriculture and the subsequent industries, in case of doubt many of them can be used as animal feed or in biogas plants. Through utilisation as a renewable raw material, however, there is the possibility of raising the value added level of such materials that have already been recycled. Even feathers are used as spring

363 Final report “KLEBSTOFFE AUF BASIS EPOXIDIERTER PFLANZLICHER OELE UND HYDROXYFUNKTIONELLER POLYESTER AUS NATUERLICHEN MONOMEREN” (BioDur), 2018, sponsored by Fachagentur nachwachsende Rohstoffe e.V.

hydrolysate as a (low quality) protein source. However, they would certainly be a basis for adhesives or, in powder form, could be a reinforcing filler. For coffee grounds, as they are produced in the manufacture of caffeine and instant coffee, there is no good utilisation to date and none is foreseeable. One waste material that accumulates in large quantities is lignin as a by-product from paper and pulp production. The chemical building blocks would be of great interest for many different applications. However, it has not yet been possible to split the lignin into fragments in such a way that the substances could be isolated in larger quantities under ecologically and economically sensible conditions. Lignin would be a source of aromatic building blocks, whereas all other renewable raw material sources can primarily supply aliphatic raw materials. There have been numerous national and international research efforts to date to use lignin as a material. Besides many approaches for the utilisation of lignin, there is still no breakthrough by far. Overall, the material utilisation of wood components is an interesting field of research [364], but at the moment, a broad industrial utilisation is not yet foreseeable.

> **There are many approaches to develop the property profile of biobased adhesives towards the characteristics of synthetic adhesives.**

The narrativ shows that there are still some bio-based adhesives used in mass applications and that many approaches exist to achieve acceptable properties already today. However, it is far from being possible to meet complex property profiles in a similar way as with synthetic adhesives. This concerns the combination of technical properties, productivity, product safety, economy and ecology. Adhesives in particular are an ideal product group for the use of renewable raw materials. The quantities are moderate in comparison to mass plastics, but sufficient to make the synthesis of raw materials economically feasible and the ecological impact large enough. They are also very versatile in terms of chemical composition and with creativity, many available new materials can be used without disturbing existing product and recycling streams.

364 https://xylochemistry.com/portal/ , (Access April 30, 2020)

The latter is the case when new polymers are added to the typical bulk polymers, which are usually not compatible with the existing plastics.

> **On an international level, there are many efforts to use renewable raw materials in adhesives.**

Consequently, there are many international efforts to use renewable raw materials in adhesives. This becomes clear when looking at the literature and the conference programmes of the international adhesive bonding conferences. Consequently, corresponding work has been and is being funded (nationally, above all by the Agency for Renewable Raw Materials e.V. (FNR) on behalf of the Federal Ministry of Food and Agriculture) to reduce dependence on international sources of raw materials. Accordingly, results have already been disseminated at several conferences in Germany focusing on the topic of renewable raw materials in adhesives and binders.[365, 366, 367]

The explanations show that we are well on the way to being able to use renewable raw materials increasingly in adhesives. However, they also clearly show that there is still an enormous need for research to reach the level of entirely synthetic adhesives. This will be discussed again in chapter 5.

> **The utilisation of renewable raw materials in adhesively bonded joints is on the right track, but also shows that there is still an enormous need for research.**

365 Workshop VALORISATION OF BIO BASED RAW MATERIALS, Fraunhofer IFAM, Bremen, 18. – 19.10.2017

366 Guelzower Fachgespraeche Band 59: Abschlussworkshop Klebstoffe und Bindemittel, Dresden 18.-19.9.2019 https://mediathek.fnr.de/broschuren/nachwachsende-rohstoffe/biowerkstoffe/band-59-abschlussworkshop-klebstoffe-und-bindemittel.html (Access April 30, 2020)

367 1. Branchentreff Klebstoffformulierung, Klebstoffe auf Basis nachwachsender Rohstoffe, Fraunhofer IFAM, Bremen, 15. – 16. May 2019.

5

Strategies for adhesive bonding technology to support circular economy and ecodesign

5.1 Introduction

Adhesive bonding is the low-heat joining of identical or different components, while maintaining the properties (see Chapter 1.3) required for the respective product. Since, with a few exceptions, the adhesive itself does not exert any damaging influence on the parts to be joined, the temperature reached by the adhesively bonded joint during joining is the decisive parameter. The solidification of the adhesive is usually carried out at temperatures below the glass transition or melting temperatures of the parts to be joined, so that the properties of the parts to be joined can be maintained during low-heat joining by adhesive bonding.

> **The adhesive bonding technology supports circular economy and ecodesign.**

In the sense of a holistic life cycle consideration for the effectiveness of the circular economy of adhesively bonded products, both the criteria for fulfilling product safety requirements and the "end-of-life" scenarios must be included in the selection of materials and in the design of the adhesively bonded joint. For both aspects, the term "controlled longevity" (see Chapter 4.1) is gaining in importance. "Controlled longevity" brings both aspects together: During the product life cycle phase "utilisation" the adhesively bonded joints meet the safety requirements, during the product life cycle phase "disposal" they enable the effectiveness of the circular economy.

There are two basic ways to achieve this "controlled longevity":
(1) the adjustment/influence of adhesion
(2) the adjustment/influence of cohesion

Both ways are reflected in the concepts listed in this chapter. In principle, a distinction must be made between adhesively bonded joints with and without the main function of transmitting mechanical loads (see in particular Chapter 5.2.9).

The focus of the explanations in this chapter is on path 2, i.e. influencing the cohesion in the adhesive. According to the current state of science and technology, path 1 (influencing the adhesion of the adhesive to the parts to be joined) still requires considerable research work, also in the field of basic research, and subsequently extensive verification and practical tests. This applies in particular to adhesively bonded joints which have to meet safety requirements according to the adhesive bonding technology quality standards [40, 71–77].

> **In terms of the "controlled longevity" of adhesively bonded products, cohesive adhesive failure is favoured when separating them.**

In principle, adhesively bonded joints offer the possibility of low-heat separation (see chapter 2.6.1, also 1.6, 3.2–3.4) without influencing the properties of the joined parts. Since adhesively bonded joints can also integrate additional functions beyond the "joining" function (see Chapter 1.5/Figure 14), separating implies a degeneration of these functions. On the other hand, in joints where the "joining" function is realised e.g. by bolting and the additional "sealing" function is provided e.g. by elastically pre-stressed, additional plastic seals, the detachment is carried out in several, often manual steps. The bolts are opened and removed, the exposed seal is removed and at least one of the two joining parts remains irreversibly with through-holes.

As a necessary supplement to mechanical recycling [368] and as a preferred alternative to purely energy recovery [369], i.e. incineration of the waste with energy recovery, chemical (raw mate-

368 Fraunhofer Umsicht, Chemisches Recycling von Kunststoffen, https://www.umsicht-suro.fraunhofer.de/de/unsere-loesungen/chemisches-recycling.html (Access April 30, 2020)

369 Umweltbundesamt – UBA; Recycling: Verbesserungsbedarf bei Kunststofabfaellen, https://www.umweltbundesamt.de/themen/recycling-verbesserungsbedarf-bei (Access April 30, 2020)

rial) recycling (see chapter 2.4.2) opens up a future-oriented perspective[370, 371] for adhesively bonded joints with plastic joining partners. This applies in particular to plastic waste with a duromer, non-meltable or soluble polymer base, composite materials with a duromer matrix resin base, non-sortable plastic waste and contaminated plastics irrespective of their polymer base. In this context, the term "contaminated plastics" includes plastic components to which (residual) adhesive still adheres after mechanical separation of the adhesively bonded joint.

In chemical recycling, plastic waste is broken down into its chemical components using chemical processes such as pyrolysis, gasification or solvolysis. These can then be reused for the production of new plastics/plastic products without the use of new fossil raw materials and without any loss of quality. The decisive developmental step, both from an economic and an ecological balance sheet point of view, is to overcome the energy-consuming, endothermic chemical processes of chemical recycling. This will be achieved by using renewable energy that is sufficiently available in the medium term and/or by developing catalytic methods that operate at mild temperatures and with high selectivity. Chemical recycling would lead to global economic savings in the billions of euros [€] by optimising the life cycle assessment and minimising dependence on non-renewable energy sources.[372]

In the future, chemical recycling should be seen as a complement to other recycling processes.

370 M. Crippa, B. De Wilde, R. Koopmans, J. Leyssens, J. Muncke, A.-C. Ritschkoff, K. Van Doorsselaer, C. Velis, C, M. Wagner; Eine Kreislaufwirtschaft fuer Kunststoffe – Erkenntnisse aus Forschung und Innovation als Grundlage fuer politische und finanzielle Entscheidungen, 2019 (M. De Smet, M. Linder, Hrsg.). Europaeische Kommission, Bruessel, Belgien.

371 A. Lechleitner, D. Schwabl, T. Schubert, T. et al., Oesterr Wasser- und Abfallw 2020, 72, 47–60, Chemisches Recycling von gemischten Kunststoffabfaellen als ergaenzender Recyclingpfad zur Erhoehung der Recyclingquote.. https://doi.org/10.1007/s00506-019-00628-w (Access April 30, 2020)

372 A. Rahimi, J. M. Garcia, Nature Reviews 2017, 1, 1–11, Chemical recycling of waste plastics for new material production; https://doi.org/10.1038/s41570-017-0046.

Dismantling strategies for adhesively bonded joints are particularly targeted when they are based on the local action of stimuli. After exceeding a threshold value of a disassembly-triggering stress that is not to be expected for the service life phase, the properties of adhesively bonded joints change in the area of the adhesive layer. An example for the triggering of such an event is the combination of mechanical overstressing and simultaneous temperature increase. As is the case when a nut is loosened to disassemble a bolted joint, the intended trigger event and its threshold value are specifically anchored in terms of sustainability in the development of the adhesive and the adhesively bonded joint through appropriate material selection and a well-considered composite design with a view to the entire life cycle. The reliable effects as well as the robust design with regard to the product-specific application are ensured by the availability of data. For this purpose, both material-related information and information characteristic of the processes taking place throughout the entire life cycle is used.

> **Dismantling strategies should be based on local triggers.**

In the case of chemically curing adhesives, whose solidification (formation of cohesion) is due to the chemical reactions of resin and hardener in the adhesively bonded joint, this can be achieved not only by thermally induced softening of the polymeric adhesive layer but also by swelling. Another possibility is the degradation of the polymer network. In this process, either the resin-hardener reactions are reversed or chain breaks are achieved in molecule chains.

The user of the adhesively bonded product must be informed which disassembly option is specified by the manufacturer. This also applies analogously to repair processes. Conversely, this means that manufacturers of bonded products gain a competitive advantage with users and consumers who act sustainably, if they take into account appropriate consumer behavior according to the product design in advance and make this known to the consumer. If durability, repairability and/or ease of recycling influence the market opportunities of adhesively bonded products, it is advantageous for the purpose of comparability to make these measurable by means of numerical values that are as easy to understand and representative as possible.

Figure 78 schematically sketches how an adhesively bonded joint that is safe and durable in the product life cycle "utilisation" can be removed by a recycler, which also applies to the repairer. These are equipped with a separation tool specific to the adhesively bonded joint, the use of which the adhesives experts and designers have integrated into the joint in a holistic way.

> **Users, repairers and recyclers must be informed about the dismantling option provided by the adhesive manufacturer.**

Digital information sources make it technically possible to pass on the instructions for separating the adhesively bonded joint to the recycler active in the product cycle "disposal". Which material-related separating ideas and specifications in the field of adhesive bonding technology could be used in the future is described in detail in chapter 5.2.

The key stakeholders are involved in the process and have access to FAIRe data in the relevant aspects of the material product world, they are the:

- user, as the focal point of the market,
- product developer, with a view to this market and future generations,
- expert, who mediates between market and holistic ideas.

In the following, the current or future necessary contributions of adhesive bonding technology to the circular economy will be explained step by step.

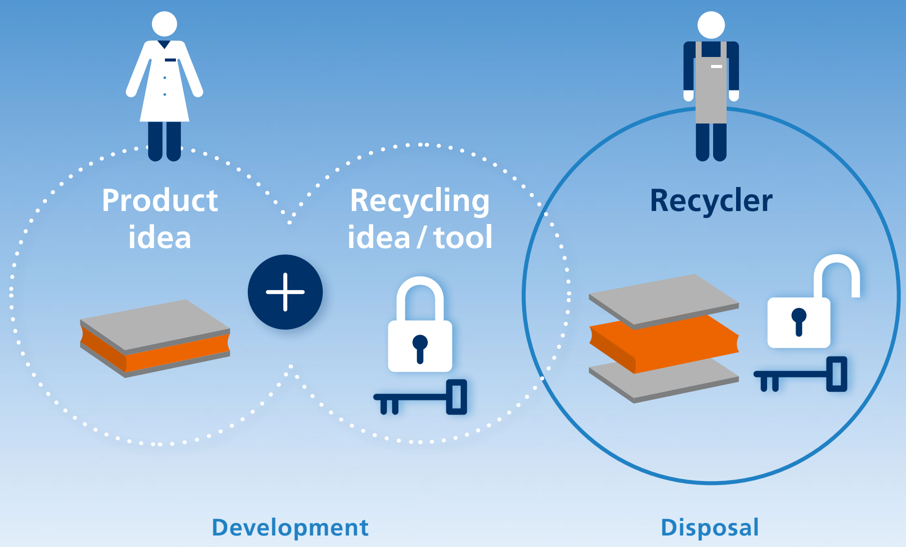


Fig. 78
Process steps and relevant stakeholders in the disassembly of sustainably adhesively bonded joints

5.2 Adhesive formulations in the context of the circular economy

5.2.1 Bonding raw materials from polymer recyclates

The recycling of bulk polymers may result in fractions that cannot be directly reconverted to the original bulk polymers because of different chemical structures, or the quantities may be too small to invest in a plant based on the recyclate.

Since adhesives are typically required in medium quantities, such recyclates can be suitable raw materials for adhesives. For example, polyethylene terephthalate (PET) from bottles, polyamide (PA) from used textiles or polyurethane (PUR) from mattresses or car upholstery can be partially converted by reaction with polyols. In the process, oligomers* with alcohol end groups formed in the process. If necessary, even the "stickies" which are produced during paper recycling and partly originate from paper adhesives can be used here. These can be used as raw materials for various adhesives. Examples of this are:

- reactive and non-reactive polyurethanes
- hot melt adhesives
- epoxy resins, especially cationically curing, or
- polyacrylates.

* Oligomers are macromolecules, which, unlike "monomers", are made up of up to 30 structurally identical or similar units. Unlike "polymers", oligomers have a defined number of units.[373]

A constant and consistent raw material quality is an essential prerequisite for this. Since adhesives are at a higher value-added stage than bulk plastics, this approach even corresponds to upcycling. Alternatively, a powder can be produced from plastic waste, which is used instead of mineral compounds such as chalk or quartz flour as a lightweight filler for adhesives.

373 https://www.chemie.de/lexikon/Oligomer.html (Access April 30, 2020)

This reduces the density of the adhesives and thus promotes lightweight construction.

> **The constant quality of the adhesive raw materials made from recycled polymer is a fundamental prerequisite for the adhesive quality.**

5.2.2 Binding of carbon dioxide

Carbon dioxide is usually the final end product when using carbon-based materials. With the use of energy, CO_2 can be converted back into higher-energy and multi-purpose materials. In nature, this happens through photosynthesis. There are already a few possibilities of binding carbon dioxide directly in materials that are suitable as raw adhesive raw material. The addition of CO_2 to epoxides, with the formation of cyclic carbonates, has been comprehensively investigated. These can then be converted into polyurethanes with amines. However, these reactions require high temperatures and pressure when binding the CO_2, so that they can only be used to a limited extent in the production of adhesive bonds.

Suitable catalysts should make it possible to carry out such reactions under milder conditions. However, it is also important to explore further ways of providing polyurethanes and polyurea derivatives with a high proportion of bound CO_2. There are approaches for this in the literature.

> **Suitable catalysts would enable the binding of CO_2 in adhesive formulations under mild conditions.**

The cyclic carbonates produced as an intermediate product can also be reacted with other substances such as alcohols or thiols. Here too, structures are created that are suitable for adhesives. However, catalysts are also needed that allow the addition reactions to be carried out under mild conditions.

Polycarbonates, aliphatic polycarbonate polyols particularly suitable for adhesives, can also contain bound CO_2. These can then also be converted into polyurethanes, whereby the proportion of bound CO_2 is significantly higher than if only the urethane groups were prepared on the basis of carbon dioxide.

In basic chemistry, many ways of reducing carbon dioxide are being investigated. Usually methane or methanol are the target products. These methods are also suitable for providing adhesive raw materials. However, as these are general, non-adhesive specific ways of basic chemistry, they will not be discussed in detail.

5.2.3 Carbon management in adhesives: Minimisation of the carbon content and adhesive raw materials in a high oxidation state

As has been shown, carbon dioxide can be bound again into usable materials by using energy. The further it is reduced, the more energy is required for this. Conversely, if one starts from substances with greatly reduced carbon, whether fossil carbon sources or vegetable oils, usable energy can be obtained during oxidation. If you oxidize completely, it is usually combustion, so that no usable substances are formed. However, partial oxidation, which is carried out in many ways in the synthesis of organic substances, can produce substances that can be used as raw materials for adhesives. However, this also means that if the proportion of greatly reduced carbon, i. e. mainly in the form of aliphatic and aromatic hydrocarbon units, in adhesives is minimal and particularly low in energy impact. The energy required to generate the adhesive raw materials from higher oxidized carbon (mainly carbon dioxide) is minimal. However, certain amounts of aliphatic chains are required for flowability and flexibility, and it is recognised that not all carbon can be in a high oxidation state. As mentioned above, the use of higher oxidised carbon species in adhesives based on fossil carbon sources only makes sense if the energy content is used in the oxidation of the fossil carbon or if recyclates with carbon in a higher oxidised state are used. When reducing carbon dioxide, it always makes sense to proceed in this way for a favourable energy balance.

If the content of organic carbon in adhesives is as low as possible, this is also favourable for the overall balance. This can be achieved by fillers and is already being implemented today for technical and economic reasons. This can be further optimized by using rheological additives and the appropriate polymer components.

5.2.4 Renewable raw materials

In the past, renewable raw materials have been used to a large extent in adhesives. Their share has declined for technical and economic reasons (see Chapter 3.6). However, more work is being done to increase this proportion again. The competition with food production always proves to be critical. Thus, wherever possible, raw material plants should be cultivated that make use of vegetation gaps or thrive in soils that are not very suitable for food production. This requires research from the agricultural sector to adhesives.

Similarly, there are few genuine waste materials, i. e. those with no material recycling possibilities at an acceptable level of added value. These include, despite considerable research efforts, lignin, but also coffee grounds from the production of caffeine and soluble coffee or feathers. In contrast, starch, cellulose, fats or proteins can be used for many purposes for the preparation of adhesive raw materials. A modification is commonly necessary.

In addition, many substances that are suitable as adhesive raw materials can be produced by fermentation, whereby certain substances can often be provided. Consideration should be given to how these substances can be used in adhesives. Only in rare cases are conventionally used raw materials produced by fermentation, examples being ethanol and acetic acid, which can be further processed into adhesive raw materials.

In this context, it should also be noted that the utilisation of side-streams of food production could also be considered as an option.

In any case, the assurance of consistent quality[374] is an essential prerequisite for the industrial use of renewable raw materials in general. This also applies without restriction to their use in the production of industrial adhesives.

The constant quality of renewable raw materials must be guaranteed for their use in adhesives.

The need for research into the (re)increased use of renewable raw materials in adhesives goes in two directions:

- One direction is the recovery of synthetic adhesives. For this, the performance must be improved, so that the same productivity is achieved as with the synthetic secondary products, for example. These are mostly non-reactive adhesives, which are used in the paper industry or for labeling, among other things.
- The other direction is the development of reactive adhesives based on renewable raw materials, primarily for use in adhesive bonding with the main function of transferring mechanical loads. Adhesives on this basis and with this function are comparatively rare so far. They often consist only partly of renewable raw materials and usually show a worse performance than comparable synthetic products. One example where relatively good properties have already been achieved is the so-called BioDur System[375]. In this system, epoxidized fatty acids are cationically polymerized with polyols based on polylactic acid, so that up to 99 % of the raw materials used are renewable. However, further improvements are necessary with regard to heat resistance and a lower curing temperature.

374 J. Geldermann; In Nachhaltigkeit; H. Corsten, S. Roth, Hrsg.; Springer Fachmedien, Wiesbaden, 2012; Planung der Produktion und Wertschoepfungsnetzwerken fuer nachwachsende Rohstoffe, DOI 10.1007/978-3-8349-3746-9_10.

375 Schlussbericht FNR Projekt "Klebstoffe auf Basis epoxidierter pflanzlicher Oele und hydroxyfunktioneller Polyester aus natuerlichen Monomeren" 14NR205, June 2018.

There is a need for research on the increased use of renewable raw materials in adhesives, both for non-reactive and reactive adhesives.

5.2.5 Degradable adhesives

At this point the complete microbiological degradation is understood by "compostability". The complete microbiological degradation is classified as "compostability". However, compostability is rarely a meaningful development goal for adhesives and other polymers, as it reinforces the "throw-away mentality" of a linear economy, and the materials in the compost or in nature, just like when they are incinerated, are converted into carbon dioxide and water without using the energy they contain. Under "compostability" the standard definition is not used here, according to which a pure visual inspection is made, but in reality larger quantities of microplastics can be formed which are not further degradable.

However, there are applications where compostability can be useful. These include pressure sensitive adhesives used to attach labels to food such as fruit or vegetables. Today, polyacrylates with a low tack are used for this purpose, so that they can be removed from the food comparatively easily, as they are often disposed of with the peels or other leftovers. This is of course only useful in this context if the labels themselves are also compostable. This can also be useful for other things that remain in nature such as markings in gardening and landscaping.

Adhesives could be based on different renewable raw materials and should be pressure sensitive for most of the envisaged applications. For this purpose, longer-chain hydrocarbon units will have to be contained, such as those found in vegetable oils, regardless of whether the adhesive base is based on starch, cellulose or proteins. The use of natural latex would also be conceivable – a solution that could also be available at short notice. As this is a pure hydrocarbon, degradation would be relatively slow, whereas it would be relatively fast with the above-mentioned starch-based adhesives, for example.

5.2.6 Adhesives with high compatibility to the substrate materials

The recycling of used adhesives is usually just as nonsensical as the recovery of printer ink when recycling paper. In contrast, it is important that the adhesive interferes as little as possible with the recycling of adhesively bonded materials. As explained in chapter 4, this is not a problem with materials that can be recycled hot, especially metals and glass, but it can certainly be problematic, especially when recycling plastic components. In order to overcome this, the adhesive should have the highest possible compatibility with plastics. This primarily concerns the miscibility. This is guaranteed if the adhesive is as similar as possible to the substrate material.

> **The recycling of used adhesives makes as much sense as the recycling of printer ink in paper recovery, which is why the adhesive should have as little impact as possible on the recycling of the parts to be joined.**

This can be implemented, for example, in the form of hot melt adhesives with the same base as the plastic part to be adhesively bonded. The tack would be achieved by a lower molar mass or the addition of tackifiers. This could also be applied to composite films, which are used in many ways in the food industry. Since layers of different polymers are often required, an additional layer would be useful here, consisting of an adhesive that is water-soluble under special conditions. In this case, the film could be shredded after collection and then the layers could be separated from each other with hot water. The separation of the resulting mixed fraction would be done conventionally via density, for example.

5.3 Circular economy appropriate product design

5.3.1 Design suitable for dismantling

Whereas up to now the product life cycle phase "utilisation" has been decisive for the design of a product, in future the product life cycle phase "disposal", i. e. the disassembly of the adhesively bonded joint and the recyclability of the materials used, must also be integrated into the product life cycle phase "development". In future, design guidelines for various material combinations and components of different sizes will have to integrate the requirements "suitable for dismantling" taking into account "repair" and "re-use". This applies from microelectronics to large components in the construction industry. Against the background of product safety in joining with the effectiveness of the circular economy, the realisation of this integration of requirements requires a deeper understanding of the existing load cases and the appropriate handling of them.

> **In addition to the product life cycle phase "utilisation", the product life cycle phase "disposal" must in future be considered in the product life cycle phase "development".**

Depending on which concept for disassembly is to be pursued, the adhesively bonded joint must, for example, be accessible for fission reagents or radiation during disassembly, so that these concepts can take effect (see Chapter 5.5). For this purpose, constructive elements can be provided, for example, which control the initiation of disassembly. Conceivable are structures which, similar to grease nipples for introducing lubricant into assemblies, introduce a splitting reagent distributed over the adhesively bonded joint, but which are sealed during the product life cycle phase "utilisation". Similar approaches could be pursued for radiation-induced disassembly concepts and integrated into the product design.

In the design of adhesively bonded joints, the occurrence of peeling stresses is generally avoided for the product life cycle "utilisation", since the adhesive in the adhesively bonded joint designed for planar load transmission and shear stress cannot withstand these linearly occurring mechanical loads. However, a design suitable for disassembly can be created in such a way that the peeling forces to be avoided in use can be specifically applied during disassembly. An example of this is so-called explosive bolts, which deliberately lead to the peeling separation of adhesively bonded parts. With these approaches, it is important to consider that the load case leading to disassembly of the adherends cannot occur during the use phase.

> **The disassembly triggers are integrated in the disassembly-friendly product design, but are definitely ineffective during the product life cycle phase "utilisation".**

5.3.2 Product designs

Adhesive bonding technology can be regarded as an "enabler" of lightweight construction:

- On the one hand, it contributes to lightweight construction through adhesive bonding technology for specific structures, e. g. stiffening elements such as ribs.
- On the other hand, by joining different materials, which are used in the component according to the specific requirements, the adhesive bonding technology can make lightweight construction possible in multi-material construction.

Consistent lightweight construction enables material savings and increased resource efficiency in all phases of the product life cycle (see chapter 2.5).

Adhesive bonding technology can be regarded as an “enabler” of lightweight construction.

The design of a product consisting of several components that can be separated from each other again in the so-called differential construction method has further advantages in addition to the potential for lightweight construction:

Repairability
If any element of the product is damaged during the product’s service life, it can be replaced without having to replace the entire product.

Design adaptations
Even minor design adaptations, such as the individualisation of products according to customer requirements, can be made in the existing process chain without having to build a completely new product line with the corresponding infrastructure. Combined with an increasing degree of digitalisation, adhesive bonding technology will enable modern, future-proof process chains and products.

5.3.3 Design and adhesive application

In the product development process, the amount of resources used must always be critically examined. This applies to the question of what quantity of which material is actually required for the product to perform its function safely. The definition of realistic requirement profiles is crucial here. To prevent overdimensioning of adhesively bonded joints, the requirement profiles on the basis of which the design of a bonded joint is based must be defined realistically, i. e. adapted to the load cases that actually occur. If the load cases are known, improved simulation tools, for example, can help to reduce the experimental effort. Reliable material models are currently still state of the art in many cases, but in the future they can help to significantly reduce the test and inspection requirements for an adhesively bonded joint. If these requirements are excessive and unrealistic, this leads to “over-engineering”.

Adhesive bonding technology "over-engineering" is avoided by defining realistic requirement profiles.

The use of adhesive bonding technology can help to increase the longevity of products, i. e. to extend the product life cycle phase "utilisation". This can also be achieved by developing adhesively bonded products with optimised resistance to ageing. Among other things, optimized surface treatment processes can be used for this purpose, which specifically adjust or improve the adhesion between the surfaces of the joined parts and the adhesive.[376, 377, 378, 379, 380, 381, 382] The knowledge about the optimized properties can then in turn be taken into account in the design.

The optimisation of the ageing resistance of adhesively bonded joints extends the product life cycle phase "utilisation".

376 H. Gleich, A. Hartwig, H. Lohse, adhaesion KLEBEN + DICHTEN 2016, 9, 34 – 38, Warum das Vorbehandeln so wichtig ist.

377 R. Wilken, H. Gleich, adhaesion KLEBEN + DICHTEN 2016, 11, 26 – 31, Kunststoffe richtig vorbehandeln – Part 1.

378 R. Wilken, H. Gleich, adhaesion KLEBEN + DICHTEN 2016, 12, 28 – 33, Kunststoffe richtig vorbehandeln – Part 2.

379 M. Noeske,D. Jost,S. Strudthoff, U. Lommatzsch, International Journal of Adhesion and Adhesives 2004, 24, 171 – 177, Plasma jet treatment of five polymers at atmospheric pressure: surface modifications and the relevance for adhesion; https://doi.org/10.1016/j.ijadhadh.2003.09.006.

380 S. Ebnesajjad, C. Ebnesajjad, Surface Treatment of Materials for Adhesive Bonding, Elsevier,2014, , https://doi.org/10.1016/C2013-0-12914-5 (Access April 30, 2020)

381 J. Comyn, International Journal of Adhesion and Adhesives 1990, 10/3, 161 – 165, Surface treatment and analysis for adhesive bonding; https://doi.org/10.1016/0143-7496(90)90099-J.

382 U. Lommatzsch, K. Thiel, M. Noeske, J. Ihde, R. Wilken; Abstracts of Papers of The American Chemical Society 258 (2019) / Meeting Abstract 245, ACS Fall National Meeting and Exposition (August 25 – 29, 2019), San Diego, USA, Solutions for lightweight construction and CO_2 footprint reduction by analysis of surfaces exposed to laser and plasma treatment

After exact knowledge of the load cases and the surface properties of the parts to be joined, the next logical step is an application technique adapted to the adhesive used and the specific requirements of the product such as process times, geometry, etc. Combined with optimized constructive design through precise design and manufacturing specifications, overdimensioning of the respective adhesive surface or adhesively bonded joint can be avoided. If optimized application techniques are used to apply exactly the required amount of adhesive only at constructionally defined points, the amount of adhesive used can be reduced and used optimally. This results in material and weight savings and increases resource efficiency.

The application technique, which is matched to the adhesive and product requirements, avoids overdimensioning of adhesive surfaces and adhesively bonded joints.

5.3.4 Graded adhesively bonded joints

When liquid adhesives are applied, the same adhesive is on both substrates. The cohesion is therefore the same over the adhesively bonded joint, but the adhesion to the two different substrates is different. When the joint is separated, it is not yet possible to plan where the break will occur. In the case of double-sided adhesive tapes, for example, an adhesive with different strengths is sometimes used on both sides, so that the breakage occurs systematically and adhesively on one side when the adhesively bonded joint is disassembled. In the ideal case, the adhesive remains completely on the substrate, whose recycling it least disturbs.

> **In the case of graded adhesively bonded joints, the breakage of the adhesively bonded joint is systematically adhesive on one side.**

In principle, this could also be achieved with liquid adhesives. However, this is far from being state of the art. Here, for example, layers of adhesive with different properties on top of each other or different adhesives that are compatible with each other could be applied to the two parts to be joined. Due to the different mechanical properties, the predetermined breaking point could then be placed at a specific point on the adhesively bonded joint during repair and recycling. This would also be possible in adaptation to the properties of the substrates. A similar concept was tested some time ago by the Fraunhofer IFAM for adhesive bonding of ultra-high-strength steels, but with the aim of achieving the highest possible strength of the joining by selectively placing stronger and more elastic layers in the adhesively bonded joints.[383]

5.3.5 Saving on secondary packaging through adhesive bonding

In the retail trade, individual packages are usually available as bundles (e. g. six beverage bottles). This secondary packaging takes up a significant proportion of the total packaging. This can be, for example, cartons or wrappings with plastic films. In principle, it is possible to joining the individual packagings with easily detachable adhesive points instead, thus saving on secondary packaging.

Hotmelt adhesives are initially suitable for this purpose, and in particular, pressure-sensitive hotmelt adhesives should be suitable. This is already possible with adhesives available today. However, implementation with the highest possible economic and ecological impact and at the same time high reliability still requires various improvements.

383 A. Hartwig, K. Albinsky, S. Gramsch-Kempkes, P. L. Geiß, Report IGF-Projekt 319ZN, 2012, Entwicklung einer Systematik zur Anpassung von Klebstoffen und Klebverbindungen an die Anforderungen beim Kleben hochfester Staehle

5.4 Detachable adhesively bonded joints

5.4.1 Preliminary note

As was shown in chapter 3.2, there are numerous approaches to realize detachable adhesively bonded joints; quite apart from the fact that any adhesively bonded joint can be detached. As described there, there are usually significant hurdles for practical use. These hurdles are often based on ecological reasons, such as the necessary use of toxic substances. Above all, however, there are economic reasons such as very expensive components, low productivity, very slow separation or separation under conditions where the adhesively bonded joint degrades anyway. There are also safety-related reasons for utilisation of adhesively bonded products, for example, if triggers for releasing the joining occur during use of the product.

The following is therefore a brief outline of some approaches to overcoming the hurdles, unless this has already been described in Chapter 3.2. In addition, a few approaches have not yet been examined in detail.

5.4.2 Detaching adhesively bonded joints with the main function of load transfer

Most of the work in the literature relates to adhesively bonded joints (see Chapter 3.2), which are often relevant to safety. In addition to the measures known so far, loosening with the so-called E-FAST method would be conceivable. This method was actually developed for the rapid curing of adhesively bonded joints.[384] The adhesively bonded joints can thus be hardened quickly, which

384 https://www.ifam.fraunhofer.de/content/dam/ifam/de/documents/Klebtechnik_Oberflaechen/Klebstoffe_Polymerchemie/e-fast-verfahren_zur_schnellh%C3%A4rtung_fraunhofer_ifam.pdf (Access April 30, 2020)

makes the application economically interesting. Later on, they can also be released again in a targeted manner.

> **The E-FAST method would be a conceivable method for releasing adhesively bonded joints with the main function of load transfer.**

In this method, heat is generated through the introduction of an electrically conductive implant at the joint, through which a high electric current is passed. The implant is a metal strip with high electrical resistance and coated with adhesive on both sides. The resistance is temperature-dependent, so that the temperature in the glue joint can be controlled with this measured variable. A lower temperature is set for the hardening of the adhesive, and a correspondingly higher temperature is set for the subsequent release of the joining. As long as the metal strip is not electrically contacted when joining is in use, premature loosening of the connection is impossible, i.e. the trigger for loosening does not occur in real use.

The same applies to the electrochemical separation of adhesively bonded joints, which is suitable for bonded joints with metallic components. Here, as described in chapter 4.2, an electric current and a moderate temperature are applied simultaneously, resulting in an adhesive failure of the joining within a very short time. The process can be applied broadly to many types of adhesive and should be correspondingly versatile.

> **For metallic parts to be joined, electrochemical separation is suitable for adhesively bonded joints with load-transmitting main function.**

Among the many approaches to soluble adhesives, a system that was only recently presented and also briefly mentioned in chapter 4.2 seems to have high potential.344 The crosslinked polymer is stable over the long term and can be dissolved again with superheated water vapor. This happens in such a way that the resulting products can be used again after drying. On the one hand, the necessary trigger for detaching in normal use can be ruled out, and on the other hand there is real reversibility.

> **The separation of load-transmitting adhesively bonded joints with superheated steam also seems to have a high potential.**

5.4.3 Detachment of adhesively bonded joints without the main function of load transfer

Adhesively bonded joints of this type are frequently used, for example, for packaging and other mass products. In these cases, it is not possible to release individual joins manually or semi-automatically. For this reason, most of the processes described are out of the question. Rather, possibilities should be considered in which, for example, the individual layers of packaging can be separated from each other in large stirred reactors and then separated. This is used, for example, with soft packaging (e. g. Tetra Pak®) to separate the carton from the other components (see Chapter 3.4).

For adhesively bonded joints without load transfer – e. g. soft packaging – separation possibilities in large stirred reactors are conceivable.

In particular, layers made of different plastics, or between plastics and aluminum have not yet been separated in this way. However, if adhesives were used which were water-soluble or at least water-swellable, this would be possible after shredding and mechanical agitation in aqueous baths. There may be concerns that packaging materials, especially for food, must be water resistant. Nevertheless, layers of water-soluble polyvinyl alcohol are already being used as barrier layers today. There is, however, a great need for research into such concepts, since potentially suitable basic adhesive are not capable of adhesive bonding the typical composite materials, especially polyolefins, polyamides and aluminium, together or even being processed as coextrudates.

In order to accelerate the degradation of the adhesive layer in a moist state, it would also be conceivable to add enzymes or other active substances to the adhesives, which only become active when the adhesive layer has absorbed enough water. This can then only be done in the case of small shreds in the recycling process. If necessary, these active substances could also be encapsulated, preferably using natural coating materials. For this purpose, encapsulations in pollen and yeast cells have been developed at Fraunhofer IFAM.

One adhesively bonded product that is generated in large quantities as previously non-recyclable waste is nappies. Due to the high moisture content, their incineration is also unfavourable. In a recycling process, the faeces would first have to be washed off and sent to a sewage treatment plant. The adhesively bonded joints themselves are relatively easy to access, so that they could be removed from the outside by attack with suitable agents. If adhesives were used for joining, which swell with hot water and then decompose relatively quickly, the films, non-wovens and superabsorber used could be separated and recycled separately. Ideally, all the films, non-wovens and tapes for sealing would be made of the same base material, so that they could be recycled together. Suitable adhesives would be, for example, modified (thermoplastic) starch or proteins. As described above, degradation and dissolution could possibly be accelerated by the use of enzymes or other, possibly microencapsulated agents. In order to develop such a system, a relatively large amount of research would still be required and, in addition, the logistics of collecting or separating from residual waste and the construction of appropriate facilities would be necessary.

5.5 Disassembly processes

In current development processes of adhesively bonded products, the repair and disassembly of products is not in the economic focus. However, the requirements of the circular economy will shift this focus. It can be assumed that disassembly processes of products for raw material recovery or repair will be essential points in the development process and product testing. The previous sections of this chapter have already explained which material and design modifications favour the disassembly of an adhesively bonded joint. Particularly relevant here are disassembly enablers such as triggers, constructive measures and disassembly aids that promote the release of the adhesively bonded joint. Even when using these disassembly enablers, the task remains to implement the disassembly process economically and on a large scale, and to test its functionality on the entire component and in large quantities. To this end, the disassembly processes must be designed, technically tested in line with the application and implemented in the plant. For each specific product and for each dismantling enabler, a bespoke dismantling process must be developed.

> **For disassembly processes, disassembly enablers are crucial.**

The following section lists different disassembly process variants and supplements these with a reference to specifically advantageous disassembly enablers:

In many cases, the fragmentation of products can be a suitable method for the recovery of materials. A wide range of different component geometries, small component dimensions and high quantities reduce the possibility of targeted disassembly and favour the use of non-specific fragmentation. Fragmentation means that joined parts and adhesively bonded joints are broken up into small fragments, so that sorting according to material type is possible. The use of appropriate shredders is possible for the fragmentation of large quantities of components. It should be checked whether the shredding process breaks up the adhesively bonded joints when the joining zone is divided up or whether fragments of adhesively bonded mixed joints remain after the shredding process. If necessary, the shredding process should be optimized in such a way that the amount of adhesively bonded fragments is reduced. It must be taken into account that the joining surfaces and thus the mass proportion of joined fragments are generally very small compared to the total mass. If the fragments of intact surfaces are also to be separated, good accessibility to the bonding surface of these fragments enables attack by intermediate influences or the use of intermediate dismantling enablers.

> **With a large number of different component geometries, small component dimensions and high quantities, the fragmentation of products can often be a suitable method for material recovery.**

Large component dimensions with a high dead weight of the pure material components favour the application of mechanical detachment of adhesively bonded joints. In the case of metallic components, the adhesively bonded joint is a weak point of the joint, particularly when subjected to appropriate induced loads e. g. peeling. In addition, the application of dynamic loads directly on the adhesively bonded joint, for example with a chisel hammer, can be used to loosen stiff and rather brittle adhesively bonded joints. For soft, elastic adhesively bonded joints, cutting in with a vibration knife or a hot blade, for example, is more effective. Hybrid adhesively bonded joints are frequently found in vehicle construction or in “white goods” as a combination of adhesive bonding with welding, clinching, folding or riveting are less suitable for this type of disassembly method, as the points of the hybrid connection act as crack stoppers to prevent peeling disassembly. Pure adhesively bonded joints in these constructions are therefore considered advantageous for disassembly.

For the mechanical detachment of adhesively bonded joints, pure adhesively bonded joints, which are used without additional joining techniques, are advantageous.

The labour-intensive processes of mechanical disassembly can be facilitated by disassembly enablers, design measures, auxiliary means or process automation. For disassembly of wide adhesively bonded joints with elastic adhesives, utilisation of hot wires or other cutting tools has proven to be advantageous. The hot tool burns or softens the adhesive locally and can be guided successively around the joint with less force. The design should ensure that the adhesively bonded joint is accessible for such disassembly aids. It should also be considered whether a separating device could be integrated into the product. For example, a heatable wire could be integrated into the elastic bonded joint of a car windshield as an insert for disassembly.

Disassembly enablers, design measures, aids or process automation facilitate mechanical disassembly.

The use of automation technology is conceivable for the mechanical detachment of large series products. Power-intensive processes can be carried out or supported mechanically by automatic machines or robots. The combination of mechanical separation after weakening of the adhesively bonded joint due to intermediary, thermal influences or the use of triggers can be helpful in reducing the amount of force required. However, the design of product-specific disassembly lines is still largely untested. In principle, however, such automated lines should be thought of in parallel to the production lines of product manufacture. Automatically guided tools and fixing devices in combination with thermal influences or triggers enable the planned stepwise mechanical disassembly of a product. The robot-assisted disassembly of an Apple iPhone is impressively described in a video.385 However,

385 https://www.youtube.com/watch?v=29leuyC3rgY (Access April 30, 2020)

disassembly lines are cost-intensive and therefore initially only suitable for products with high-quality materials that have been produced in large quantities.

> **The use of automation technology is conceivable for detaching adhesively bonded large series products, but the construction of product-specific disassembly lines is still untested.**

Disassembly by heat input is a means of disassembling products both in combination with mechanical disassembly and on its own. Heat should preferably be applied directly into the adhesive layer in order to avoid damaging polymeric substrates and to reduce the energy consumption of metallic substrates. There are various possibilities to burn an adhesive at high temperatures or at least soften it at lower temperatures. Softening or burning can prepare an effective mechanical release. Local heat input can be achieved by methods that are already used for rapid curing of adhesives according to the state of the art. These include induction and microwave radiation. The advantage is that, in contrast to rapid curing, the heat input does not have to be precisely controlled in order to protect the adhesive. The heat input can be combined with triggers in the adhesive. Various fillers are available for this purpose, which react to the input of electric current, magnetic fields or electromagnetic radiation by heating up. Heating of the adhesive layer can also act as a trigger for chemical components, which in turn weaken the adhesive layer. For example, blowing agents could be used to cause adhesives to foam up when a certain temperature is exceeded, thus massively weakening the adhesively bonded joint. Particularly suitable for the disassembly by heat input of adhesively bonded joints are the physical hot melts, which reversibly change from the solid to the liquid phase when heat is applied and thus cancel out the cohesion of the adhesive.

> **Disassembly by heat input is an independent disassembly method, but can also be combined with mechanical disassembly.**

The last example of disassembly processes is disassembling through media influence. Adhesively bonded joints can be sprayed with liquids, steamed or immersed in liquids that weaken or dissolve the adhesive or weaken the adhesion. Disassembly liquids is particularly suitable for aqueous adhesive dispersions and is used successfully in this area both in the trade, for example to remove wallpaper, and in serial products, for example to remove labels from returnable bottles. However, the media influence does not have to be limited to water. Special chemical baths can also cause the detaching of selectively sensitive adjusted adhesives without damaging the joined parts. In particular, various acids, alkalis or oxidizing agents can have a highly damaging effect on the polymeric adhesives. They can be used advantageously as liquids for dissolving specific adhesives. The medial influence can be combined well with mechanical dissolving. The influence of liquids can be combined with mechanical methods and the adhesive is weakened by the active medium and can be destroyed by small forces.

> **The targeted medial influence on an adhesively bonded joint can also be combined with mechanical detachment.**

Overall, there is a wide range of practicable possibilities for disassembly processes of adhesively bonded joints, which can be applied to different product classes. The economic applicability of this range is greatly enhanced if triggers or constructive possibilities for disassembly are already taken into account during product development. The adhesive bonding does not prevent the disassembly of products, but offers a starting point for the detaching of joints. However, for an economical disassembly, the disassembly capability must be included in the specifications of the planning at an early stage of product development.

> **The adhesive bonding offers a starting point for detaching the material compound.**

5.6 Digitalisation in the effectiveness of the circular economy in adhesive bonding technology

5.6.1 Preliminary remark: adhesive bonding technology – digitalisation and circular economy

In addition to the approaches to the utilisation of adhesive bonding technology in the circular economy described in the previous paragraphs, there is an increasing debate about the relationship between another megatrend, digitisation, and the social objectives of the circular economy. The example of the circular economy shows that existing information deficits can be overcome with the help of digitisation, thus providing a more reliable basis for decision-making. New markets with specific applications can thus also be created for adhesive bonding technology.

> **Digitisation helps to overcome existing information gaps for adhesive bonding technology.**

The networking of industry, also known as Industry 4.0, creates cyberphysical systems that digitize product and process information and transfer it along production processes. Digital twins – the digital image of products – can transmit environmental information, for example the material composition of products. Furthermore, in the context of adhesive bonding technology, information for the later release of adhesively bonded joints must be brought together in the digital twins. This contributes to a reduction of the existing information deficit around the circular economy.

Extensive efforts are being made at both European and national level to select and structure material and production-relevant data and make it available to users in virtual marketplaces (see the comments in Chapter 3). Irrespective of this, the information can also be made available selectively, i. e. on a manufacturer- or product-related basis, especially in connection with the circular economy. For example, this could be specific information from product manufacturers concerning recycling and disassembly of products. In this context, new business models will be established that are also highly relevant for the manufacturers and users of adhesives. In the following sections, the main aspects will be discussed in more detail.

5.6.2 Simulation to reduce the experimental effort

In order to integrate a process into production, a great deal of experimental effort is required for verification. With the help of digital material models, the experimental effort can be reduced. This can lead to life cycle predictions that allow an adequate design of the component. Validated models can also enable shorter product development cycles with less experimental effort and thus the faster adoption of new materials and construction methods that meet the requirements of the circular economy.

> **Digital material models can reduce the experimental effort.**

5.6.3 Long-term monitoring of adhesively bonded joints using Structural Health Monitoring – SHM

Many load-bearing adhesively bonded joints, for example in the automotive, wind power and aerospace industries, are subject to long-term cyclical loads that can lead to local material fatigue and thus to premature failure of the structures.386 A complete check (see chapter 1.9.2) of the condition of an adhesively bonded joint is not possible with current non-destructive testing

386 T. Augustin; J. Karsten; B. Koetter; B. Fiedler In Composites Part A: Applied Science and Manufacturing 105, DOI: 10.1016/j.compositesa.2017.11.015; 2018; 150–155, Health monitoring of scarfed CFRP joints under cyclic loading via electrical resistance measurements using carbon nanotube modified adhesive films.

(NDT) methods.387 Therefore, the research and development of systems for structural monitoring of adhesively bonded joints with the main function of transmitting mechanical loads is an important research topic. This is especially true for adhesively bonded joints with safety requirements according to the adhesive bonding standards for quality assurance.40,71–77 These structural monitoring systems are called SHM systems. SHM stands for "Structural Health Monitoring" and is described by the German Society for Non-Destructive Testing (DGZfP) as a "continuous or periodic and automated method" for monitoring structures.388 For this purpose, sensors are permanently integrated into the structure to be monitored.389 The integration of an SHM system into a structure means a reduction in maintenance costs, a more resource-saving replacement of wearing parts and a significant increase in safety.385 Against this background, Structural Health Monitoring – SHM contributes to the effectiveness of the circular economy of adhesively bonded structures.

> **The development of SHM systems is an important research topic and contributes to the effectiveness of the circular economy of adhesively bonded structures.**

5.6.4 Digital Twin

Digitisation makes it possible to store relevant product data containing information on disassembly and recycling, for example, in a virtual mirror image of the product, the so-called

387 T. Loebel; D. Holzhueter; M. Sinapius; C. Huehne, International Journal of Adhesion and Adhesives, 2016, 68, 229–238. A hybrid bondline concept for bonded composite joints; https://doi.org/10.1016/j.ijadhadh.2016.03.025.

388 http://www.dgzfp.de/Fachaussch%C3%BCsse/Zustands%C3%BCberwachung (Access April 30, 2020)

389 A. Trilaksono; N. Watanabe; H. Hoshi; A. Kondo; Y. Iwahori; S.-I. Takeda, OJCM 03 (03) 2013, 63–87, Continuous Damage Monitoring of a Thin Composite Structural with Mismatched Stiffener in a Combined Joint Using Fiber Bragg Grating under Tension and Three-Point Loading; doi: 10.4236/ojcm.2013.33008.

"digital twin". All adhesives or adhesively bonded components (see below) are to be provided with a "Digital Twin", which enables the selection of the best possible disassembly process. This requires specific information on physical conditions such as temperature, radiation etc.

For example, adhesively bonded products are fitted with an RFID chip containing the interoperable data mentioned above. This includes the mechanical stress on the adhesively bonded joint, which leads to failure. In addition, the RFID can be used to retrieve all the data of the materials and adhesives that may be required for disassembly, for example. In addition, it is conceivable that, for example, a lifetime estimate or potentially critical events that the structure has "experienced" could be recorded and additionally stored by appropriate SHM systems. The necessary sensor technology and ways of storing and reading this information are currently state of the art (see Chapter 5.6.4).

For the development of suitable models, the complex relationships between adhesion and cohesion in the area of adhesively bonded joint, joining properties, geometry and load cases (including superimposed load cases such as temperature, humidity and mechanical load, continuous load) must be understood. The deeper the understanding is here, from the atomic to the macroscopic level, the better the prediction accuracy of the models and the more efficiently they can be used in product development.

> **The depth of understanding of the complex relationships in the area of an adhesively bonded joint determines the efficiency in product development.**

5.6.5 Linking the development of adhesively bonded products suitable for recycling with digitalisation (data)

As shown in Chapter 4 and illustrated in Figure 79, the global digital transformation of product research and development, the economy and society is driven on the one hand by the availability of secure, energy-efficient, financially viable and high-quality capacities for the collection, processing and evaluation of data from various sources (data-driven innovation). On the other hand, the utilisation of the available digital platforms and their infrastructure is subject to regionally varying regulations and standardisation. Bringing these together requires interoperability and the involvement of all key stakeholders. Comparable to the introduction of innovations based on artificial intelligence (AI), this poses great challenges, especially for small and medium-sized enterprises (SMEs).[390]

With regard to the life cycle, required and generated data contribute to and are available from the European Circular Dataspace (→ see Fig. 79).

> **A common language must be developed for data exchange.**

It can be expected that the availability and use of a common language will be used for data exchange. This common language is based on standardizing ontologies, both technically and regulatory (see chapter 3.2). In the implementation of the European Green Deal[391, 392], which goes hand in hand with the mobilisation and promotion of (materials or environmental) research, this applies, for example, to the exchange of information between and within cooperating networks of representatives of business, civil society and local, regional or national public authorities.

One aim of such efforts is to provide product purchasers with reliable, comparable and verifiable information when purchasing a product, including an adhesively bonded product. On the one

390 T. Daubenfeld, Nachrichten aus der Chemie 2020, 68 (2), 29, KI-Wueste Mittelstand?.

391 E. Maire; "Implementing the Circular Economy in the EU"; Vortrag praesentiert anlaesslich der 10th ISCC Global Sustainability Conference; Brussels, Belgium; 12 February 2020; downloadable from https://www.iscc-system.org/stakeholders/annual-iscc-global-sustainability-conference/ .

392 European Commission, "The European Green Deal"; Bruessel, Belgien, 11.12.2019, zugaenglich ueber https://ec.europa.eu/info/sites/info/files/european-green-deal-communication_en.pdf.

hand, this information enables sustainable purchasing decisions, on the other hand it prevents "green washing" of products by product suppliers. To this end, standardised methods for securing 'green claims' are to be established. For this purpose, the introduction of an electronic product passport is being considered, in which the following are explicitly executed:

- origin
- composition and
- instructions for repair, disassembly and handling after the end of life handling.

> **The aim is to provide reliable, comparable and verifiable information for (adhesively bonded) products.**

In the course of the digital transformation, as shown in Figure 80, the training of translators will be of great importance. On the one hand, these translators are familiar with the standards; on the other hand, they act impartially with regard to the (adhesively bonded) product. Their task is that of a mediator in the exchange of material-, regulation- and data-based information between key stakeholders in sustainable development processes. An Open Translation Environment as a digital tool to support their work is being developed in the Horizon 2020 joint project OntoTRANS [393]. The integration of translators/intermediaries in adhesive bonding technology decision-making and application-related product design is given high strategic priority in order to increase competitiveness, especially of SMEs. However, the "mediating function" described above can only be successfully implemented if the competence of the translators with regard to their conformity to the European digital marketplaces and their ontologies is directly linked to technology-specific qualifications, which in this context requires the development of adhesive bonding technology qualifications and their implementation.

393 Ontology driven Open Translation Environment – OntoTRANS; Grant agreement ID: 862136; 1 April 2020 – 31 March 2024; https://cordis.europa.eu/project/id/862136 (Access May 30, 2020).

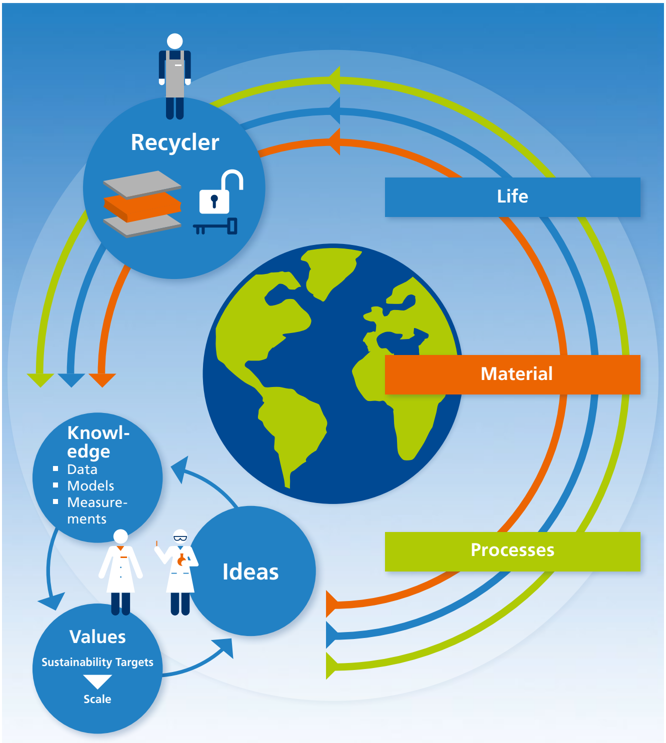


Fig. 79
Sustainable material development for imaginative adhesive bonding technology products with lifelong integrated and digitally always available disassembly idea

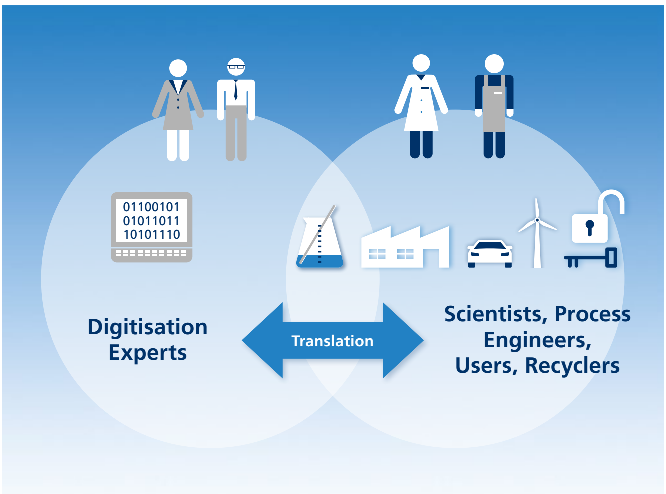


Fig. 80
The product-related translation in the interplay of the players in the adhesive bonding technology life cycle

The task of "translators" is the impartial transfer of material-, regulation- and data-based information between the participants of sustainable development processes.

On the other hand, in the course of the digital transformation, the implementation of ideas for the development of future-oriented, sustainable and adhesively bonded products within the framework of iterative processes will depend on the following:

- Material and process-related data and metadata must be FAIR: findable, accessible, interoperable and reusable.
- As far as possible, they must enable consideration of the expected requirements and stresses during the manufacturing, utilisation and end-of-life phases as early as the design phase.

In the future, modeling and simulation across scales and process steps will cover much broader spatial areas and time spatiotemporal, i. e. four-dimensional, time spans. The development and consolidation of the digital tools and infrastructures required for this purpose require joint efforts, which are managed across domains in pre-competitive or competitive networks. At present, interdisciplinary material modeling in Germany, such as large-scale research activities at universities and research institutions is at the forefront throughout Europe. Material characterisation and process engineering will follow in the medium term.

In the European context, Germany is among the leaders in the research activities of interdisciplinary material modelling.

5.6.6 Integration of upstream and downstream manufacturing steps into process chain modelling and optimisation

As shown in Chapter 4 and illustrated in Figure 81, a bonding process does not just contain a chain of individual process steps. It comprises several process steps to be carried out in a targeted relative time sequence as well as a targeted spatial arrangement and structure of materials that build on one another, which are changed as operands in the process. So far, it has been possible to look at each of the required process steps as well as the necessary materials, energy expenditure and the human or machine operator actions that change the operands as part of a local optimisation.

The use of digital tools and the availability of material and process-related data along the entire process chain within the framework of FAIR data concepts will allow the developers of adhesives in the future, across the entire life cycle as part of a holistic view, also with regard to optimal:

- material efficiency
- cost efficiency and
- energy efficiency

while at the same time protecting the environment. It is essential here that all the combinations to be considered meet the safety-related and material-related technological requirements. This requires a detailed knowledge of materials.

> **Digital tools as well as material- and process-related data allow in the future a maximum of identification regarding material-, cost- and energy efficiency with a holistic view and long-term stability.**

In adhesive bonding technology, one of these requirements is the safe handling of the build-up of a long-term stable adhesion. For this purpose, a professional treatment and quality control of the different surfaces of the parts to be joined must be provided in the area of the adhesively bonded joint. In many cases, this can be achieved by using local and dry process steps, e.g. by laser or atmospheric pressure plasma. The adhesion quality achieved is comparable to wet chemical process steps, which usually cannot be used locally and therefore cover the entire part to be joined. For this consideration, cost aspects must also be taken into account in terms of sustainable material and process development. The use of e.g. process-accompanying measuring methods for quality assurance provides additional process information and enables the significant reduction of scrap.

Right: Fig. 81
Process steps and players in quality-assured adhesive bonding technology

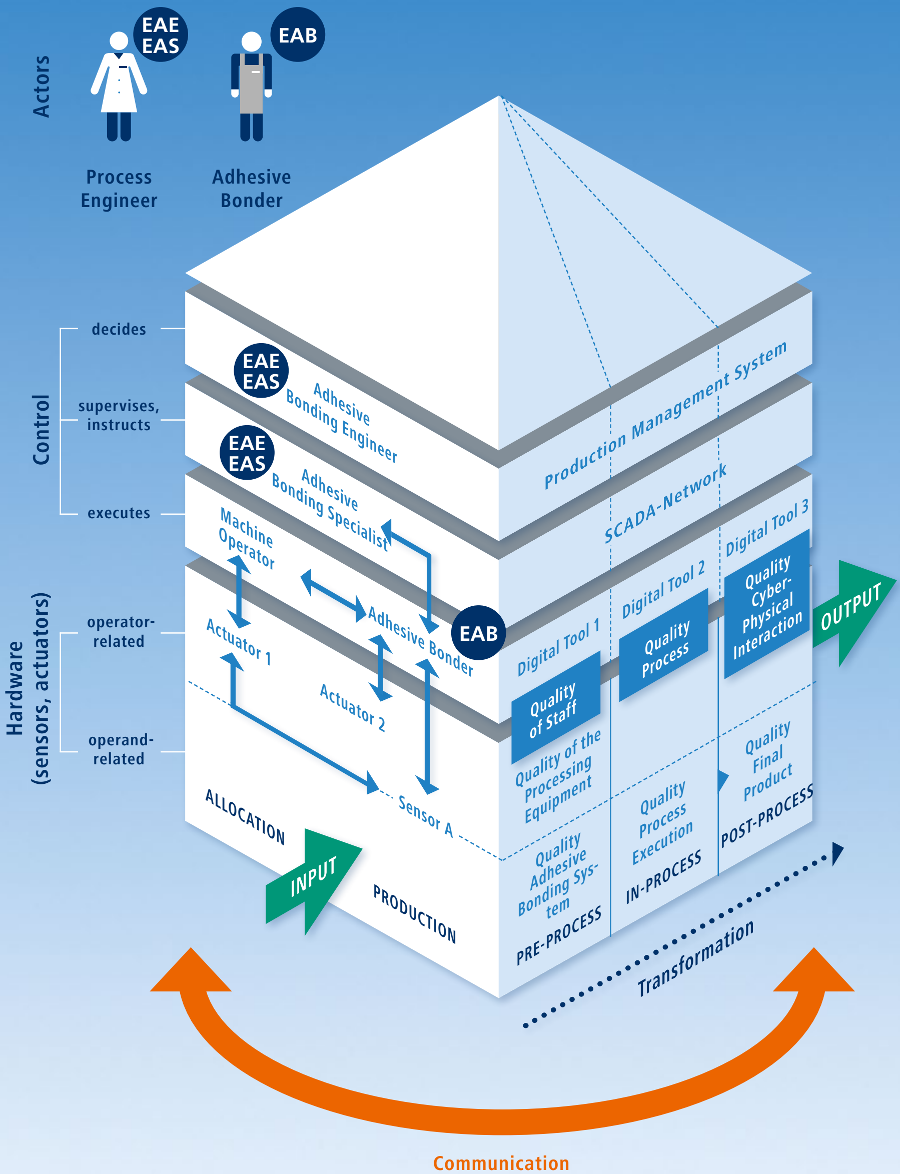
For a PEF-based overview of the overall "adhesive bonding" process with a focus on the environmental impacts, the standardised elaboration of product category rules (PEFCR), which are to be developed in Community committees, is also necessary. This is still open in particular for material surfaces and their integration into a general PEF system. Current projects of the Community Committee on Adhesive Bonding Technology (GAK) only consider the life cycle of adhesively bonded joints with regard to greenhouse gas emissions (Product Carbon Footprint – PCF).

> **Product category rules for the environmental footprint (PEFCR) are still to be developed.**

The ontology-based elaboration and incorporation of cost aspects, environmental aspects and material data aspects into adhesive bonding technology process steps that contribute to the build-up of adhesion is being advanced for dry and wet chemical cleaning and pretreatment processes at the Fraunhofer IFAM in collaboration with external cooperation partners. In the future, the development of corresponding technology will be carried out in the interplay of diverse data and databases in awareness of the sustainability of products and production steps in the life cycle. In this case, modeling is integrated at the planning stage, e.g. with regard to the expected aging or possible recycling options, based on the comprehensive material and process steps. → see Fig. 81 [394]

> **Future sustainable developments of adhesively bonded products and adhesive bonding technology production will include ageing and recycling modelling.**

394 M. Noeske, W. Leite Cavalcanti, H. Bruening, B. Mayer, A. Stamopoulos, A. Chamos, T. Krousarlis, P. Malinowski, W. Ostachowicz, K. Tserpes, K. Brune, R. Ecault; In Adhesive Bonding of Aircraft Composite Structures Non Destructive Testing and Quality Assurance Concepts; W. Leite Cavalcanti, K. Brune, M. Noeske, K. Tserpes, W. Ostachowicz, M. Schlag, Ed); Springer International Publishing: Basel, 2020.


Actors
EAE
EAS
Process Engineer
EAB
Adhesive Bonder
Control
decides
supervises, instructs
executes
Hardware (sensors, actuators)
operator-related
operand-related
EAE
EAS
Adhesive Bonding Engineer
EAE
EAS
Adhesive Bonding Specialist
Machine Operator
Adhesive Bonder
EAB
Actuator 1
Actuator 2
Sensor A
ALLOCATION
INPUT
PRODUCTION
Production Management System
SCADA-Network
Digital Tool 1
Digital Tool 2
Digital Tool 3
Quality of Staff
Quality Process
Quality Cyber-Physical Interaction
OUTPUT
Quality of the Processing Equipment
Quality Adhesive Bonding System
Quality Process Execution
Quality Final Product
PRE-PROCESS
IN-PROCESS
POST-PROCESS
Transformation
Communication

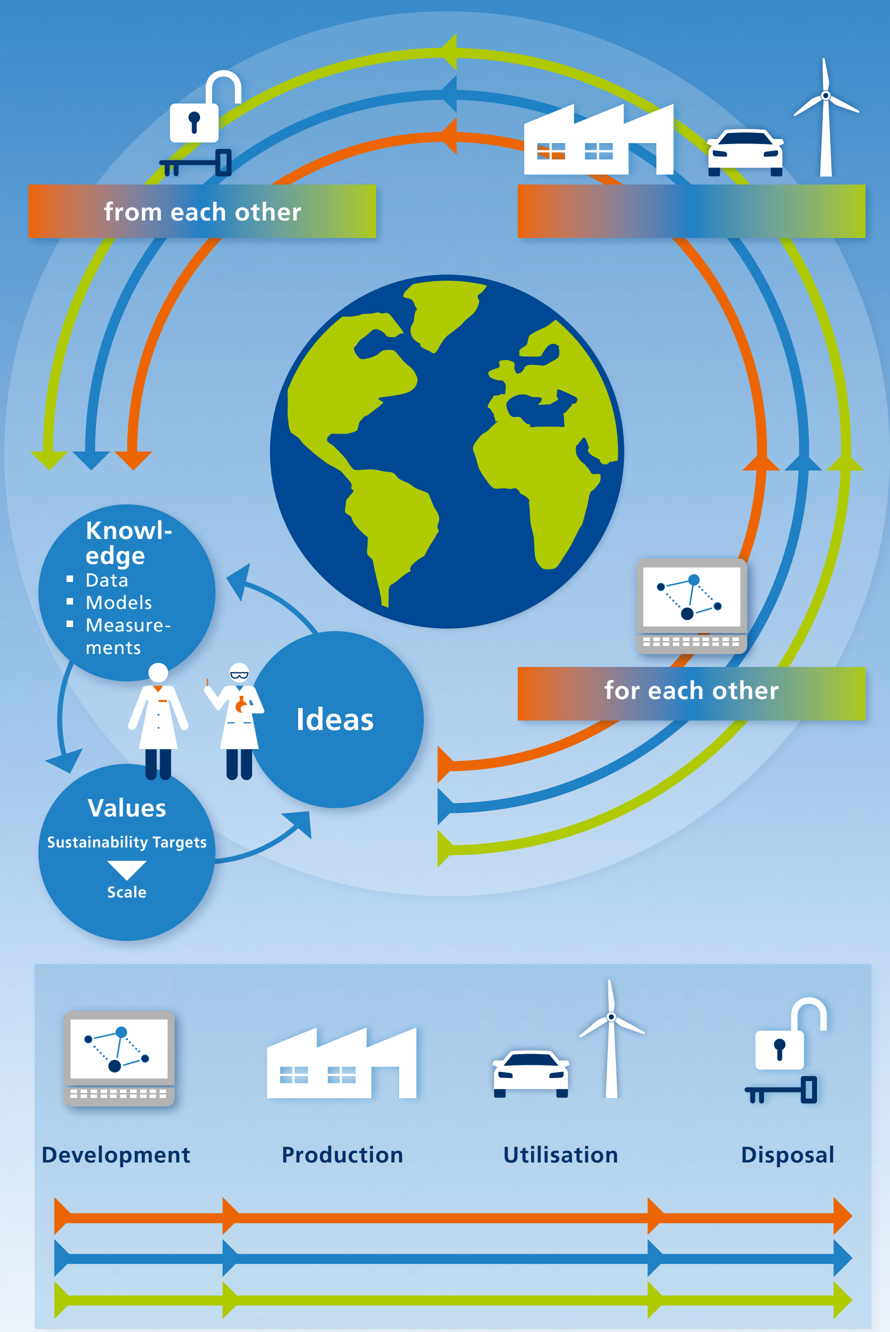
Right: Fig. 82
All key stakeholders in the life cycle use digitised information to holistic design, application and utilisation of adhesively bonded materials

5.7 Outlook with regard to the digitalisation of the effectiveness of the circular economy in the field of adhesive bonding technology

In modern and future-oriented, adhesively bonded multi-material composites of the 21st century, materials show more than their design-related physical presence or their construction-related relative geometric arrangement. In addition to their material properties, they are used in adhesively bonded joints in combination with their data and, above all, metadata. In terms of a holistic view, this makes the inclusion of "end-of-life" procedures already visible in the product life cycles "development" and "production". A generation-spanning communication of FAIR (meta-)data is ensured by the standardised combination of textual, conceptual and spatial-pictorial information in ontologies, which also include the temporal dimension.

> **In the 21st century, materials become additionally visible through their material presence or spatial arrangement in joining with their (meta-)data, including "end of life" scenarios.**

In contrast to the past, the historical material- or activity-related information will be digitised in the future. While the materials were previously in the foreground, their inseparable relationship with data will become more important for all product life cycle phases. Not only the ecological value, but also the economic value of these connections far exceeds the material value, especially in adhesive bonding technology. In addition, the focus on "material to safe product" also gives environmental aspects and social development opportunities a long-term dimension in terms of sustainability. This is achieved by looking at adhesively bonded


from each other
Knowl-
edge
▪ Data
▪ Models
▪ Measure-
ments
Ideas
for each other
Values
Sustainability Targets
Scale
Development
Production
Utilisation
Disposal

joints, which combine the effectiveness of the circular economy with product safety and durability. The relevant key players are assuming their responsibilities in cooperation (→ see Fig. 82).

> **In the future, materials will be inseparably linked with data on all product life cycle phases, which means that the economic value of these relationships will far exceed the material value, even in the context of adhesive bonding technology.**

Already, adhesively bonded products are an implicit part of the Circular Economy. In the future, the relevant stakeholders – be it in production, application, repair or careful disposal of adhesively bonded joints – will be able to experience it interactively and make it accessible for comparative considerations.

The view of a sustainable adhesive bonding technology thus includes three equally supporting pillars of sustainability (→ see Fig. 83). Economic, environmental and social aspects are reflected in sustainable products in a holistic life cycle perspective.

> **In terms of sustainability, the view "from material to safe product" in adhesively bonded joints gives a long-term dimension to environmental aspects and social developments, combining effectiveness of the circular economy with product safety and durability.**

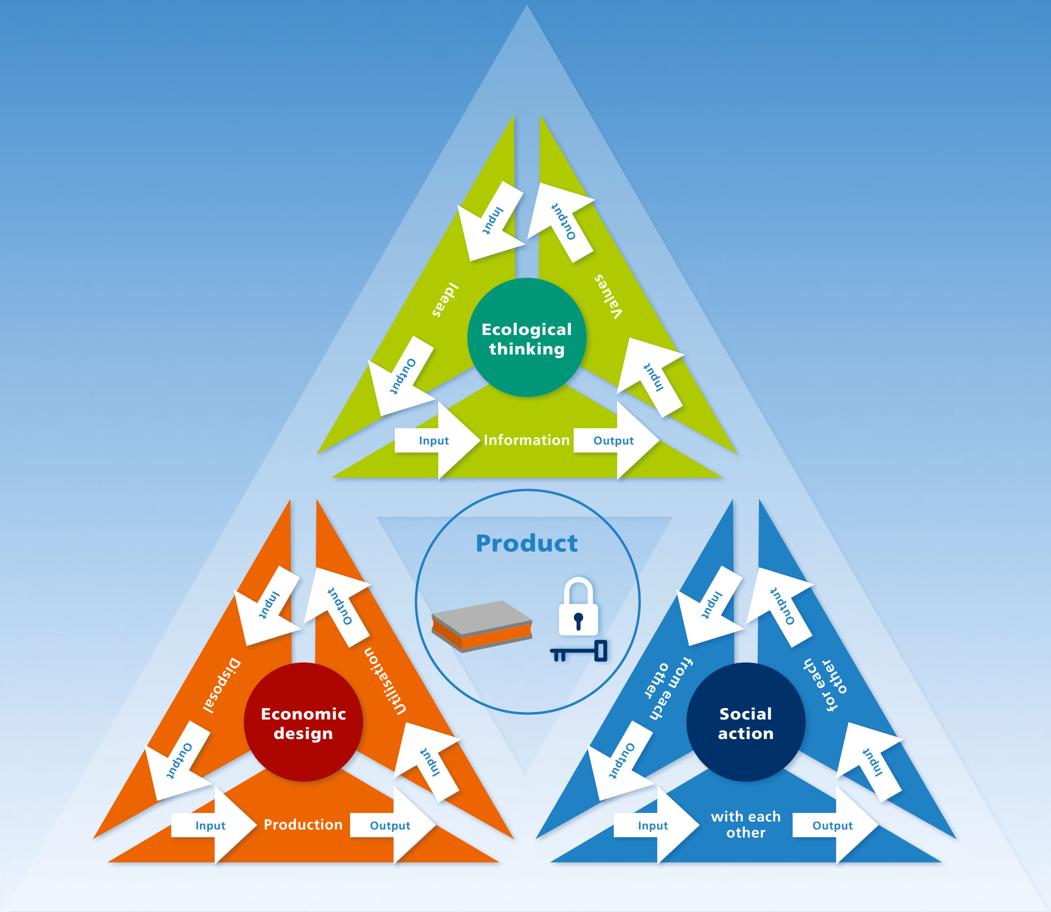
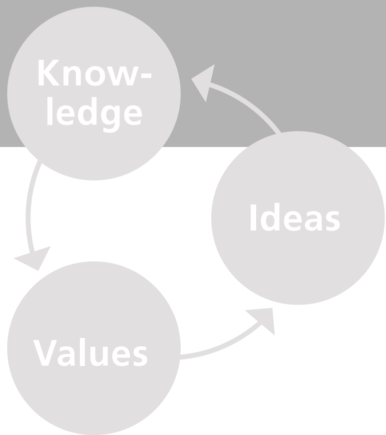


Fig. 83
Tripod model of sustainable adhesive bonding technology



Know-
ledge
Ideas
Values