An approach for agile planning of disassembly and recycling of complex products

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Abstract: Manufacturing companies nowadays are more than ever compelled to adapt to the challenges of constantly changing conditions in the product creation process. The exchange of digital data and data processing are pre-requisites for improvements of agility from initial idea to disassembly and recycling. The 3D PDF format offers not only the ability to visualise 3D data without installing or licensing a CAD system, but also allows the data to be dynamically adjusted, commented and animated in a template container. In this paper, a concept for the use of 3D PDF is presented regarding a defined workflow for disassembly and recycling within the product creation process. After having identified a distinctive field of studies with the help of the model, it is to work out a new use case. Later in the paper, a workflow is developed and finally a prototypical example of the 3D PDF document is implemented.

Keywords: disassembly; recycling; design for X; sustainability; product creation process; 3D PDF.

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1 Introduction

Although manufacturing has been in steady decline in advanced economies for decades, manufactured goods are still understood as the tangible evidence of progress, innovation and competitiveness. To stay competitive, manufacturing industries are forced to adapt their business processes to the recent IT technology which facilitates the entire product life cycle – from first idea of a product to its disposal and recycling. This optimisation to agile processes includes the entire product development process, starting from product planning and requirements management until dismantling and recycling of the product (McLay, 2014).

Life cycle issues are becoming increasingly important to designers as such issues have become of much greater interest to business owners, consumers and regulators. Regulators are responding to the increased community awareness and are beginning to recognise that some aspects of sustainability require regulation to be achieved (Jonasssin, 2008; Ryan, 2014). International standards such as the ISO 14000 series have been developed for environmental considerations across the whole life cycle and have been implemented across a variety of sectors (Kuo, 2006).

In general, recycling is defined as the "return of production and consumption waste into the economic cycle". This includes not only the recycling and reuse of waste material, but also the further use and recycling of used parts in new ways (Fees, 2016). These terms are to be distinguished. To further use' means to utilise already used products for any other than the original purpose. This contrasts with the reuse, whereby the product is used for the same purpose (Jemala, 2013). It includes the removal of functional parts of a vehicle to be scrapped and their reinstallation in another, still drivable vehicle (Lambert and Gupta, 2005). Recycling refers to the reuse of waste materials and production waste in a similar production process (Duflou et al., 2008). One example for this type of recycling is to melt down old vehicle parts, in order to reuse the resulting raw materials for new vehicles. The last type is recycling, whereby waste material and production waste is integrated within a production process that they have not yet passed through (Perry et al., 2012). For example, old car seats are shredded to use the fibres in a new process for the insulation (Rost, 2015).

In the automotive industry, legal requirements for the disposal and recycling of car wrecks prevail. In a directive of the European Parliament, automobile manufacturers are encouraged to avoid waste as far as possible. Therefore, the reuse and recycling should take precedence. To make this possible, all EU member states have to take measures in order to take back end of life vehicles (ELVs) for processing and recycling (European Parliament, 2000). Thus, automobile parts do not have only to be dismantled but also to be sorted by criteria such as material, reusability and processing ability (Santini et al., 2010). The dismantling of hazardous substances, such as the built-in airbag pyrotechnics must be clearly described for recycling companies to minimise the potential danger during further disassembly (Romeiro Filho and Rosa de Lima, 2011).

The support for such disassembly and recycling activities is not sufficient yet, despite of progress in development of IT tools. The starting point for the corresponding case study is a company in the field of mechanical engineering that offers its customers, among other things, maintenance contracts (Peruzzini and Germani, 2014). The company sells several products, each of which contains detailed service documentation. These include 2D drawings of the individual product and various bills of materials (BOMs), with which, for example, spare parts can be ordered. In addition, a service manual even includes instructions for the assembly and disassembly of different components in individual steps with appropriate drawings (Bogue, 2007; Gaustad et al., 2010).

For the creation of the service documentation, the aggregation of engineering design data across-the-board and the processing of this data are necessary (Fukuda et al., 2013). The design engineer team has to revise its 3D models, to create screenshots and to adjust them to the desired assembly/disassembly steps based on design for X rules (Go et al., 2012; Riascos et al., 2015). Product manufacturing information (PMI) and annotations must be processed appropriately. BOMs have to be extracted and reformatted from the product data management (PDM) and other part lists from associated XML files. Once the data is complete, the service documentation with more than 500 pages can be printed and distributed to the authorised service staff.

The process of creating an assembly instruction often takes a long time, since many arrangements between different departments are needed. In addition, the process could still yield some disadvantages: if errors are found in the documentation, an updated version must be created, printed and distributed. Due to its extent, the service documentation is often confusing and only slightly supports service staff when ordering replacement parts. In particular, in case of conflicting requirements an agile approach is beneficial.

To make the creation process and the usability of the service documentation more efficient, providing an IT tool for the automation of the process of agile disassembly planning is necessary.

As both a web-research and an analysis of the product documentation of largest product lifecycle management (PLM) providers did not result in a solution but only in numerous prototypes for distinct purposes (Smith and Chen, 2011; Smith et al., 2012; Xia et al., 2014), we can assume that currently no specialised commercial software for disassembly and recycling is available. Thus, the following research questions arise:

1 Can such software based on a standard IT basis technology be developed?
2 Can this software cover the whole process of disassembly and recycling with all its roles?
3 Is the developed approach applicable to products of any complexity (primarily cars)?

For several reasons, the 3D PDF technology was used to create and utilise the corresponding application for the optimisation of the process of product service (Katzenbach, 2015).

The remainder of this paper is structured as follows: in Section 2 the requirements of the automotive industry are described, followed by the requirements for the corresponding 3D PDF document in Section 3. Analysis of the existing use cases for 3D PDF is shown in Section 4. Concept for creating a 3D PDF recycling document and its implementation are subjects of the following Sections 5 and 6. Section 7 gives the conclusions and outlook.

2 Requirements of the automotive industry

Additional pre-requisites and requirements need to be added to the use case already worked out in order to develop a suitable concept. At first, the basics of how environmental factors, laws and challenges are to be considered in the automotive recycling are described in this section. On this basis, the requirements on the use case to be developed are acquired and implemented in the concept. The following sections elaborate the subject of disassembly of cars for recycling.

2.1 Environmental factors and legal situation in the automobile recycling

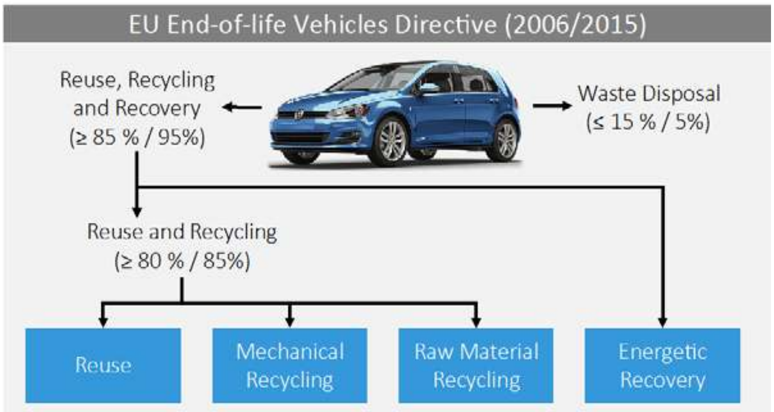
ELVs consist of lots of poisonous substances such as brake and battery fluids, CFCs, lead and oils – but also of recyclable materials such as steel, copper, light and precious metals or glass and rubber.

The industry has a large vested interest in that as much of it comes back into circulation. The bigger the supply, the lower the price of the materials from which, for example, new cars are produced. On average, each car wreck is weighing nearly a ton, which makes up to 500,000 tons of scrap every year (Doll, 2015).

As early as 1994, the recycling act in order to reduce waste was adopted in Germany. Here, the use of natural resources is promoted and human and environment protection and the recycling of waste are encouraged (KrWG, 2013).

In 2000, the European Parliament has issued a directive requiring "… the proper functioning of the internal market to reduce the environmental impact of end of life vehicles and thereby contribute to the protection, preservation and quality improvement of the environment and energy conservation, and to avoid distortions of competition in the community" (European Parliament, 2000). At the latest by 2006, the reuse and recycling of old cars should be at least 85% and since 2015, it has to rise to at least 95%, as shown in Figure 1. For the automotive industry, this means to increasingly regard recycling possibilities in the design and manufacture of vehicles.

Figure 1 EU ELV directive (see online version for colours)



Source: Krinke (2005)

In addition to the statutory requirements, the automotive industry has a vested interest in reusing as many materials as possible to secure the raw material supply. "Especially ELVs are a major source for the production of secondary raw materials. The goal of the BMW Group is to close material cycles and to contribute to the conservation of natural resources" (BMW Group, 2009).

2.2 *Challenges for the automotive industry*

An early planning of recycling possibilities is very important, because "in this phase of product development not only 80% of the costs of a product are specified, but also more than 95% of the materials and manufacturing processes are defined, and thus the resulting environmental damage" (Eppler, 1996). An insufficient planning often causes problems in the various phases of the product life cycle, especially in the design and the recycling phase (Kara et al., 2006). The trade-off is done between the short-term goals of the different actors (Nakamura and Yamasue, 2010; Li et al., 2013). For example, in the design phase, a simple solution for mounting components by gluing, which prevents an environmentally friendly dismantling is preferable (Herrmann, 2010).

The constant developments in the automotive industry also require a more efficient planning effort to overcome the challenges in the recycling and waste management phase (Cappelli et al., 2007). For example, the amount of installed batteries will increase by the frequent occurrence of electric cars (van Schaik and Reuter, 2010). "Above all, the metals used in the batteries are connected in their preparation and processing with greenhouse gas and pollutant emissions. […]. Therefore, and also for economic reasons, it is important to develop and establish an efficient recycling process for worn-out batteries as soon as possible" (Schaal, 2014). Alternative fuels such as liquefied petroleum gas (LPG) require special recycling processes, as it causes additional security risks when dismantling the LPG powered vehicle.

In the 1980s, airbags were extra equipment for luxury class sedans; nowadays up to 15 airbags are installed in a car as a standard feature (Handwerksblatt.de, 2011). The disposal of these pyrotechnic units is becoming increasingly important at new car models.

In addition, electronic components along with wiring harnesses and many circuit boards with appropriate materials, such as copper, precious metals, or rare earth compounds are incorporated. Due to the worldwide growing shortage of raw materials, for companies it is more and more important, to systematically remove, recycle and reuse these materials (Schaal, 2014).

"The raw material consumption of the German automotive industry has increased steadily in recent decades. This is caused not only by growing production numbers, but also the increasing vehicle weight across all segments" (Bethge, 2014).

Another indication of the growing need for efficient recycling processes within the automotive industry is the fact that air conditioners are now also an integral part of the standard equipment, even in small cars. Thus, the coolant must be drained and disposed of, in addition to remaining liquids such as gasoline, oil or brake fluid at the disposal of an old vehicle.

2.3 Current solutions to meet EU recycling targets

In order to promote the exchange of dismantling information, now 71 automobile manufacturers have joined forces to achieve the goal of an 'information database for the efficient recycling of ELVs' called international dismantling information system (IDIS) (Volkswagen, 2015). In version 5.35, the database includes a total of 956 vehicle models, 2,024 variants and is available in 30 languages and in 39 national states. The disassembly information provided includes instructions for categories such as: batteries, pyrotechnics, fuels, draining, catalysts, tires and other pre-treatment.

These include instructions for the safe triggering of airbags and information about which parts are recyclable (IDIS, 2015).

The template for the process of recycling ELVs is oriented to the documents published by BMW. Other automobile manufacturers have elaborated processes that describe the recycling process of their ELVs. For example, VW has also a process to recycle their cars. However, here in the official version, the focus is on post-shredder technologies (PST), more precisely, the recycling of materials after shredding by means of the so-called VW SiCon process. The aim is to mechanically prepare the residues derived from the shredding process, which is described briefly in Section 2.3.1.

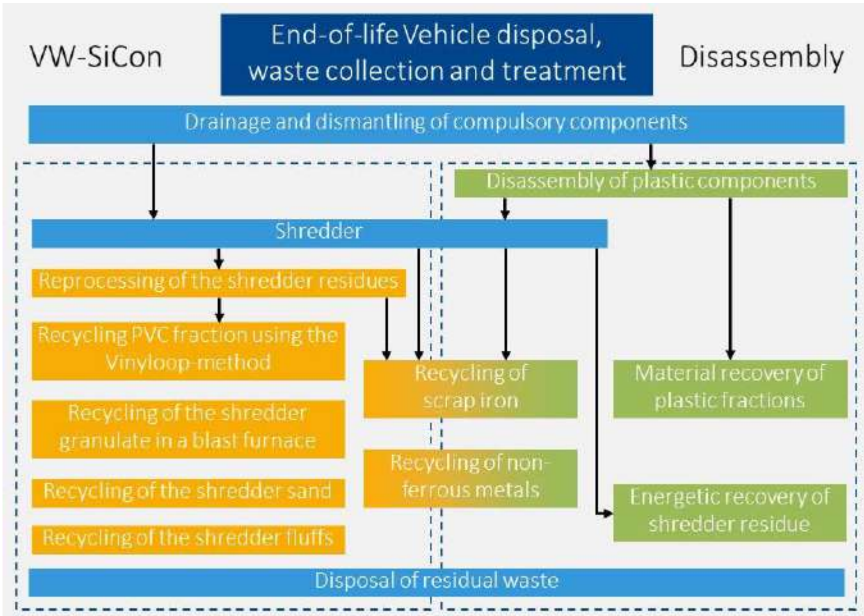
In contrast, the BMW-process discusses the reception of ELVs and describes all necessary steps to be taken prior to compaction. In these phases, most communication effort occurs, including the data acquisition and the passing of recorded data to workshops or shredder companies. Furthermore, certificates of destruction must be provided to the last owner of the vehicle. In addition, it is conceivable to return the information on the use and exploitation of the vehicle to the automobile manufacturers, so that estimates for the production of other models can be made.

2.2.1 Process for recycling ELVs according to VW

In the VW process, the procedure of vehicle reception, recording of the vehicle data and issuing the certificate of destruction is described textually short. The draining and dismantling of obligatory parts, for example, the removal of the battery, pyrotechnic components and fluids, is illustrated in Figure 2.

The dismantling process is described here very imprecise, because the paper is focusing on the post-shredder process called VW SiCon (in Figure 2 marked in orange). The VW-process overlaps in the processes before shredding with the process of BMW, which is described in Section 2.3.2.

Figure 2 VW process for recycling ELVs (see online version for colours)



Source: Krinke (2005)

2.2.2 Process for recycling ELVs according to BMW

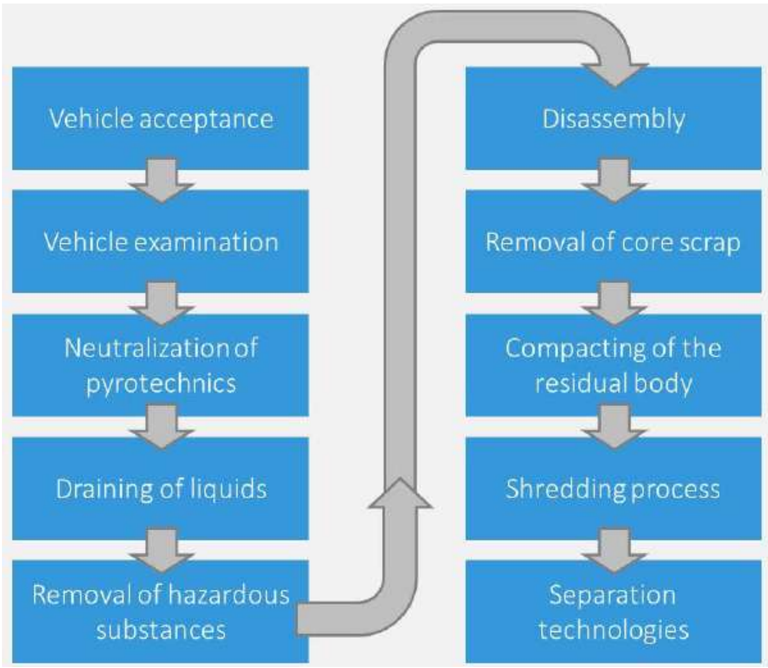
The process described in this section has been created with reference to (BMW Group, 2009). The process is illustrated in Figure 3. The recycling process begins with the vehicle adoption. This is done at recognised collection points or dismantling facilities.

In the next step, it is about the vehicle recognition, followed by the issuing of the certificate of destruction. All the necessary vehicle accompanying documents required for the further steps of the recycling process are created here. Thereafter, the parts to be dismantled are prescribed. In addition, the vehicle data is gathered for the operating software. After that, the certificate of destruction can be issued.

After the ELV is accepted and all information is gathered, the neutralisation of the built-in pyrotechnics is conducted. This step is carried out first, in order to minimise the security risk in the further process steps. Here, among other things, all the built-in airbags of the vehicle are triggered with the help of special tools and seat-belt tensioners are dismantled. Subsequently, the vehicle draining starts, including the removal of all liquids, such as residual fuel, oil, brake fluid or cooling fluid. The aim is to guarantee the non-dripping vehicle (Bundestag, 1997).

After that, the pollutants are removed from the vehicle. These include all substances under Directive 2000/53/EG Annex 1 (European Parliament, 2000), such as catalysts, batteries or tires. Thereafter, the dismantling of sellable used parts and materials begins. The removed parts are treated depending on the evaluation of the state of the vehicle and respectively can be provided to repair shops or used parts dealers.

Figure 3 Recycling process generally described (see online version for colours)



In the next step, the solid scrap is removed, which includes the engine, transmission and optionally the axes. This is followed by the compacting, in order to prepare the transport to a shredding facility. Arriving there, shredding of the stripped vehicle takes place – and then sorting and ranking the different materials. At the end of the process, PSTs are applied; with the aid of preparation of a varietal recyclable material is possible.

3 Requirements for the 3D PDF recycling document

Basically, 3D design allows the 3D models of the individual components to be assembled step-by-step using a computer and the sequence of the assembly operations to thus be specified. Similarly, the way back can be used for disassembly. However, when it comes to larger and complex systems comprising thousands of components, performance problems can quickly arise, which is why the engineers usually only perform assembly at the level of individual assemblies or modules. In addition, companies would also need additional CAD workstations for disassembly planning of large assemblies, which are relatively expensive to buy and maintain. One recommended alternative is therefore to use a lightweight format, which ideally can be animated to make the assembly operations easier to understand.

That is the reason why our solution for 3D disassembly planning is based on the 3D PDF technology, which is able to convert 3D models from all common CAD systems into the tessellated U3D or PRC format, making it more than 90% 'lighter' than the original models (Emmer et al., 2013). 3D PDF documents and the embedded models can be viewed using the normal Adobe Reader, which is free of charge and installed on practically every computer. Another major advantage is that the 3D models can easily be combined within the document with 2D information such as detailed views and drawings, which means that the 3D PDF is very similar to conventional assembly documentation. It includes also animations which are helpful to demonstrate complex products. The documentation can be compiled to a great extent automatically with the help of the server solution PDF Generator 3D and appropriate templates which are helpful to match a dedicated use case.

3.1 Basic functionality

This section presents all the necessary requirements for the concept for 3D PDF recycling document. These requirements are derived by using scenario techniques (Chermack and Koehler, 2013). First, these requirements are described textually and then summarised for further processing in eight functional (F1–F8) and seven non-functional categories (NF1–NF7).

The 3D PDF disassembly instructions mainly include a 3D model of to be dismantled sub-assembly or the complete automobile. To keep the overview, the documentation of the car should be split into several sub-documents, so that the file still remains usable despite the embedded highly detailed models. Due to a large and complex model, the loading time of the document is greatly increased and thus the user can no longer work with the document efficiently. The 3D PDF recycling document displays an overview of all available sub-documents of the automobile. These sub-documents are 3D PDFs each, that are linked to the overview and can be opened with a click.

Furthermore, the document contains one or more BOMs to provide an overview of the mechanical components enabling an additional technical view to the 3D view. The technical view contains material properties and additional annotations. That means that selected parts in the 3D model are also highlighted in the BOM. Vice versa, the user can select components in the BOM, which are then highlighted in the 3D model.

For a better understanding, the model can be animated. This allows individual dismantling steps to be explained more precisely and allows additional information to be added using text or audio files. Warnings for certain components, such as the built-in airbag pyrotechnics, must be shown by annotations in order to keep the risk of accidents during disassembly as low as possible. "The necessary safety precautions, specified by the vehicle manufacturer, for triggering ignition devices and special work instructions must be observed" (Bundesanstalt, 2014).

Removed parts that can still be used should be selectable in the 3D PDF document in order to fill a database to facilitate the resell of the parts. Alternatively, it is possible to share documents with parts dealers directly to ascertain whether parts are required beforehand, using the data collected during the disassembly.

3.2 Reading the metadata

The metadata, such as BOMs and material properties of the product, are located in different systems and in different formats. In order to transfer the data into a 3D PDF, it is necessary to carry out the conversion using a tool that is integrated into the workflow. For a specific use case it is only possible to use a determined system landscape, in which the output formats are specified.

3.3 Import of the 3D models

The 3D models also need to be adapted and integrated into the workflow. During the engineering design phase of the product life cycle, the 3D models are created as detailed as possible. Additional assembly steps that are needed to assemble the product are defined in the phase of production planning. The knowledge from these phases must be included for dismantling in the 3D PDF recycling document. For the disassembly procedure, the following points should be noted:

Sub-assemblies that can be removed and reused completely must be identified after inspection. Materials, which must be removed prior to recycling, such as batteries, pyrotechnics, etc., require labelling and warning signs. Areas of the vehicle that contain liquids must be labelled properly in order to dispose them correctly.

To ensure a well-structured information flow and to emphasise important notes, the dismantling information needs to be sorted into different categories. The following points give an overview and can support the assembly process:

- Dangerous components must be labelled with warnings.
- Components, for which recycling is no longer possible and that may cause problem in the shredder, must be marked to ensure the upstream dismantling.
- Components, that are reusable and can be sold or recycled as used parts, are to identify.
- Information on the materials is useful to facilitate the separation of the components. So, in most cases, plastic parts are dismantled before the shredding process in order to recycle and reuse them separately.
- The weight of various parts is important information for the disassembler in order to better assess the operations. For example, some operations cannot be performed alone. The weight is automatically calculated in some 3D CAD systems based on volume and material and can be added to the BOM.

3.4 Repatriation of the data collected from the disassembly

Companies have to develop systems to deal with the data from the recycling phase of the product life cycle. A centralised database that processes the information of the recycling phase and optionally also receives usage data could be valuable in the development of future vehicle models (Chen, 2016). The data obtained here, is gained throughout the whole life cycle of the product, including the service life of the vehicle. For example, it may be enough to pass the unique vehicle ID, based on which the age can be determined. Furthermore, a brief statement to the tribological condition of important parts can be made in which weaknesses can be identified. The mileage performance of the engine or even the complete vehicle can be taken in favour of the designer to provide a basis for subsequent evaluations.

3.5 Handover documents

Documents that are exchanged between the various departments and actors have been defined and their contents described based on Figure 5. The contents may vary depending on the participant and the phase of the process; for example, the documents can be enriched with additional information by the disassembler. The handover documents accompany the vehicle or parts of it at its recycling processes, thereby supporting the information flow.

3.6 Protection of design knowledge

Disassembly instructions are provided by the vehicle manufacturer and can be used by various external companies that specialise in the dismantling of automobiles. By sharing 3D models and BOMs, a certain amount of expertise is passed on as well. To prevent the disclosure of detailed knowledge, it is necessary not to adopt the 3D models one-to-one from the construction. Instead, they can be simplified so that they can be used during disassembly, but revealing nonetheless not too much information about the construction knowledge. Therefore, it is important to consider this aspect when creating the 3D PDFs.

In addition, it is necessary to ensure that only authorised companies and their employees can use the documents by using the digital rights management system (Stjepandić et al., 2015). Thus, it is even possible to grant or withdraw read or write rights after distribution of disassembly instructions (Biahmou and Stjepandić, 2016).

Table 1 Implementation of the functional requirements of the recycling document

#	*Requirement*	*Implementation*	*Status*
F1	3D model of the product	The handover documents 1, 2, 3 and 5 are providing the integration of the 3D model, which is converted to a 3D PDF by the design engineer.	✓
F2	Animations	The creation of animations should be carried out by the production-planning department using 3D PDF Pro.	✓
F3	Description of individual steps	The description of individual step will be carried out by the production-planning department using 3D PDF Pro.	✓
F4	Colouring of materials	The colouring should be done with the aid of the stored materials in the BOM. A process step to automate the colour-coding must be implemented.	✓
F5	BOM	The conversion of any format into JSON needs to be implemented and integrated with the workbench in the process.	✓
F6	Document overview	This requirement is implemented by adding a document overview to the first page of the 3D PDFs. The implementation is located in the template.	✓
F7	Associating BOM and model	The associating is automated based on a unique ID, following the 3D conversion.	✓
F8	Warnings	The design engineer can insert warnings to the finished 3D PDF. For that, the template provides text boxes and a colour-coding in the BOM.	✓

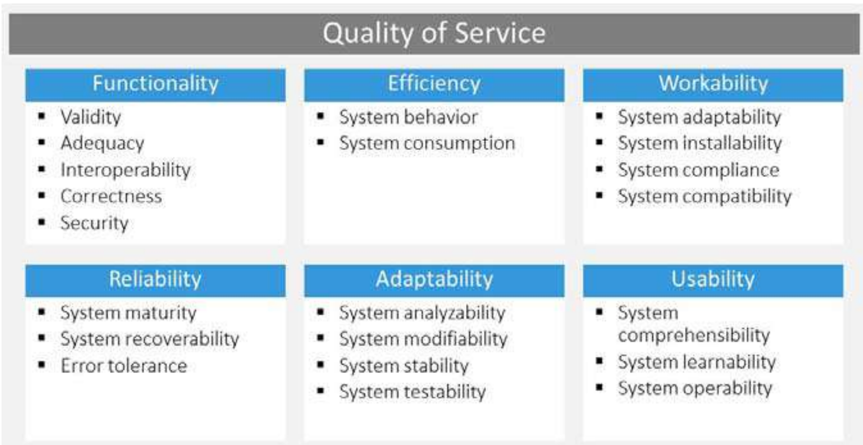
3.7 Overview of the acquired requirements for the recycling document

In the previous sections, the individual requirements for the 3D PDF recycling document were specified. The functional aspects of the document, which have been discussed before, are presented and summarised in Table 1. Thus, the implementation of the individual requirements in the concept can be checked later on. In addition to the functional requirements, also non-functional requirements are imposed on the recycling document.

These non-functional requirements are not directly critical for the concept, however, can make a difference in a future implementation of the concept, because, according to Emmanuel (2010), “non-functional requirements […] are often only experiential, testable and measureable when the whole system is established”. He also advises not to formulate the non-functional requirements in a later phase, as they are often ‘time-consuming and expensive’ to implement.

According to Rupp (2007) the so-called quality of service is formulated and summarised according to the DIN EN ISO 66272 in Figure 4. To acquire non-functional requirements for the 3D PDF recycling document, individual requirements were selected from this figure that should be considered for implementation.

Figure 4 Quality of service according to DIN EN ISO 66272 (see online version for colours)



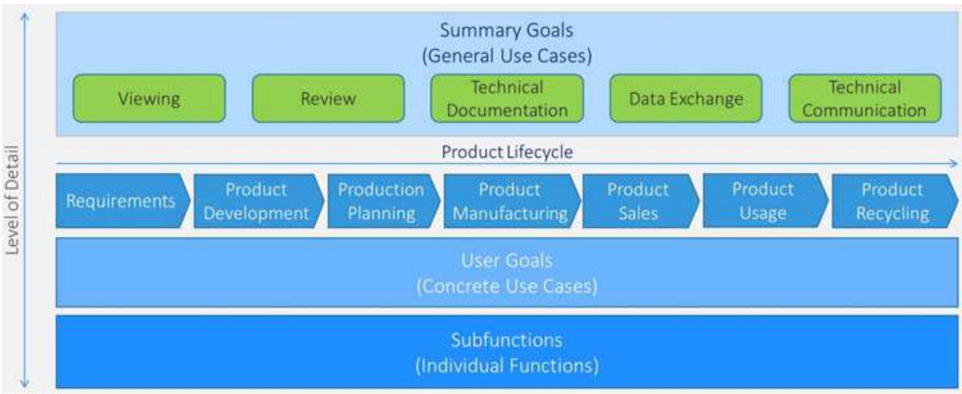
4 Analysis of the existing use cases for 3D PDF

In order to evaluate and classify the existing use cases, evaluation criteria need to be established first (Section 2). In addition, a distinction of use cases is necessary to determine the individual functionalities that are provided by the use of 3D PDF (Kuo, 2006). In this pivotal section, existing use cases are analysed, structured and classified into a self-developed model by means of a literature research and expert interviews (Guo et al., 2013). In order to do that, a horizontal categorisation into the product life cycle has been defined and a vertical categorisation, based on the use case goals was implemented (Beckett, 2015). The purpose of this method is to obtain an overview and simultaneously identify gaps, where 3D PDF still has the potential to support additional phases in the product life cycle. Section 3 summarises the results of the analysis and describes in which field the new use case impacts the product life cycle.

Regarding the issue presented here, the collected use cases describe existing application models and partly not yet reached ways in which the 3D PDF format can contribute to processes in the field of mechanical engineering (Emmer et al., 2013). The use cases assist in PLM, by optimising individual processes and facilitating a more effective communication between all parties involved (Katzenbach et al., 2015). The case study presented in Section 4 shows how complex service documentation on paper can be replaced by drawing free 3D PDF documents, thereby not only providing more flexibility, but also supporting the user in his work. In a 'big picture' (Figure 4) this use case would be classified as the use case service documentation. A good overview of computer aided disassembly planning is given by Santochi et al. (2002).

In the case study, the data for the embedded BOM from an XML file is read and only associated to the 3D data during the actual creation of the respective 3D PDF. The resulting file could also consist of an assembly instruction in addition to a 3D PDF. This instruction is adopted from screenshots and descriptions included in the document previously created and automatically transferred into another document using the server-based solution. To rank the relevance of the existing use cases, they were divided into different levels according to their complexity and accuracy. For horizontal classification according to the level of detail, three levels of goals are used that the use cases can be geared to.

Figure 5 Schematics for use case structure (see online version for colours)



5 Concept for creating a 3D PDF recycling document

During the creation and use of a 3D PDF recycling document various actors are involved that occur in several successive phases, as depicted in Figure 5 with the developed phase model. Fernandes and Canciglieri Junior (2015) gives an overview on similar tools.

The first actor in the use case '3D PDF recycling document' is the design engineer. With the aid of 3D CAD software he designs the vehicle, is already vigilant about recyclability of as many materials as possible used in the car and he develops processes to extract them back from the vehicle (Tang et al., 2002; de Souza and Borsato, 2016). Depending on the manufacturer, collaboration with the production planner is possible that is responsible for the creation of assembly instructions. However, since the design engineer is doing the main task, only he is listed (Ferrao and Amaral, 2006). To avoid transferring engineering design knowledge in the recycling documentation, the 3D model needs to be revised before its integration (Liese et al., 2010). This involves a certain concept that focuses on the individual disassembling steps. Thus, modules that are to be removed as a whole and parts with danger potential should be highlighted.

The second actor is the evaluative disassembler of a recycling plant. He receives the car wreck and has the opportunity to obtain the appropriate 3D PDF recycling document. He is authorised to use the document and is allowed to open it by entering a password. Then, he updates the basic vehicle data with additional vehicle-specific usage data, such as the lifespan, the mileage, etc. It is even possible to record particularities for the subsequent disassembling, for example, the use of foreign manufacturers' parts.

The enhanced recycling document and the respective vehicle are then handed over to the third actor, the executive disassembler in the recycling company. He is able to register and to record possible peculiarities and his assessment of the reusability of dismantled parts during the disassembly process.

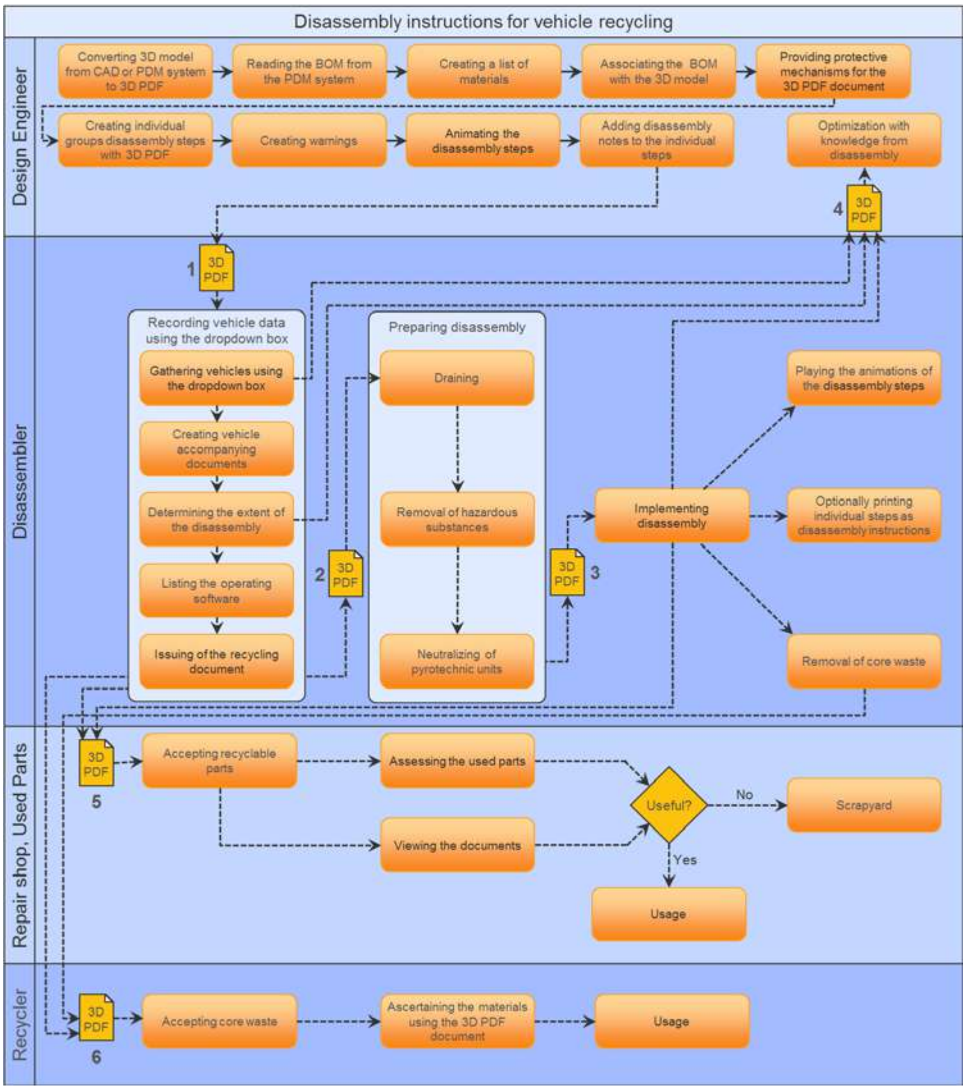
The fourth actor is the supplier for used parts. He receives the disassembled components that might be reusable in order to pre-process them or to sell them directly. Among the parts, he gets an assessment with additional information about the respective part in a 3D PDF that has been enriched with information of the disassembler. The provided information helps the decision making to reuse or recycle the respective parts. For example, parts from damaged vehicles could be highlighted and, thus, tested for cracks in the material in order to guarantee a safe reuse. To prevent the transport of not required parts, the 3D PDF can be send in advance during this process step providing an overview of all available parts to the supplier of used parts.

Concurrently, the fifth actor receives the remaining stripped vehicle and core scrap among with additional information about the ELV, such as data referring weight and materials comprised. For this actor the recycling process is prioritised, whereby the remnants of the vehicle are crushed in a shredding mechanism and the resulting raw materials are separated. The recycling process could be facilitated using the information provided in the recycling document. In this way, determining the particular processing steps would be easier; for example, a pre-sorting step could be implemented in the process. An integration of the 3D model for this process step is not absolutely necessary, which is why the handover document plays a subordinate role.

Using the defined phases and actors, the necessary transfer documents have been defined. Hence, an adapted workflow can be developed in this section that defines all the data for the recycling document. In order to get an overview of the roles of the different actors and the data generation, the swim-lane diagram in Figure 6 was created. The diagram represents the central workflow for creating and using the recycling document, wherein the digits 1 to 6 constitute the different handover documents.

In order to develop an industry-oriented approach, a data source must be defined first: a PDM system, individual Excel spreadsheets, XML documents or database systems. For the use in a 3D PDF document, the data must be converted in the first step for the creation of the recycling document as described in Table 1.

Figure 6 Workflow for creating the 3D PDF recycling document (see online version for colours)



To export the 3D model from the 3D CAD system used, generally only one file is needed in addition to the 3D PDF Converter or the server solution of the 3D PDF Generator. For a correct representation of the model, a custom template must be created that determines at which point the 3D content is displayed and that implements required functions. The embedding of the 3D model is the central step and fulfils the functional requirement F1.

For importing the BOM, it is necessary to convert the source information in a JSON object. The conversion from any format needs to be implemented and integrated with the help of Adobe LiveCycle Workbench into the overall process of converting. The import and conversion is a prerequisite for the fulfilment of requirement F5.

The list of materials used derived either directly from the 3D CAD system or from the PDM system used in the company. To integrate the list, another conversion is needed to transfer all the necessary data into the appropriate JSON object for the associated 3D PDF. At the same time the colour-coding of the parts in the 3D model can be made. For this purpose, the colours for important material properties are defined previously. The colouring fulfils requirement F4.

The associating of the BOM and the 3D model (requirement F7) is done during the conversion process. In this step, the data is compared on the basis of unique IDs. To carry out the comparison, firstly the list must be converted to an appropriate format. Since the data is customer-related and very diverse, no standard procedure can be used. It is important that either the BOM refers to the 3D model via ID or vice versa.

The last step of the workbench process is to provide the created 3D PDF document with protective mechanisms. For this purpose, the digital rights management module is suitable which is managed using the Adobe LiveCycle Server. An integration of protection mechanisms in the 3D PDF meets the non-functional requirement.

In the same process, the reader extensions of the document could be enabled. Its activation allows users to use functions that are initially only available in Acrobat Pro. These functions include the possibilities to import and export data, to customise form fields, to insert attachments and to save the document.

To prepare the vehicle data for the disassembly, it is necessary to create groups and disassembly steps for each vehicle model. The production-planning department can carry out the preparation, since this department is also engaged in the assembly where many process steps are similar.

6 Implementation of a sample workflow

The document contains a 3D model and a BOM. Further data have been inserted manually. The model data include the construction of the vehicle model, the model name and the component currently displayed. Additional document data is available, such as information about the type of document, a document ID and a revision ID. To allow the design engineer to make modifications directly, a dropdown box is integrated into the 3D PDF. This dropdown box allows specifying the properties of the mechanical components, including information about reusability and recyclability.

The first step of the process is to create the 3D PDF document using the Adobe LiveCycle Server in combination with the installed 3D PDF Generator. Here, the previously developed workbench process is already integrated. Once the 3D PDF is created, the design engineer can work with it. One of his tasks is to identify parts to define their way of disassembly.

For the development of customised 3D PDFs, Acrobat JavaScript is used, based on version 1.5 of JavaScript. The BOM can be imported, e.g., from an Excel document into a JSON file. Then, the converted files are read to later insert them directly into the 3D Script during the writing process.

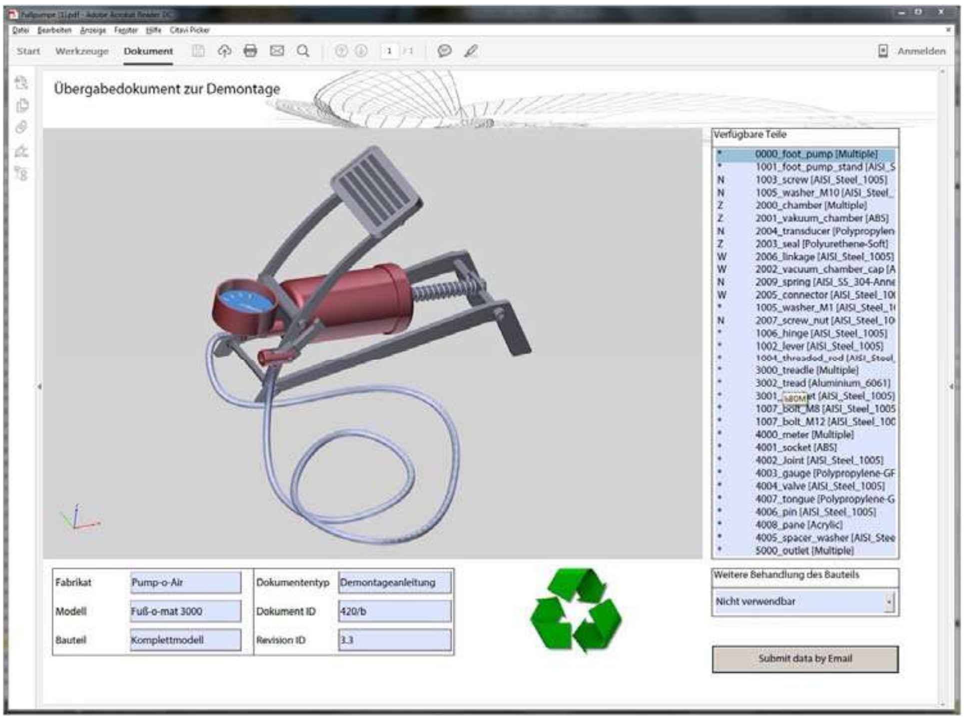
The data is previously selected, since only some of the columns from the table are crucial for the 3D PDF. This includes the part name and the material. These steps are done by hand in the current implementation, but can be automated on the basis of the flexibly designed workbench process later on.

The creation of 3D PDF takes place after the step previously described. After creating the document, the previously read list is optimised and imported into the 3D PDF. At the end of this process, another step (apply usage rights) is realised where the reader extensions module equips the created 3D PDF with additional rights. This includes the ability to save the customised PDF.

The BOM of the appropriate model was available in the CAD software. Thus, it has been exported firstly to use it in the 3D PDF. There were several ways to export the BOM, such as a text file. In order to obtain the data as well organised as possible, an Excel spreadsheet has been selected as the export format. Data such as BOMs are available in table form in PLM systems. This type of export represents a relatively accurate workflow for productive solutions and allows the subsequent implementation.

Various requirements from Table 1 are met within the created sample document (Figure 7). These include F1, the embedding of the 3D model, F5, the integration of the appropriate parts list and F7, the realisation of the interactive associating of BOM and 3D model. Requirement F4, the colour-coding of different materials has been adopted only partially. The basic functionality of the colouring of individual components is already feasible, but those settings cannot yet be saved persistently.

Figure 7 3D PDF sample document (see online version for colours)



7 Conclusions and outlook

Subject of this study was investigating to what extent agile planning of disassembly and recycling can be covered by means of standard IT base technology such as 3D PDF. As a spin off results a use case for the topic of 3D PDF in the product development cycle, to define a workflow and to develop an appropriate concept.

Proper assessment of the environmental impact needs accurate insight in the way in which a product is dealt with at the end of a life cycle (Borsato and Peruzzini, 2015). By developing the concept of preparing a recycling document, this goal was achieved. Furthermore, it was planned to develop a prototypical sample document, which is described in the last section of this work.

In this study, a model was developed in order to obtain an overview of existing use cases and classify them during the analysis phase. This analysis shows the fields of study where 3D PDF still has potential that has not been exploited sufficiently. The result of the analysis was that the product life phase 'recycling' was not sufficiently pronounced and the workflow to be developed will be located in this field. Subsequently, basic research was described and requirements for the appropriate use case were collected. Using that knowledge, it was possible to develop a concept that demonstrates how 3D PDF technologies can contribute to streamline the recycling process of ELVs. The exact procedure, starting from the creation of the 3D data until the application of the document, was developed and described precisely.

Based on the developed concept, a prototypical 3D-PDF was presented which constitutes a part of the extent of the intelligent recycling document. The created 3D PDF template provides a basis for future realisations. In order to implement future developments efficiently, the template was designed as flexible as possible, e.g., to be implemented into the portal OpenDesc.com (Bondar et al., 2015). To enable multiple product life cycles, product design should also explicitly address full coverage of requirements for design for X (maintainability, upgradeability, modularity and disassembly, etc.) (Pullan, 2014; Kim et al., 2016). The objective of this further development is the implementation of all of the derived requirements (Yuzup et al. 2015).

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