DOI: 10.22032/dbt.57806

Simulation in Produktion und Logistik 2023
Bergmann, Feldkamp, Souren und Straßburger (Hrsg.)
Universitätsverlag Ilmenau, Ilmenau 2023
DOI (Tagungsband): 10.22032/dbt.57476

Simulation of a Factory for the Integrated Manufacturing and Remanufacturing of Batteries

Simulation einer Fabrik zur integrierten Herstellung und Wiederaufarbeitung von Batterien

Leonard Overbeck, Finn Brunnenkant, Oliver Brützel, Gisela Lanza
wbk Institute of Production Science, KIT, Karlsruhe (Germany);
leonard.overbeck@kit.edu

Abstract: The current trend of increasing usage of batteries in electro-mobility and other applications can only be ecologically and economically sustainable if the batteries are not disposed at the end of their lifecycle but re-entered into the value chain. To benefit from the economies of scale, the re-introduction of the used batteries (or their components) into the linear manufacturing system would be favourable. This poses new, complex challenges to production planning and control, which can be tackled with the help of discrete event simulation (DES). For its application in an integrated factory which includes common linear production and circular processes, new modelling and control approaches are needed. These approaches are presented in this paper, applied to a planned production system in a research environment, and used for performing experiments, which give deeper insights into the requirements and economic viability of the integrated manufacturing and remanufacturing of batteries.

1 Motivation

Battery technology is globally on the rise, also in Europe and Germany where many production facilities will be established in the upcoming years (Eddy et al., 2019). This is only ecologically sensible if the batteries will re-enter the value stream after usage because they contain rare, dangerous, and toxic materials, for example manganese, nickel, cobalt, and lithium. Furthermore, Europe must reuse these materials to become less dependent on imports. The ultimate goal would be a circular factory where new batteries are built side-by-side with the remanufacturing (which includes dis- and reassembly (Wurster et al., 2022)) of used batteries. This has the potential to re-introduce still functioning components from old batteries directly in the manufacturing process of new batteries and thus save material, money, energy, and effort.

2 Related work

The analysis of the so-called ReX processes (Reuse, Repair, Refurbish, Remanufacture, Recycle, etc.) in general has been of increasing interest in research in the last years because it will be a key requirement for a truly green economy.

Research by Kampker et al. (2021) on the ReX of lithium-ion batteries (LIBs) showed that different disassembly degrees are possible at pack, module, and cell level, with cell-level disassembly being optimal according to their study. Fleischer et al. (2021) illustrated the technical feasibility of disassembling battery packs fully automated to defined levels, while Wurster et al. (2022) presented a control algorithm for a hybrid battery disassembly factory with manual and autonomous workstations.

Work on simulating the cost and energy requirements in linear battery production was carried out by Ventura Silva et al. (2022). Simulation was used by Alfaro-Algaba and Ramirez (2020) to identify the optimal disassembling process for remanufacturing LIBs. While minimizing the disassembling costs, the authors consider the costs for remanufacturing as constant and do not model the manufacturing processes.

The organization of ReX processes and manufacturing, i.e. forward and backward material flows under the same roof, is defined as a circulation factory by Cerdas et al. (2015), where complex material flows are identified as a challenge. Looking at simulations in integrated remanufacturing the existing research can be divided into approaches modelling parameters on network level and on factory level. Approaches on network level include the research of Deveci et al. (2021) regarding optimal locations for recycling plants, Standridge and Hasan (2015) investigating the general demand of remanufacturing capacities, and the investigation of future scenarios of LIB demand by Huster et al. (2022). A framework for DES for integrated remanufacturing on factory level was presented by Wakiru et al. (2021), who focus on logistic costs of spare parts where costs of labor and machines are considered as a constant factor for each remanufactured part. Although the presented publications deal with simulation of disassembling battery packs or simulation of circular remanufacturing, no researcher captures the disassembling and (re)assembling processes in one model. Instead, the costs of reassembling are considered to be constant and no analysis of machine utilization and overall machine effectiveness are performed. But such key performance indicators (KPIs) are crucial for the accurate planning and dimensioning of such factories.

There is a research gap concerning the integrated consideration of manufacturing and ReX in one plant. The goal of this paper is to close this gap and use discrete-event simulation to evaluate the potential of the integration of LIB manufacturing and remanufacturing of battery cells in one plant.

3 Approach

Closing the research gap, this paper presents a DES model of an integrated manufacturing and remanufacturing factory that allows the performance analysis of each single process unit. The approach follows the guideline for simulation studies of (VDI 3633). The overall objective (step *target definition*) of the simulation study is to demonstrate the feasibility of a circular factory for batteries and to investigate the relevance of each individual ReX station. In the following section 3.1, first, the general concept of the disassembling and recycling processes concerning LIBs and their interfaces to remanufacturing are described (step *system analysis)*. In the following section 3.2, the structure and functioning of a single modular ReX station is explained, which primarily contributes to the *model formalisation*. Finally, in section 3.3 the control of the material flow and the associated integration into manufacturing are presented.

3.1 Line concept for integrated battery (re-)manufacturing

Modelling ReX processes for LIBs has some challenges, of which the following are focused by this approach:

- Optimal process chain variants for remanufacturing and recycling can vary, mainly depending on the type-material mix of the returning batteries.
- The required disassembly level of the LIB depends on its state of health (SoH).
- The behavior of disassembly and recycling processes depends on prior process steps, battery types, and characteristics of the battery.

To meet these requirements, the re-entering flow of used LIBs is processed by modular ReX stations which are connected by a dynamic material flow through automated guided vehicles (AGV). The stations represent individual ReX processes for LIBs and have individual behavior depending on which batteries they currently process. The dynamic material flow is defined by the decision after each ReX station about the next transportation target. The resulting layout for the circular factory is shown in Figure 1. Below the ReX area consisting of the stations ReX 1 to N, the linear LIB manufacturing area with micro environments is located. In addition, there is a buffer for products that are suitable for reuse, a buffer for remanufacturing, as well as storage for recycled materials in their pure form. After each modular station the outflowing parts, such as battery packs, modules cells, sheets, etc., represented by moving units (MU), can either (1) leave the ReX process chain and be reused directly, (2) leave the ReX process chain via a buffer and be remanufactured, (3) finish the recycling process as recycled goods, or (4) get to another disassembly level, where the successor station might be every modular ReX station from 1 to N, depending on the defined process chain of the MU.

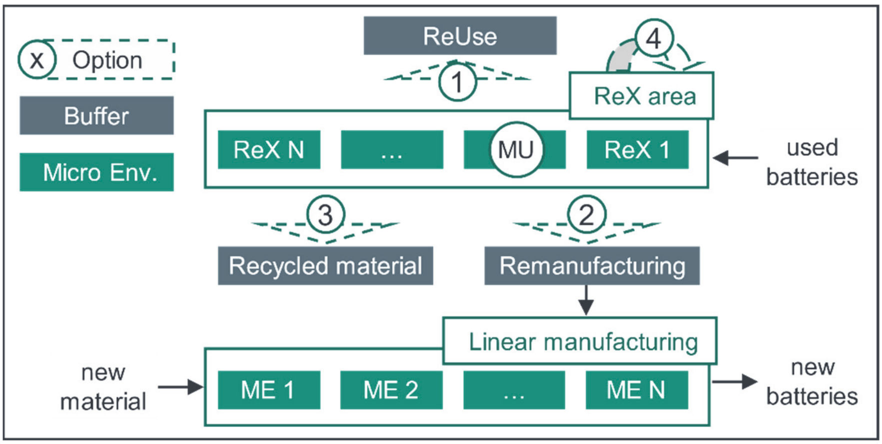


Figure 1: Design of the circular factory with ReX area on top and linear manufacturing on the bottom. Illustration of potential next stations of a moving unit (MU) on a modular ReX station.

ReX process chains are individual for each end-of-life (EOL) battery and are chosen based on characteristics like battery type, SoH, and size. Assigning a ReX process chain variant to an incoming EOL battery takes place at the very beginning of the ReX process chain at the appraisal station and can be readjusted after each disassembling.

3.2 Modelling of modular ReX station

To address dynamic material flows and varying ReX station behaviours in simulation, a new modelling approach for generic material-disaggregation stations is introduced. Each modular ReX station must receive information about which products or goods represented as moving units (MUs) it shall create. In addition, information about qualities, quantities, and destinations of the resulting output MUs is required. All information should be individual for each kind of product or good that can enter the modular ReX station. The required information is provided by the central *Process_table* matrix. A schematic representation is shown in Figure 2 on the right, with the modular ReX station representing *Diss 2* and the incoming MU being a battery module. This information determines the column and row index of the matrix, returning a unique *config_table* that specifies the behaviour of the modular ReX station. All classes of MUs contain a parameter describing their cell type, which leads via the index of *config_table* to information about the quality of the process. Some MUs can have optional parameters, like in this case the number of cells *No_cells*. If a parameter is listed in the column *Multiplier*, the number of generated outputs MUs is multiplied by this parameter. The *isEndproduct* parameter defines whether the output MU will pass through further modular ReX stations or its ReX process chain is complete and it enters linear production. The structure of a modular ReX station is shown on the left in Figure 2. MUs enter and leave the ReX station via airlocks, enabling process-specific atmospheres, i.e. oxygen exclusion. After entering through the airlock, the MU occupies the first station (deportioner). Here, the processing time and required energy are simulated. Then the product is divided and moved to the portioning stations of the ReX station. The connections between the stations are configured in such a way that the quantities arriving at each exiting station correspond to the defined quantities and are adjusted to the qualities from the *config_table*.

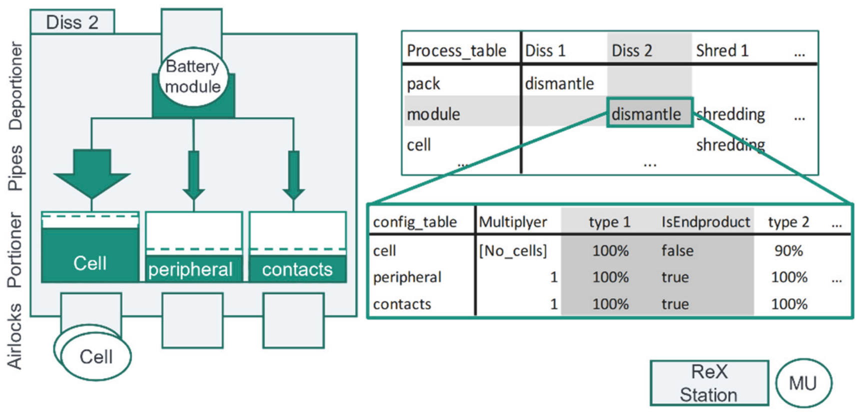


Figure 2: Concept of modular ReX station (left) and Process_table with Config_table (right). Example for battery module (MU) entering station Diss 2

The quantity of generated output MUs leaving a modular station is equivalent to the number of components of the input MU. For example, is a battery module disassembled, as many cells as this module contains are generated. This may lead to a cluttered situation at the exit airlock of the stations. To prevent traffic jams, the MUs are stored and transported between ReX stations in magazines, which have a capacity between 5 and 100 units, depending on the type of MUs. Furthermore, MUs that represent packs, modules, or cells will only share a magazine, if they share the same decision about reusing, remanufacturing, or further disassembly.

3.3 Material flow control

Each output MU of a modular station is transferred to an exit buffer and has four successor options (see Figure 1). The next target station of the exiting MU is defined by the method *material flow control*. If it is an endproduct, (1) the MU will be stored as recycled material in a storage. If *isEndproduct* is false, the exiting MU will be (2) transferred to the next designated modular station. Otherwise the output MUs will not be disassembled further but, (3) be transferred to a buffer for ReUse if the MU characteristics, such as product and SoH, allow reuse, or (4) be transferred to the appropriate manufacturing station.

Pseudocode for material flow control

```
if MU not isEndproduct
     get successor from process_chain
     move to successor
elseif MU meets criteria for reuse
     move to it’s buffer for reuse
elseif MU meets criteria for remanufacturing
     move to it’s buffer remanufacturing
     get remanufacturing station with shortest queue
     move to remanufacturing station
else
     move MU to it’s buffer for recycling
```

Parts leaving the overall ReX process via (3) are first stored in a buffer between the ReX area and the linear manufacturing area. When one ReX part is entering the linear production line, this part is subtracted from the original production plan for linear production. Then, to determine the station in the manufacturing step where the ReX parts enter, the station of this manufacturing steps with the lowest utilization is selected. The magazine is then transported from the buffer to this station and the parts are from now on treated as new ones. This way, parts entering the linear manufacturing have a direct influence on the behavior of both systems. This allows detailed evaluations of the individual processes and raw material consumption can be determined. These analyses can help to improve the planning and control of integrated remanufacturing factories.

4 Use Case

The developed approach is applied to a use case based on the AgiloBat production system for the agile production of battery cells (Ruhland et al., 2022; Andersen et al., 2022).The production system uses micro environments to achieve a high adaptability. A DES model of this production system in the software Plant Simulation from

Siemens was created and described by Overbeck et al. (2022). This simulation model covers already various technology alternatives to produce battery cells and can model different future scenarios of market and technological development. For the current paper, circular processes are added, partly based on the solutions developed in the research project DeMoBat (Gerlitz et al., 2019). In section 4.1 the final model is presented, followed in section 4.2 by the *implementation* of recycling processes. Finally, the *experiments and analysis* are demonstrated in section 4.3.

4.1 The integrated simulation model

The existing simulation model of agile cell production is extended by a source of used battery packs, disassembly, and recycling stations, and follows the design presented in Chapter 3. A cutout of the resulting model is shown in Figure 3, which includes the ReX area (A), linear manufacturing (B), buffers for ReX parts capable for reuse (C), buffers for ReX parts that will be re-introduced into manufacturing (D), and buffers for finished recycled goods (E). The ReX production consists of an inspection for incoming batteries (1), battery cell deactivation (4), and disassembly and recycling processes that are represented by modular ReX stations which are as follows:

- disassembling stations for packs (2), modules (3), cells (5), cell stacks (6), and electrodes (7)
- mechanical processing stations: recovery electrolyte (8) and shredder (10)
- pyrolysis station (9), pyrometallurgy station (11) and hydrometallurgy station (12)

The image section of the linear production in Figure 3 shows the manufacturing of electrodes and contains stations for mixing of slurry (13), coating of the electrodes in sheet-to-sheet (14) and coil-to-coil (15) processes, calendaring (16), slitting (17), cutting (18), and stacking (19). The shown detail is limited to the processes of electrode manufacturing but the complete simulation model also includes cell assembly and cell activation of (re)manufactured cells.

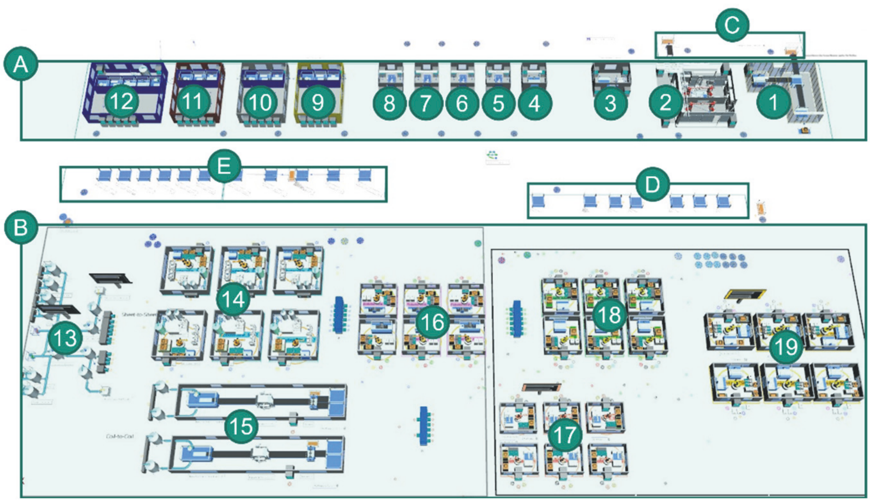
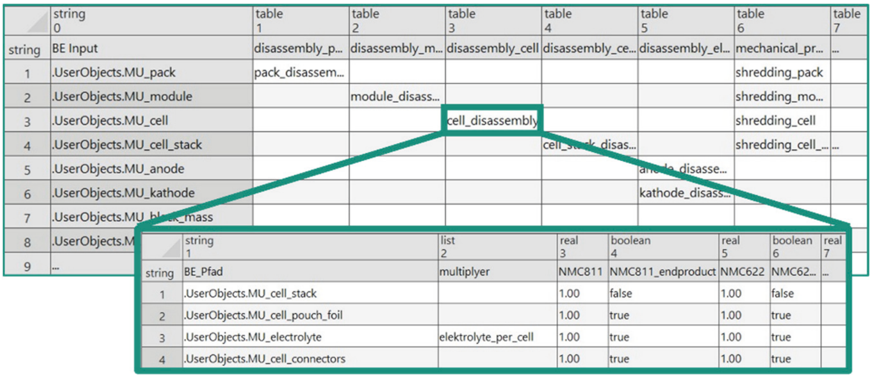


Figure 3: Cutout of electrode manufacturing and ReX area in Plant Simulation model

4.2 Configuration of ReX Stations

All possible disassembly degrees of batteries and further material recovery techniques for LIBs shall be investigated with the help of the simulation model. These feasible combinations of disassembling and recycling steps are recorded as process chain variants in accordance with Doose et al. (2021).

The chemical-technical behaviour of the process chains is embedded in the form of a matrix (Figure 5). It defines for each modular station and possible input MUs the output MUs with corresponding quantities, qualities, and information about further decomposition. A challenge is that the same modular station reacts differently to the same inputs that have undergone different previous treatments. For example, the hydrometallurgy station reacts differently to black mass that has been previously pyrolyzed than to untreated black mass. To account for the dependency on preceding process steps some process steps generate their own MUs with a corresponding identification. For example, black mass is represented by the MU *Black_Mass,* and after pyrolysis the corresponding MU is *Black_Mass_pyro*.



	string 0	table 1	table 2	table 3	table 4	table 5	table 6	table 7
string	BE Input	disassembly_p...	disassembly_m...	disassembly_cell	disassembly_ce...	disassembly_el...	mechanical_pr...	...
1	.UserObjects.MU_pack	pack_disassem...					shredding_pack	
2	.UserObjects.MU_module		module_disass...				shredding_mo...	
3	.UserObjects.MU_cell			cell_disassembly			shredding_cell	
4	.UserObjects.MU_cell_stack				cell_[illegible]k_disas...		shredding_cell_...	...
5	.UserObjects.MU_anode					a[illegible]e_disasse...		
6	.UserObjects.MU_kathode					kathode_disass...		
7	.UserObjects.MU_bl[illegible]k_mass							
8	.UserObjects.M[illegible]							
9	...							

	string 1	list 2	real 3	boolean 4	real 5	boolean 6	real 7
string	BE_Pfad	multiplyer	NMC811	NMC811_endproduct	NMC622	NMC62...	...
1	.UserObjects.MU_cell_stack		1.00	false	1.00	false	
2	.UserObjects.MU_cell_pouch_foil		1.00	true	1.00	true	
3	.UserObjects.MU_electrolyte	elektrolyte_per_cell	1.00	true	1.00	true	
4	.UserObjects.MU_cell_connectors		1.00	true	1.00	true	

Figure 4: Process table with information for ReX stations

4.3 Experiments

One exemplary experiment to gain deeper insights into the functionality of the circular factory, which is presented in the following, aims to investigate the effect of different battery characteristics on the utilisation of the individual ReX stations and production stations. The analysis includes throughput and occupancy times of the processing stations. Other analyses, which are not presented here, looked at buffer occupancy, AGV travel times, and the consideration of recycled material quantities.

Input for the simulation is a production plan and a delivery list of EOL batteries. The production plan contains 2610 battery cells of the type NMC 811, representing the estimated production capacity of the modeled manufacturing system over a 30-day period. The delivery list consists of 200 EOL battery packs. The used batteries are fed into the system at 24-hour intervals in batch sizes of 10. The SoH of each incoming LIB is normally distributed with the mean value determined by the scenario and a standard deviation of 5%. The expected mean SoH for the three scenarios is chosen as 0.85, 0.75, and 0.7, respectively, based on automotive industry standards which consider a battery reached EOL when it has lost 20% to 30% of its original capacity

(Barco et al., 2020). Returned battery packs are suitable for reuse, if their SoH is greater than 0.85. If it is lower, it is sent to the pack disassembly station. The modules obtained from dismantling have a SoH randomly drawn from a normal distribution with a 5% standard deviation, using the SoH of the originating pack as the mean value. Modules with SoH above 80% are reused, those between 70% and 80% are fed into the manufacturing system, and those below 70% are further disassembled. The cells' SoH fluctuates by 20% around the SoH of their originating disassembled module. Cells with a SoH higher than 80 % are remanufactured, cells with a lower SoH are recycled. Simulation runs were conducted for each scenario with a 30-day simulation time, and the material flows are displayed in Table 1.

Table 1: Material flow (throughput) of EOL components in the circular factory

Mean SoH	Dismantled packs	Reused modules	Remanuf. modules	Dismantled modules	Remanuf. cells	Recycled cells
0,85	107	192	168	6.7	20	120
0,75	196	102	360	84.4	40	220
0,70	200	22	216	108	80	560

Figure 6 demonstrates how material flows affect the utilization of individual stations. The graph shows that components leaving the system for reuse do not impact following ReX stations or the linear production area, while redirecting used components increases the load on ReX processes before the reintegration point and linear production processes after the reintegration point, leading to underutilization of upstream resources like coating and drying (14). Notably, recycling stations experience high utilization in low SoH scenarios but low to minimal utilization in medium to high SoH scenarios, resulting in less, moderate, and high influence of linear manufacturing for low, medium, and high SoH scenarios respectively.

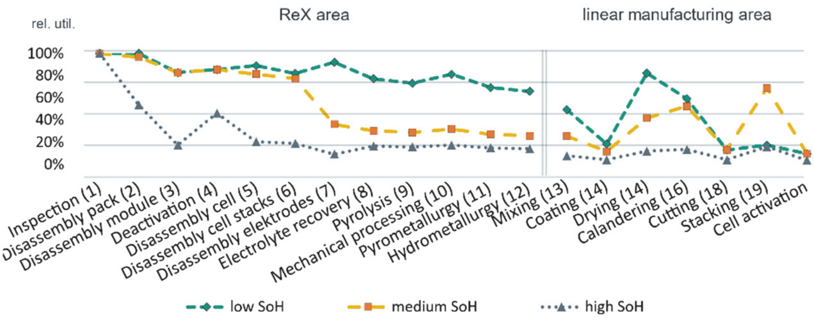


Figure 5: Relative utilization of ReX stations (left) and linear manufacturing stations (right) for scenarios of LIB with low SoH, medium SoH and high SoH

From an environmental and economic standpoint, maximizing the reintegration of disassembled components into the manufacturing process or declaring functional components suitable for reuse is desirable. However, certain components will still require recycling and manufacturing. Proper sizing of ReX and manufacturing stations is critical and simulating expected EOL battery returns can help design optimal facilities for this task. The presented experiment tackles the complex production planning and control challenge of line balancing in a circular plant. Following Rabe et al. (2008), the model verification method "review" was performed for the model with experts and the criteria *suitability, comprehensibility* and *feasibility* applied.

5 Summary and outlook

Preliminary research on the use of DES in remanufacturing of LIBs exists but not on an integrated consideration at the factory level. This research gap was tackled by the presented approach, which allows the integrated modelling of processes for ReX as well as manufacturing in one simulation model and at the same time considers the particularities regarding the domain of LIBs. A special challenge in modelling ReX processes for LIBs is the variety of possible process chains with different effects on the recovered components or materials. In response to the challenge of multiple process variations and the multitude of material flow decisions required, a design based on modular stations capable of representing a variety of process outcomes depending on its input materials was introduced. In addition, the approach includes an integration of ReX parts and materials into a modular production system for batteries, which allows a detailed analysis of individual machine utilization and line balancing. The presented approach was implemented in Plant Simulation for the AgiloBat agile battery production system and possible disassembly and recycling processes were implemented. It was illustrated to what extent technological and economic analyses can be performed for optimal system design and control. It was shown how the required capacity of process steps depends on the SoH of the returning batteries. In future research, the model could be extended to simulate energy consumption and the environmental impact of each process for a multicriteria analysis. Furthermore, the model can be extended by integrating scrap material from the cell production due to start-up problems or defective products directly into the ReX system.

Acknowledgment

The authors thank the German Ministry of Education and Research (BMBF) for funding the project *AgiloBat2* (03XP0369A) as well as the Ministry of Economics, Labor, and Tourism of Baden-Württemberg for funding the project *BatterieZellFab* (WM34-42-57/30) and the project *BatteReFAB* (WM34-42-57/25).

References

Alfaro-Algaba, M.; Ramirez, F.J.: Techno-economic and environmental disassembly planning of lithium-ion electric vehicle battery packs for remanufacturing. Resources, Conservation and Recycling 154 (2020)

Andersen, A.-L.; Andersen, R.; Brunoe, T.D. et al.: Towards Sustainable Customization: Bridging Smart Products and Manufacturing Systems. Cham: Springer International Publishing 2022.

Braco, E.; San Martín, I.; Berrueta, A. et al.: Experimental assessment of cycling ageing of lithium-ion second-life batteries from electric vehicles. Journal of Energy Storage 32 (2020).

Cerdas, F.; Kurle, D.; Andrew, S. et al.: Defining Circulation Factories – A Pathway towards Factories of the Future. Procedia CIRP 29 (2015), pp. 627–632.

Deveci, M.; Simic, V.; Torkayesh, A.E.: Remanufacturing facility location for automotive Lithium-ion batteries: An integrated neutrosophic decision-making model. Journal of Cleaner Production 317 (2021).

Doose, S.; Mayer, J.K.; Michalowski, P. et al.: Challenges in Ecofriendly Battery Recycling and Closed Material Cycles: A Perspective on Future Lithium Battery Generations. Metals 11 (2021) 2.

Eddy, J.; Pfeiffer, A.; van de Staaij, J.: Recharging economies: The EV-battery manufacturing outlook for Europe, McKinsey, 2019.

Fleischer, J.; Gerlitz, E.; Rieβ, S. et al.: Concepts and Requirements for Flexible Disassembly Systems for Drive Train Components of Electric Vehicles. Procedia CIRP 98 (2021), pp. 577–582.

Gerlitz, E.; Kaiser, J.-P.; Hofmann, J., 2019: DeMoBat, KIT Karlsruhe. https://www.wbk.kit.edu/intern/DeMoBat/index.php, Accessed 26.04.2023.

Huster, S.; Glöser-Chahoud, S.; Rosenberg, S. et al.: A simulation model for assessing the potential of remanufacturing electric vehicle batteries as spare parts. Journal of Cleaner Production 363 (2022).

Kampker, A.; Wessel, S.; Fiedler, F. et al.: Battery pack remanufacturing process up to cell level with sorting and repurposing of battery cells. Journal of Remanufacturing 11 (2021), pp. 1–23.

Overbeck, L.; Voigtländer, S.; Lanza, G.: Optimal line configurations for agile production systems for battery cell manufacturing. In: 16th CIRP Conference on Intelligent Computation in Manufacturing Engineering, Online, 13.-15.07.2022 (without page numbers).

Rabe, M.; Spiekermann, S.; Wenzel, S.: Verifikation und Validierung für die Simulation in Produktion und Logistik. Berlin, Heidelberg: Springer 2008.

Ruhland, J.; Storz, T.; Kößler, F. et al.: Development of a Parallel Product-Production Co-design for an Agile Battery Cell Production System. In: Andersen, A.-L.; Andersen, R.; Brunoe, T.Ditlev et al. (Eds.): Towards Sustainable Customization: Bridging Smart Products and Manufacturing Systems. Cham: Springer International Publishing; Springer 2022, pp. 96–104.

Standridge, C.R.; Hasan, M.M.: Post-vehicle-application lithium-ion battery remanufacturing, repurposing and recycling capacity: Modeling and analysis. Journal of Industrial Engineering and Management 8 (2015) 3, pp. 823–839.

VDI 3633: Simulation of systems in materials handling, logistics and production - Fundamentals, 2014.

Ventura Silva, G.; Thomitzek, M.; Abraham, T. et al.: Simulation-based Assessment of Energy Demand and Costs Associated with Production Scrap in the Battery Production. SNE Simulation Notes Europe 32 (2022) 3, pp. 143–150.

Wakiru, J.; Pintelon, L.; Muchiri, P.N. et al.: Integrated remanufacturing, maintenance and spares policies towards life extension of a multi-component system. Reliability Engineering & System Safety 215 (2021).

Wurster, M.; Michel, M.; May, M.C. et al.: Modelling and condition-based control of a flexible and hybrid disassembly system with manual and autonomous workstations using reinforcement learning. Journal of Intelligent Manufacturing 33 (2022) 2, pp. 575–591.