Chapter 2
Fundamentals

2.1 Topical placement

The disassembly planning belongs to the field of environmentally conscious manufacturing and product recovery.[1] This already indicates that the manufacturing seems to play a role or the disassembly has influence on the manufacturing, or both. This is a little bit surprising, but the steps before the manufacturing, e.g., the design of a product, have a major influence on the complete life cycle, which includes manufacturing and disassembling. Because of this all-embracing influence of the design, several design directions with explicit environmental focus have been established. The main three are design for environment (DfE), design for disassembly (DfD), and design for recycling (DfR). The DfE focusses on the environmental impact on the whole life cycle of a product. This starts with the extraction of materials and ends with the final disposal. In between the start and end, the material or product could be reused and recycled many times in order to avoid emission of harmful substances and excessive use of energy.[2]

Thus, the DfE can be understood as umbrella for all more special design directions, like DfD, DfR, and even design for assembly (DfA). But since the focus is rather on the end of life of the products, DfD and DfR are more relevant than DfA. The DfR concentrates on design attributes for separating and recycling the comprised material in a cost-effective manner at the product's end of life.[3] But the DfR should not be in the main focus

[1] Cf. Ilgin / Gupta (2010): *ECMPRO: A review*, pp. 563–565.

[2] Cf. Bevilacqua / Ciarapica / Giacchetta (2007): *Development of a sustainable product lifecycle*, pp. 4073 et seq.

[3] Cf. Masanet / Horvath (2007): *Assessing the benefits of design for recycling*, p. 1801.

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when it comes to disassembly planning, because the interest is primarily on the embodied material. When items or modules should also be reused, the DfD is the relevant design direction. According to the definition of disassembly—which includes all planned processes that separate products into modules, items, and/or material[4]—the DfR can be seen as one part of the DfD. The reason is that deriving design issues for a planned process with the result of material to recycle equals the goal of the DfR. Thereby, the DfD is the combination of all design considerations to facilitate the disassembly process (i.e., minimising the complexity of the structure of the product, increasing the use of common materials and items, and easily removable fasteners and joint types).[5] This especially includes an evaluation of a current product design with, e.g., index-based approaches,[6] and, moreover, design recommendations to facilitate the disassembly of a product.[7]

But even though an optimal design is found for all phases of the life cycle, the design does not have to be optimal at the end of life of the product. This problem might occur because of changing needs for material or parts for recycling or reuse, respectively, changes in legislation, too little estimated abrasion of items, etc. Hence, the longer the life cycle the greater is the danger of a suboptimal design. Note that long life cycles are positive in terms of an environmental conscious manufacturing and product recovery. Thereby, not necessarily the complete product has to have a long life cycle. At least the embodied materials and items should have one. On the other hand, it means that all aspects with regard to the product recovery need to be flexible in terms of quantities, conditions, and limitations. This affects not only the disassembly planning, but also the logistics.

The reverse logistics (as pendant to the forward logistics) is a branch of logistics that focusses on reverse flows, i.e., from the consumer back to the manufacturer or a company that is entrusted with the recovery of used

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[4] Cf. Seliger (2011): *Montage und Demontage*, p. S97.

[5] Cf. Güngör (2006): *Evaluation of connection types in DFD*, p. 36.

[6] Cf. Kroll / Hanft (1998): *Quantitative evaluation of product disassembly*, Kroll / Carver (1999): *Disassembly analysis*, Veerakamolmal / Gupta (1999): *Design efficiency for disassembly*, Zeid / Gupta (2002): *Disassembly cost index*, Villalba et al. (2004): *Recyclability index as a tool for DfD* (in combination with Villalba et al. (2002): *Quantifying the recyclability of materials*), Desai / Mital (2003): *Evaluation of disassemblability*, and Desai / Mital (2005): *Design for disassembly*. In a broader view the index can also be a maximal process value reduced by disassembly cost, cf. Kwak / Hong / Cho (2009): *Eco-architecture analysis for end-of-life*.

[7] Cf. Viswanathan / Allada (2001): *Configuration analysis to support product redesign*, Viswanathan / Allada (2006): *Product configuration optimization for disassembly planning*, and Giudice / Kassem (2009): *End-of-life impact reduction*.

products so that the product or material is again usable in a market.[8] This includes the planning, implementing, and controlling of the backward flows to the recovery or proper disposal site.[9] Thereby, the retrieval of the used products should be efficiently dealt with.[10] Moreover, the view of reverse logistics can also be extended to the inclusion of material selection aspects. Hence, it is not just collecting and transporting products and material, but, furthermore, the decision which recovery option (see below) is used.[11] This selection is already an aspect that is common with the disassembly planning, only that after disassembling we call them usage option to differentiate between general recovery option and the result of the disassembly.

The reverse flow is not independent from the forward flow. There exists a strong impact from both flow directions on the capacities for storage, transportation, etc. Thus, a simultaneous consideration is favourable, if not necessary for an optimal planning. This combined consideration is focus of the closed-loop supply chain.[12] Thereby, the system is only a closed loop when the product returns to the original producer. Otherwise, it is an open-loop system with forward and reverse flow, which starts at a producer, goes to a consumer, and ends at a different recovery company.[13] Note that not only end-of-life products cause a reverse flow. Also product recalls, service and warranty returns, even rework, etc. can be seen as reverse flow.[14]

A main logistical aspect of the closed-loop supply chain is the placement of facilities and the allocation of flows between them, i.e., the network design. For this aspect it is already of interest what recovery options exist at this stage.[15] The common options are:[16]

- (direct) reuse,
- repair,

[8] Cf. Fleischmann et al. (1997): *Quantitative models for reverse logistics*, p. 2.

[9] Cf. de Brito (2003): *Managing reverse logistics*, p. 20.

[10] Cf. Demirel / Gökçen (2009): *MIP model for remanufacturing in reverse logistics*, p. 1197.

[11] Cf. Jamshidi (2011): *Reverse Logistics*, p. 254.

[12] Cf. Guide Jr. / Jayaraman / Linton (2003): *Contingency planning for CLSC*, p. 278, Ilgin / Gupta (2010): *ECMPRO: A review*, p. 567, and Savaskan / Bhattacharya / Van Wassenhove (2004): *CLSC models with product remanufacturing*, p. 239.

[13] Cf. Fleischmann et al. (1997): *Quantitative models for reverse logistics*, p. 4.

[14] Cf. Zarandi / Sisakht / Davari (2011): *Design of a CLSC model*, p. 809, and Inderfurth / Teunter (2001): *Production planning and control of CLSC*, p. 1.

[15] Cf. Ilgin / Gupta (2010): *ECMPRO: A review*, pp. 571 et seq.

[16] Cf. here and in the sequel Thierry et al. (1995): *Strategic issues in product recovery*, pp. 118–120, de Brito (2003): *Managing reverse logistics*, pp. 61 et seq., and Goggin / Browne (2000): *Towards a taxonomy of recovery*, pp. 179 et seq.

- refurbishing,
- remanufacturing,
- cannibalisation,
- recycling,
- incineration, and
- disposal.

Thereby, the reuse option is the one with the least extra effort. This means that the product can either be directly reused or minor repairs are done.[17] This might apply to unused spare parts, resold products, or carriers and packaging. The repair option returns a used product back to working order. This comes along with a lower quality than the new product and could be executed at the consumer's location. It requires already some small amount of disassembly and reassembly. The refurbishing is analogue to the repair, but the used product is brought to a specific quality including a possible upgrade in functionality. Nevertheless, the overall quality is lower than that of the new product. The remanufacturing brings the product back to a quality of a new product.[18] Therefore, these products are "as good as new".[19] Cannibalisation or retrieval denotes the recovery of a limited number of parts from the used product to be used for, e.g., repair work. Thereby, the focus is not on the complete product anymore, but shifted to the constituent parts. These parts can be single items or modules. When it comes to recycling, incineration, and disposal, the original product (and its constituent parts) is not of interest anymore. With recycling and incinerating material and energy, respectively, are recovered. Lastly, the disposal represents the loss of any value for today. It is quite possible, that land-filled waste is going to be recovered in the future. This depends on technology and whether it becomes economic beneficially.

These recovery options can be ordered according to several criteria. In pursuance of Gerrard / Kandlikar, the preference ordering is reuse, remanufacturing, recycling, incineration, and lastly disposal.[20] Even legislative regulations provide a preference ordering for waste, nowadays. Accord-

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[17] Cf. Fleischmann et al. (1997): *Quantitative models for reverse logistics*, p. 11.

[18] Cf. Guide Jr. / Jayaraman / Linton (2003): *Contingency planning for CLSC*, p. 278.

[19] Companies like Caterpillar have even set up an extra brand (e.g., Cat Reman) to distribute these remanufactured products. Cf. `http://catreman.cat.com/`. Other companies like Jungheinrich established a series for refurbished trucks (e.g., Jungheinrich JungSTARs). Cf. `http://www.jungheinrich.de/en/used-trucks/jungheinrich-jungstars/`.

[20] Cf. Gerrard / Kandlikar (2007): *Assessing the impact of the ELV Directive*, p. 23.

ing to German law, five waste handling options exist in the following ordering:[21]

1. avoiding,
2. preparing for reuse,
3. recycling,
4. other recovery, especially energy recycling and filling, and
5. disposal.[22]

Thereby, the reuse corresponds to avoiding, remanufacturing, refurbish, repair, and cannibalisation, the preparing for reuse, material recycling to recycling, energy recycling to other recovery, and disposal to disposal. Note that "filling" is seen as disposal in this work.

Taking a look at the recovery options, we find that in many of them disassembly is undertaken. It applies to repair, refurbishing, remanufacturing, and cannibalisation, because only with disassembly the parts to exchange or retrieve can be accessed. But most likely, disassembly is also necessary for recycling, because not the complete core consists of material that is going to be processed in the same way. Moreover, in an environmentally conscious system disposal should be reduced as much as possible. This means that not the complete core is going to be disposed of. At least hazardous material and possibly recyclable material or reusable parts should be extracted and processed separately. This again makes disassembly necessary. Furthermore, we see that not only one recovery option has to be applied to a core (except for product reuse, repair, refurbishing, and remanufacturing). All in all, disassembly is one of the key issues in the product recovery.

When it comes to the planning of the disassembly, one might think that it equals the assembly planning or that it is just the reverse of it. For some aspects this might be the case, but definitely not for all. One indicator for the necessity of a separate disassembly planning is the existence of quite a few research articles in the literature. Moreover, LAMBERT lists significant differences. These are:[23]

1. a not completely reversible assembly process,
2. less value added obtained in disassembly processes,

[21] Cf. 6 KrWG (Gesetz zur Frderung der Kreislaufwirtschaft und Sicherung der umweltvertrglichen Bewirtschaftung von Abfllen – Kreislaufwirtschaftsgesetz).

[22] In the literature (land) filling and disposal are synonymously used terms. Why the filling is differentiated from the disposal in German law and equal to energy recycling is not clear. It might be that with filling the theoretical possibility exists to recover this waste later and process it with new techniques. In this context, the disposal might be an option, which expresses the final loss of the material (e.g., ocean dumping).

[23] Cf. LAMBERT (2003): *Disassembly sequencing: A survey*, pp. 3721 et seq.

3. uncertainty about the condition of the constituent parts,
4. uncertainty about the quantity of core supply,
5. a variety in supplied products,
6. mainly human labour instead of automated assembly lines and robots, and
7. usually not complete disassembly, which introduces the disassembly depth into the consideration.

In addition to these properties, there might also exist uncertainty about what parts the core consists of. Depending on the product the consumer might have replaced parts of the product by different ones. If this is the case, non-genuine parts are inserted into the product.

For the above reasons the separate research field of disassembly planning is established. As mentioned above, disassembly occurs in different recovery options, which results in planning problems with particular properties. In addition, keeping the developed models understandable and usable the models should include all necessary aspects. And in general, the necessary aspects are problem dependent. A first group of such problems is the repair and refurbishing. Here, the cores are partly disassembled in order to reach the damaged parts and afterwards reassembled. The main focus is clearly to gain a functioning product with as little disassembly and reassembly effort as possible.[24] This group of problems shows parallels to maintenance planning.

A second group is the disassembly with regard to remanufacturing. Thereby, the cores are disassembled "completely" and reassembled to gain an "as good as new" product. From a disassembly point of view, it is a special case of the repair or refurbishing—namely, the worst case—, because all other disassembly options result in an incomplete disassembly. On the other hand, from a planning point of view, this worst case of the disassembly—the complete disassembly—is easier than the planning of incomplete disassembly, which incorporates the disassembly depth as a further decision to make. The term completely with regard to the disassembly does not literally mean a complete disassembly. If it would be a complete disassembly in the literal meaning, all items, i.e., every semiconductor, screw, etc., would be separated from each other and no connection between items would remain. This is usually not the case. In general, groups of items stay together, e.g., a relay. Such a relay could be further disassembled but no one does it, because it is seen as an item.[25] This view is a level of abstraction necessary

[24] The interpretation of disassembly and reassembly effort depends on the decision maker.

[25] Note that there might exist situations where a relay must be disassembled, e.g., for valuable material.

for modelling disassembly processes. Otherwise, the model becomes too big to handle. Hence, depending on the level of abstraction, an item could be as big as a complete engine of a ship (or even bigger) or as small as a transistor only visible with an electron microscope.

The last group is the disassembly planning. It embodies the recovery options cannibalisation, recycling, incineration, and disposal. These options do not aim to have a complete product in the end. The individual items and modules after the disassembly might be used for reuse, recycling, incineration, and disposal.[26] Again, the disassembly can be complete or incomplete. Especially this group of the disassembly planning is characterised by the diverging structure, i.e., one core leads to several items and modules. Since the disassembly planning is the focus of this work, a more detailed look onto the existing planning problems can be found in the following.

2.2 Literature review on disassembly planning

The term disassembly planning comprises many aspects around the concrete disassembly process. It includes product representation, related product design/redesign issues, and disassembly sequencing with disassembly level and end-of-life options.[27] But when taking a look in the literature, one might find the term as a kind of generic term. Hence, in the sequel we shall use it as such. Under this generic disassembly planning five main fields have emerged that preferably consider quantitative problem statements. These five are disassembly sequencing, disassembly-to-order planning, disassembly scheduling, disassembly line balancing, and flexible disassembly system planning. Thereby, a

Disassembly sequence is a listing of subsequent disassembly actions, where an action is, e.g., dividing an assembly into two or more modules or separating one or more connections between parts.[28] Finding the preferably optimal sequence of all possible sequences is the goal of the disassembly sequencing. The

Disassembly-to-order planning aims at finding the optimal quantities of cores to be disassembled in order to meet the demand of parts and material from a mix of cores. Thereby, these cores can have parts in common. If the common parts occur across different cores, the term *commonality*

[26] Note that incineration is seen as a material recycling option in the sequel.

[27] Cf. Lee / Kang / Xirouchakis (2001): *Disassembly planning and scheduling*, p. 697.

[28] Cf. Lambert (2003): *Disassembly sequencing: A survey*, p. 3721.

is used, and if they occur within a core, we find the term *multiplicity* in the literature.[29] In general, the optimisation criterion is either a cost minimisation or a profit maximisation.[30] The

Disassembly scheduling can be seen very similar to the disassembly-to-order planning as "problem of determining the order quantity of the used products to fulfil the demand for disassembled parts."[31] But scheduling should furthermore include a timing of disassembling.[32] This does not mean that scheduling is always a multi-period planning. It just means that, in addition to the quantities, the ordering is relevant for the decision maker. The

Disassembly line balancing solves the problem of assigning disassembly tasks to an order of stations such that the disassembly precedence relations are satisfied.[33] The optimisation criteria can be profit, cost, (cycle) time, number of workstations, levelled utilisation, etc. or combinations of these.[34] The

Flexible disassembly system planning is another relative big research area. It belongs to the field of automated disassembly and has a different (machine) layout than the disassembly line.[35] Nevertheless, the planning is somewhat similar to the line balancing with the exception of the layout and the focus on the automation, i.e., the aim is to plan the disassem-

[29] Cf. Taleb / Gupta (1997): *Disassembly of multiple products*, p. 950, Lambert / Gupta (2002): *Demand-driven disassembly optimization*, p. 123, and Lee et al. (2004): *Disassembly scheduling*, p. 1360.

[30] Cf. Lambert / Gupta (2002): *Demand-driven disassembly optimization*, p. 122, together with Ilgin / Gupta (2010): *ECMPRO: A review*, p. 579.

[31] Lee / Xirouchakis / Züst (2002): *Disassembly scheduling with capacity constraints*, p. 697.

[32] Cf. Kim / Lee / Xirouchakis (2006b): *Two-phase heuristic for disassembly scheduling*, p. 196.

[33] Cf. Altekin / Kandiller / Ozdemirel (2008): *Profit-oriented disassembly-line balancing*, p. 2677.

[34] Cf. McGovern / Gupta (2007): *Balancing method and GA for disassembly line balancing*, p. 693, Altekin / Kandiller / Ozdemirel (2008): *Profit-oriented disassembly-line balancing*, p. 2677, Koc / Sabuncuoglu / Erel (2009): *Disassembly line balancing using an AND/OR graph*, p. 870, and Agrawal / Tiwari (2008): *ACO to disassembly line balancing and sequencing*, p. 1414.

[35] Cf. Ilgin / Gupta (2010): *ECMPRO: A review*, p. 579, and Wiendahl et al. (2001): *Flexible disassembly systems*, p. 723.

bly with values (e.g., cost and revenues) and problem specific resources considered.[36]

There also exist approaches which combine, e.g., sequencing and scheduling aspects or sequencing and disassembly-to-order aspects,[37] without an established taxonomy. These are still subsumed as disassembly planning in the sequel. Another interesting albeit small research area is the active disassembly. Here, the focus is on the self-disassembly of a core or parts of it.[38]

In preparation of Table 2.1 containing the relevant literature, the used properties are discussed in the sequel. (The corresponding references to the properties can be found in Table 2.1.) When it comes to disassembly planning, one has to deal with uncertainties in general. Nevertheless, there exist **deterministic** models. Either because of valid information about the cores or the uncertainty is just neglected. For example, valid information can be gained by testing all incoming cores before the planning, which includes RFID, or by permanent maintenance of products by a company, which corporates with the disassembling facility. A second category is the one of **quasi-stochastic** models. Thereby, "quasi-stochastic" denotes a combination of deterministic and stochastic models in this work. This applies to planning situations, where uncertainty exists, but the probabilities, rates, and expectations of uncertain values are used in a deterministic style planning. The last type in this context is the **stochastic** modelling and planning. Models in this category explicitly incorporate distribution or density functions of stochastic variables into the model.

The considered uncertainties we find in the relevant literature regard the condition or quality of the cores and the quantities (i.e., yields or availability). In addition, the possible damaging during the disassembly process is another uncertainty to cope with. In this context, some articles differentiate between **destructive** and **non-destructive** disassembly.

Furthermore, a differentiation of planning situations covering just a single or multiple periods is useful, too. In this regard, the single-period planning is seen synonymously to the static planning, because within the single period (which could be infinitely long) no changes in data occur. For the **multi-**

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36 Cf. Tang / Zhou / Caudill (2001): *Integrated approach to disassembly planning and demanufacturing operation*, p. 778, and Williams (2007): *A review of research towards computer integrated demanufacturing*, p. 773.

37 Cf. Santochi / Dini / Failli (2002): *Computer aided disassembly planning* and Xanthopoulos / Iakovou (2009): *On the optimal design of disassembly*.

38 Cf. Ijomah / Chiodo (2010): *Application of active disassembly to extend profitable remanufacturing*.

period planning a change of data (quantities, limits, etc.) from period to period is assumed. Thus, a multi-period planning is assumed to always be dynamic in our overview. Moreover, the dynamic planning could further be clustered in planning with just different values of parameters for each period and planning with changing values of parameters. The latter could also be seen as dynamic planning with uncertainty, because of the fact that, when parameter changes within the overall planning occur, the parameters are not certain. For our consideration the distinction between multi-period (dynamic) and single-period (static) is sufficient.

The next aspects are concerned with the input side of the disassembly process. Here, **multi-core** and single-core approaches can be differentiated. Multi-core indicates the simultaneous consideration of more than one different core, e.g., a car and a truck. On the other hand, with a single core approach either the car or the truck is planned, but not both together. Thereby, it does not matter if only one unit or hundreds of units of the same core are considered. A further property tied to the cores is that of common parts, which is already discussed above. In addition, cores can contain **hazardous** parts. These can be as small as batteries or just material like lead. In this case a special treatment is necessary. Besides, for an economic consideration certain cost factors might be of interest, e.g., transportation and order cost, which are subsumed as **acquisition cost**.

In addition, the availability of cores might be limited, which is a supply limitation for the disassembly process. Besides this, further **limits** can exist—like distribution, (cycle) time, disassembly cell sizes, and storage space. Along with the storage space limitation the **inventory holding cost** can also be of interest. This cost component might be extended by **set-up cost** and **disassembly cost**. The latter accrue with almost every disassembly process—maybe not with active disassembly. When disassembling a core **completely** the disassembly cost is relatively high compared to an **incomplete** disassembly. Therefore, an incomplete disassembly planning is very promising. But when a core is literally not completely disassembled, it does not mean that the planning is an incomplete one. The differentiation is carried out by the number of relevant disassembly states. The disassembly state is the result of the disassembly process in terms of which items and modules are gained from the core. And if this set of items and modules is identical for all units of a core and a priori given, it is complete disassembly planning, because the modules can be seen as an (abstract) item. If, on the other hand, the disassembly state or states need to be determined with the planning, it is incomplete disassembly planning. Note that even for a complete disassembly many disassembly sequences might exist. Besides, http://www.springer.com/978-3-658-03117-6

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