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Framework for Worker Assistance System to Enable Disassembly Processes Towards Circular Economy

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Abstract

Climate change, one of the most significant threats to humanity, underscores the urgent need to advance the circular economy, particularly in promoting sustainability. Implementing R-strategies such as refurbishment and remanufacturing within the home appliances industry is central to establishing sustainable and environmentally friendly business models. Key processes, such as workpiece disassembly, reassembly, and component status evaluation, are inherently more complex and variable than conventional production workflows. This requires workers with extensive experience handling comparable products and a deep understanding of critical decision-making processes. Due to the skilled worker shortage and the impact of demographic shifts, developing precise and comprehensive work instructions is increasingly vital for maintaining process quality. A worker assistance system is essential to meet this need, providing robust decision support to ensure accurate and sufficient decision-making. This paper proposes a framework for a worker assistance system tailored to the application of R-strategies in washing machine production. Data from an industrial scenario validates the framework and identifies critical information that should be incorporated into the system, enhancing the applicability and feasibility of the framework in real-world contexts. Within the framework, potential data sources and information flows are proposed, and illustrative processes are employed to demonstrate the derivation of work instructions utilizing the framework.

1. Introduction

The circular economy has emerged as a prominent topic in both research and industrial sectors over the past decade. The term is conceptualized as an economic model that aims to enhance resource utilization efficiency by minimizing material waste [1]. Within this framework, closed loops are established for products, parts, and raw materials, which are designed to yield ecological, economic, and social benefits [2]. The circular economy holds significant importance for manufacturing industries, where raw materials constitute a crucial expenditure in the value chain. The dynamic nature of the raw material market renders the circular economy invaluable for stabilizing supply chains and decoupling production performance from potential raw material shortages [3,4].

The circular economy is particularly important for manufacturing processes in the home appliance industry. Home appliances frequently depend on finite resources such as metals (e.g., copper, aluminum, rare earth elements) and plastics derived from fossil fuels [5]. The production of these materials is energy-intensive and contributes to greenhouse gas emissions. The circular economy advocates reusing, refurbishing, and recycling these materials, thereby reducing reliance on virgin resources and mitigating environmental degradation [6]. Enhanced resource efficiency can significantly lower the carbon footprint of home appliances by reducing energy-intensive production processes and minimizing landfill emissions [7].

The circular economy is getting increasing attention not only from the manufacturer's perspective but also from the consumer's viewpoint. A 2021 report about the circular economy by consulting firm Capgemini revealed that over half of consumers were comfortable with the concept of using pre-used resources in home appliances [8]. This suggests a strong foundation for market acceptance in this sector. For instance, washing machine counterweights made from cast iron can be reused in subsequent product life cycles, which remain in good condition even reaching the end-of-life phase of the product. However, Eurostat statistics from 2023 indicated that the circular material use rate in the European Union has stagnated at 11% since 2012, with only a 0.5% increase in ten years. Therefore, enhancing this rate requires practical solutions within the industry [9].

Different decision-making processes are involved in manufacturing processes in the circular economy, especially when determining which part can be used further in the next product lifecycle based on its usage condition. In this context, manufacturing processes develop towards dynamic instead of static [10]. Dynamic processes also mean increasing complexity, indicating that even in the same product variant, different tasks need to be performed. This requires workers executing the manufacturing processes to react to respective scenarios and apply the correct actions. Therefore, during the application of the circular economy, worker assistance should also enable workers to adapt to complex and dynamically changing scenarios.

The necessity of worker assistance in the context of the circular economy is also influenced by the global trend of a skilled worker shortage, which is caused by various factors such as an aging population, urbanization, migration, and mismatched education and skills [11]. In Europe, the aging population significantly impacts manufacturing industries, making it increasingly difficult to hire skilled workers. For example, statistics from the German Federal Employment Agency indicate a substantial shortage of qualified workers in mechanical engineering, operating engineering, and electrical engineering [12]. These fields are particularly vital to manufacturing industries, especially those producing home appliances. The index of skilled workers in Germany published by the consulting company HAYS also shows that the demand for skilled workers in the engineering sector at the beginning of 2024 increased by 126% compared to 2015 [13].

The trend towards the circular economy and the skilled worker shortage pose a dilemma for manufacturing companies. On the one hand, these companies are urged to apply more sustainable and environmentally-friendly business models, ensuring development towards the circular economy. On the other hand, the skilled worker shortage hinders them from using the circular economy in their manufacturing processes on a large scale. Therefore, comprehensible worker assistance is necessary to decrease or eliminate the impact of insufficient worker experience on applying the circular economy.

The subsequent Chapter 2 explores the R-strategies employed in the circular economy, which are essential for the manufacturing processes of home appliances. During the implementation of R-strategies, workers require clear and comprehensible guidance. The concept of worker assistance is then introduced. Another critical term, the depth of

disassembly, is also discussed, as the present work focuses on disassembly processes. For the framework development, the general design approach derived from the Design Science Research is introduced in Chapter 3. Following the design approach, development requirements and associated work are analyzed in Chapter 4. In Chapter 5, based on this analysis, a framework for a worker assistance system to facilitate circular economy processes is designed. The corresponding systematic solution is proposed. Validation is conducted to demonstrate its practical applicability through a case study in the home appliance industry.

2. State of the Art

The circular economy presents challenges for manufacturing, especially in implementing sustainable R-strategies like refurbishment and remanufacturing. These processes require informed decision-making as components vary in condition, necessitating dynamic adaptation. The shortage of skilled workers further complicates scaling these strategies. Effective worker assistance systems are crucial to guide operators in selecting and executing suitable R-strategies. This chapter explores current research on R-strategies, worker assistance, and disassembly depth, providing a framework for enhancing decision-making and process execution in circular manufacturing.

2.1 R-strategies in the circular economy

Manufacturers have long recognized the constraints of linear consumption and manufacturing processes. The conventional “take-make-dispose” model within a linear system depends on extensive resource extraction and disposal, which contributes to the rapid escalation of ecological damage and the emission of substantial greenhouse gases [14]. Consequently, various enablers for a circular economy have been developed, with the application of R-strategies being a frequently discussed option.

R-strategies are crucial in the transition from a linear to a circular economy. These strategies are directly aligned with the principles of designing out waste, retaining value in products and materials, and fostering systematic resource efficiency [15]. Multiple R-strategies are collectively referred to as circularity strategies. Potting et al. developed a 9R framework to categorize all R-strategies, including refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover [16]. Within this framework, these R-strategies are divided into three categories based on their circularity level. A higher circularity level signifies reduced natural resource consumption and less environmental impact. As the circularity level increases, the following three categories are defined in ascending order:

1. Useful application of materials
2. Extend the lifespan of the product and its parts
3. Smarter product use and manufacture

The first category focuses on reusing resources under specific conditions. The R-strategies in this category, recover and recycle, address limited aspects of the circular economy, primarily targeting raw material or energy consumption. The second category aims to extend the product or part lifetime and is more relevant in the manufacturing context. This category includes reuse, repair, refurbish, remanufacture, and repurpose. The last category is defined as the highest circularity, addressing the elimination of unnecessary resource consumption or identifying more meaningful consumption. Refuse, rethink, and reduce are allocated in this category.

This work discusses worker assistance during circular economy processes. The application scenarios of R-strategies occur during the manufacturing processes of home appliances, where workers require clear and intuitive instructional information. Therefore,

the R-strategies focusing on value retention of home appliances discussed in the following sections are from the second category to provide informed decision support for workers to conduct, e.g., refurbishment and remanufacturing.

2.2 Worker assistance during the application of R-strategies

Worker assistance has been frequently discussed in the manufacturing context. Entering the era of Industry 4.0, worker assistance is not only limited to physical support, such as helping workers lift heavy loads, but focuses more on providing informational support during decision-making processes [17,18]. The informational support aims to enhance productivity and ensure quality, which are two main target indicators of manufacturing performance.

The shortage of skilled workers underscores the critical need for well-defined worker assistance, particularly within the context of the circular economy, where processes like refurbishment and remanufacturing necessitate specific technical skills. A lack of expertise or experience can lead to inadequate element assessment or strategy selection when applying R-strategies. Unlike traditional manufacturing, the circular economy processes involve non-standardized inputs (e.g., used parts in varying states), requiring workers to make informed and often complex decisions [19]. These variations do not necessarily increase physical workload but significantly enhance cognitive workload, as workers must make decisions based on heterogeneous data and information. In this context, a key role of worker assistance during applying R-strategies is to guide less experienced workers to ensure correct and efficient task execution.

As the first step in addressing the challenges mentioned above, it is essential to identify what kind of worker assistance workers need within the circular economy. A research report published by the German Federal Ministry of Labour and Social Affairs categorized worker assistance based on three dimensions: degree, type, and purpose. Figure 2-1 provides an overview of the categorization and dimensions. [20].

Digital worker assistance		
Degree of assistance	Type of assistance	Purpose of assistance
<i>Low</i>		
<i>Medium</i>	<i>Physical</i>	<i>Compensatory</i>
<i>High</i>	<i>Sensorial</i>	<i>Preserving</i>
<i>Variable</i>	<i>Cognitive</i>	<i>Enhancing</i>

Figure 2-1 – Categorization of worker assistance based on degree, type, and purpose according to Apt et al. [20]

In Figure 2-1, the degree of worker assistance varies from low to high, indicating the level of support provided. It can range from basic guidance and light physical support to advanced decision-making and adaptive strategies. Systems that can adapt to different complexity levels and requirements are considered to have a variable degree of worker assistance.

The report also summarized three types of assistance: physical, sensory, and cognitive. Physical assistance provides tools to aid physical tasks, such as ergonomic workstations. Sensory assistance supports workers using sensory functions, including AR-worker assistance. Cognitive assistance provides real-time information, including task guidance and decision-making support. Digital work instructions are needed to contain sufficient information for successful task execution.

Worker assistance can be implemented for compensatory, preserving, and expanding purposes. Compensatory assistance addresses individual deficits, such as helping workers with disabilities or age-related challenges. Preserving assistance maintains health, safety, and efficiency in the workplace, such as reducing physical strain or preventing repetitive stress injuries. Worker assistance can also enhance worker abilities and improve overall productivity, such as integrating training or advanced task capabilities.

Within the circular economy, there are various decision-making levels within the value creation level of a company that need to be supported. One of the critical levels observes the workstation, where workers conduct critical steps to realize value retention. This level is considered where the actual value creation takes place. [21] Therefore, worker assistance for applying corresponding R-strategies in the present work can be classified as cognitive and capability-enhancing. Cognitive support involves providing contextual information during the execution of R-strategies. Instructional information does not replace or automate operators' activities but facilitates informed decision-making, enhancing their capabilities. The generic applicability of work instructions suggests that a variable degree of support best describes the intended assistance.

2.3 Disassembly Depth

One crucial informal support required by the worker during the application of R-strategies is the knowledge of the extent to which the product needs to be disassembled to reach the target part. This concept, known as disassembly depth, is frequently discussed in disassembly sequence planning (DSP). It refers to the level or extent to which a product, assembly, or system is disassembled into its individual components, subcomponents, or modules during a disassembly process. Essentially, disassembly depth measures how “deep” into the product structure the disassembly goes, depending on the specific objectives of the process.

Various researchers have defined disassembly depth from different perspectives. Generally, disassembly depth is determined based on the necessary effort required to conduct a disassembly task, where this necessary effort is defined according to different standards. Navin-Chandra defined disassembly effort as the required steps to disassemble parts to reach the target element [22]. In von Werder's work, weights were assigned to the disassembly of each part, and the aggregation of these weights represents the disassembly effort [23]. Disassembly depth increases as the aggregation of weights increases. Additionally, Langella observed disassembly depth from an economic perspective, indicating that disassembly depth is defined by the absolute ratio between the cost of disassembly and the cost of assembling the product [24]. These definitions provide a numerical value to describe disassembly depth but do not account for the difficulty and complexity of individual disassembly steps, thus limiting their applicability to specific scenarios.

To address the challenges posed by varying difficulties and complexities in different steps, Ritthoff et al. proposed a general comparison approach to compare disassembly depth between similar products [25]. Their approach was derived from the standard file DIN EN 45554 [26], which aims to generally assess the ability to repair, reuse, and upgrade energy-related products. This approach records the steps needed to reach the same core element across product variants. The mean value of these steps is calculated, and each variant's percentage deviation is determined. These percentages are evaluated on a scaled system, allowing for variant comparison. This approach enables quantitative comparison and simplifies determining disassembly depth from assembly instructions. However, it is intended for comparison rather than absolute assessment and requires a reference product.

To conduct an analytical and mathematical evaluation of disassembly depth, the approach proposed by Giudice is analyzed [27]. Giudice presented an equation to calculate the absolute value of disassembly depth, considering the specific difficulties and complexities associated with each step.

$$dd = dd_{SC} + \beta \cdot dd_{JC} = \frac{1 + n_d}{n} + \beta \cdot \frac{\sum_{k=1}^h \alpha_k \cdot f_{d_k}}{f}$$

In this equation, dd_{SC} represents spatial constraints, and dd_{JC} indicates constraints through fasteners and their difficulties in removal. In detail, dd_{SC} is calculated as the total number of components to be removed ($1 + n_d$), including the component whose disassembly depth is currently being evaluated) divided by the total number of components n . And dd_{JC} is determined by the number of fasteners of the k -th type to be removed (f_{d_k}), the total number of fasteners (f), and the number of fastener types (h).

During the calculation, two coefficients are involved. α_k represents the difficulty of disassembling a fastener of the k -th type, and β indicates the greater weight of dd_{JC} compared to dd_{SC} . The product manufacturer can subjectively determine the two coefficients, although objective determination methods can be considered. For instance, α_k can be determined by the required time or torque to disassemble a fastener, with a value between 0 and 1. β is a subjective parameter typically rated between 1 and 2. This coefficient is crucial when comparing multiple products.

The value of dd varies from 0 to $1 + \beta$. The maximum value is achieved when all components/assemblies of the product need to be disassembled ($dd_{SC} = 1$), and all fasteners present in the product have maximum difficulty of disassembly ($dd_{JC} = 1$).

Giudice's approach facilitates comprehensive evaluation, taking into account the challenges associated with removing fasteners. It provides a clear presentation of the distance between assessments of disassembly depth and enables the comparison of different product types. This approach addresses all the challenges mentioned above. Therefore, it is applied to determine disassembly depth when disassembling a home appliance. The application of disassembly depth will be discussed in Chapter 5.

3. General design approach

The Design Science Research (DSR) methodology proposed by Hevner et al. [28] is applied to derive the general design approach in this work. Hevner et al. developed the methodology as a rigorous, problem-oriented paradigm for creating and evaluating IT-based artifacts that address real-world organizational challenges. Their methodology outlines a general framework for developing a system, starting with the initial problem definition and ending with demonstration and evaluation based on real-world data. Two complementary frameworks, the three-cycle view [28] and the seven DSR guidelines [29], form the core of the DSR methodology.

The three-cycle view consists of the relevance cycle, the rigor cycle, and the design cycle. The relevance cycle connects the research and solution development to its application domain, which is the home appliance industry in this work. In this cycle, requirements from the application domain are analyzed and elicited. The rigor cycle discusses the existing knowledge base, including theories, frameworks, and methods, to provide a firm theoretical foundation for the design. In this cycle, the current research trend is analyzed to determine the existing challenges according to the requirements analysis. Research gaps are correspondingly identified. The last cycle, the design cycle, is the core of the DSR methodology, iterating between developing the artifact and testing against requirements. This cycle aims to achieve the satisfactory performance of the designed solution, ensuring the challenges are addressed and solved.

The seven DSR guidelines are distilled from the DSR paradigm to ensure both the rigor and relevance of any development applying DSR. The seven guidelines are introduced briefly in the following:

1. **Design as an Artifact:** The core outcome of the design is a purposeful IT-based artifact that addresses the target problem.
2. **Problem Relevance:** The design tackles an existing problem in the real world, ensuring practical impact.
3. **Design Evaluation:** The design is demonstrated through rigorous methods such as case studies.
4. **Research Contributions:** The design yields verifiable contributions.
5. **Research Rigor:** Both the construction and the evaluation of the design are grounded upon existing methods.
6. **Design as a Search Process:** A systematic search through possible solutions is needed, balancing environmental constraints and design objectives.
7. **Communication of Research:** The research is communicated effectively to both technical and managerial audiences.

Though the two frameworks of the DSR methodology provide a comprehensible explanation for utilization, the theoretical description from Hevner et al. remains high-level and lacks a concrete application process. Peffers et al. [30] distilled the DSR methodology into a pragmatic six-activity DSR process—each step explicitly derived from Hevner et al.’s guidelines and cycles. The process aims at a nominal process model researchers can follow to design and develop the IT-based solution. These six activities are adopted for this work:

1. **Identify Problem & Motivation:** The high-level challenge is reframed as a concrete problem in its real-world context.
2. **Define Objectives:** The problem relevance is translated into functional targets.
3. **Design & Development:** The system is designed and constructed using theoretical foundations and technical approaches.
4. **Demonstration:** The designed system is demonstrated with real-world scenarios.
5. **Evaluation:** The designed system is assessed against the objectives to measure effectiveness and identify further development necessities.
6. **Communication:** The designed system is discussed with technical and managerial audiences for transformability and applicability.

In the upcoming chapters, this work will follow the DSR process developed by Peffers et al. and construct the targeted worker assistance framework. The activity “Identify Problem & Motivation” has been discussed in Chapter 1, and the state of the art has also been introduced in Chapter 2. Chapter 4 will focus on the activity “Define Objectives”, and Chapter 5 covers the activities “Design & Development”, “Demonstration”, and partially “Evaluation”, as the framework is yet to be developed in a practical and industrial environment to conduct a comprehensive evaluation. The activity “Communication” is completed in Section 5.3 and provides the outlook in Chapter 6.

4. Requirements and related work

Worker assistance in the circular economy can be categorized into two main components: decision support and context-specific work instructions. Decision support is crucial for selecting appropriate R-strategies, as the status of components in the circular lifecycle varies. Workers require a data-driven system to quickly determine the most suitable approach, such as remanufacturing or refurbishing. The system should dynamically recommend strategies based on the condition of the components and sustainability goals,

utilizing data aggregation from sources like lifecycle data, condition monitoring, and predictive analytics. Accurate and real-time data is essential for informed decision-making.

Furthermore, the worker assistance system should facilitate bidirectional information exchange between the virtual (digital space where context-specific instructions are stored) and the real world (physical space where workers conduct their respective work processes). Workers should receive instructions and provide feedback on the system. The system should support inputs like barcode scanning for step confirmation and allow immediate feedback for quality checks. These inputs contribute to the improvement of the worker assistance system. They refine the alternative catalog for better component assessment and R-strategy selection.

Context-specific work instructions provide relevant information to workers, minimizing the effort in identifying key details. Instructions must be tailored to components, process stages, and worker roles to enhance cognitive assistance. Research over the past decade has established a common understanding of context in manufacturing, despite varying applications. Studies [31] and [32] defined context as user-, environment-, and system-related information, while [33] enhanced process relevance. In general, contextual information falls into four categories: user, environment, system, and process.

Nuy et al. constructed a detailed data model for context-specific work instructions by utilizing the Digital Twin (DT) [34]. They created a process-centric data model, with process data as the foundation. Four essential data types were identified: product, resource, context, and process data. Definitions of these four data types share a common understanding of the abovementioned contextual information. A concise description of these four data types is presented below:

- Product data encompasses information on the central object under consideration, including assemblies, subassemblies, and geometric data.
- Resource data provides details on the tools, machines, and auxiliary materials necessary for the tasks.
- Context data includes attributes of the instruction user, such as personal data, skills, and experience, as well as the environment, including physical impacts and climate, and the information device, such as software and network.
- Process data consists of steps, sequences, and other task-specific details for executing the instructions.

The model was designed to replicate the physical and functional characteristics of the products, resources, and processes. The DT concept facilitated bidirectional real-time data exchange, thereby improving adaptability and context specificity. This approach aligns well with the requirement for bidirectional information exchange outlined earlier. The case study in their work further demonstrates the functionality and adaptability of the data model. Figure 4-1 offers an overview of their data model.

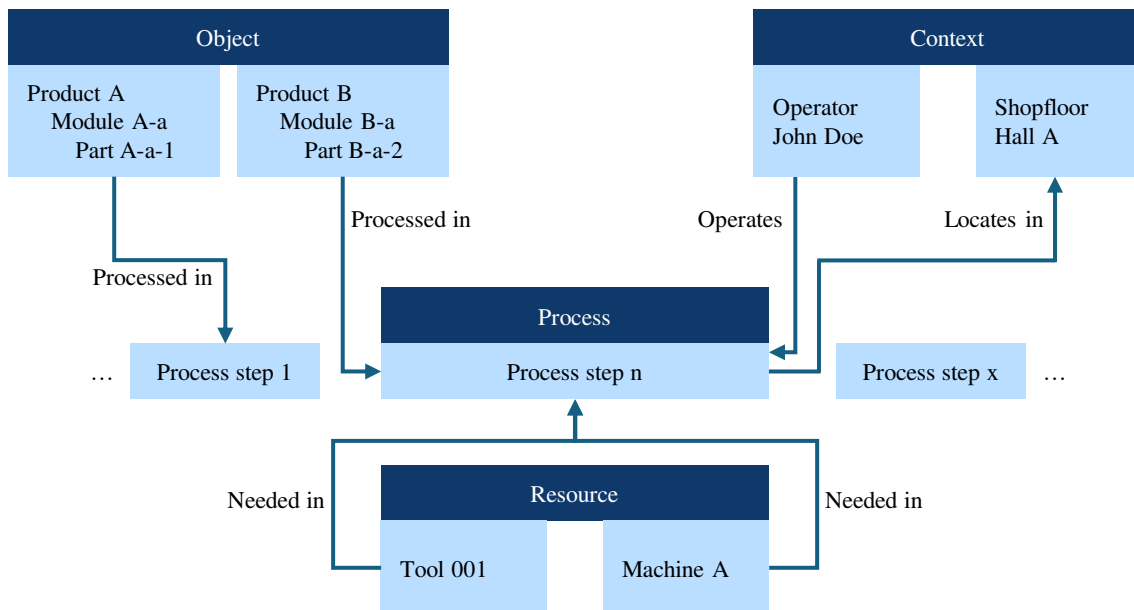


Figure 4-1 – Data model for a digital twin for context-specific work instructions

Nuy et al. propose a digital transformation-based solution for digitizing context-specific work instructions. However, their static approach necessitates users to select predefined instructions, which may not adapt to varying component conditions. For instance, remanufacturing a motor and refurbishing a washing machine door require different disassembly levels. To address this, a worker assistance system should dynamically provide instructions based on the selected R-strategy, ensuring both optimal strategy selection and effective execution on the shop floor.

5. Conception of the framework

5.1 Framework structure

The framework presented in this work comprises three primary sectors: the alternative catalogue, the disassembly graph, and work instructions. The alternative catalogue outlines various scenarios that implement different R-strategies. For each scenario, a list is provided indicating which modules are pertinent. To clarify, the product is described in a hierarchical structure, where a product consists of multiple modules, each composed of multiple parts.

The disassembly graph determines the necessary disassembly depth to access these modules. Once the disassembly depth is identified, the required disassembly processes can be defined. This process enables the provision of corresponding work instructions, as the work instructions model is process-centric, and contextual information is associated with each process step.

The following sections present detailed introductions of the alternative catalogue and the disassembly graph. Ultimately, the alternative catalogue and work instructions are integrated together through the disassembly graph, providing informal worker assistance to reduce the cognitive workload.

Alternative catalogue of R-strategies

The utilization of alternative catalogues enhances decision-making support by clearly visualizing feasible R-strategy pathways, aligning with sustainability objectives emphasized in the circular economy. An alternative catalogue acts as a structured tool to define and evaluate various scenarios for implementing R-strategies, such as refurbishment

and remanufacturing. It provides a product-centric framework for identifying and organizing scenarios, each tailored to specific product conditions and the applied R-strategy.

Figure 5-1 illustrates an example of an alternative catalogue. In this catalogue, each scenario specifies the actions required to achieve the desired outcome. For instance, a machine may need refurbishment by replacing specific modules with a detailed list of relevant modules and parts provided. In this context, the modules can be located in different positions within the product and relate to each other via parts through different hierarchical layers. Figure 5-1 introduces several example scenarios applying different R-strategies, repair, refurbishment, and remanufacturing. The scenario “repair” focuses on repairing and maintaining specific parts or modules so that the product can be put into the market again with its original function. “Refurbishment” aims to restore a used product. This product might not function as desired, and specific functional modules may need to be replaced. In this scenario, the product is partially disassembled and brought up to date after refurbishment. In a “remanufacturing” scenario, the product is completely disassembled to obtain used parts or still functional modules. These obtained parts or modules will be used to produce a new product with similar functions. These obtained parts or modules will be used to produce a new product with similar functions. By offering multiple scenarios, the alternative catalogue enables stakeholders, typically production planners and staff on the disassembly line, to explore and identify effective processes based on the parts involved, operational complexity, and resource utilization.

In this context, the primary outcome of an alternative catalogue is the list of relevant modules for each scenario. This list provides the allocation in the disassembly graph, indicating the pathway to reach these modules and the necessary disassembly of corresponding parts. The use of the disassembly graph is discussed in the following section.

	Repair Repair of optical damage of Module I	Refurbishment Replacement of Module III	Remanufacturing Complete disassembly to obtain parts and modules	...
<i>Part 1-B</i>	✘	✘	✓	
<i>Part 1-C</i>	✘	✘	✓	
<i>Part 1-E</i>	✓	✓	✓	
<i>Part 1-F</i>	✓	✓	✓	
<i>Module I</i>	✘	✓	✓	
<i>Part 2-C</i>	✘	✓	✓	
<i>Part 3-B</i>	✘	✓	✓	
<i>Module III</i>	✘	✓	✓	

Figure 5-1 – An example of an alternative catalogue

Disassembly graph with disassembly depth

A disassembly graph visually represents the structure and relationships between product modules during the disassembly process. It provides a comprehensive breakdown of how

modules are interconnected through individual parts and identifies the sequences and dependencies necessary to disassemble the product effectively.

According to the scenarios defined in the alternative catalogue, disassembly needs can vary by disassembly depth. Generally, the circular economy requires non-destructive disassembly, and two types of disassembly can be categorized: complete disassembly and selective disassembly.

Complete disassembly refers to the disassembly of all modules and parts of a product, indicating the deepest level of disassembly. This process is inherently linked to assembly, as the disassembly sequence is essentially a reverse of the assembly sequence. However, due to the constraints of certain parts that can be realized through adhesion, non-destructive disassembly to separate these parts is often challenging. Furthermore, complete disassembly is generally not a cost-effective or optimal solution. In this study, which focuses on remanufacturing and refurbishment in the home appliances industry, complete disassembly is restricted to modules at a predefined disassembly depth. These modules are crucial for achieving the product's corresponding functions, and further disassembly of these modules is not considered. Complete disassembly is applied when the product is not intended to be reassembled as a whole and returned to the market. The primary objective is to obtain reusable or repairable parts or modules that can be utilized to assemble other products.

In the circular economy, selective disassembly is more frequently employed than complete disassembly to replace or upgrade specific functional modules. Unlike complete disassembly, selective disassembly does not aim to dismantle the entire product to obtain basic parts. The selective disassembly process focuses on extracting a specific part or module from the system. All disassembly processes irrelevant to extracting the targeted part or module are disregarded. This approach allows for economic disassembly and minimizes unnecessary resource consumption. Consequently, selective disassembly is typically planned with a defined disassembly depth, which dictates the pathway the disassembly should follow and can be interpreted as disassembly sequence planning. Compared to complete disassembly, selective disassembly is used in scenarios where only a specific part or module of a product requires repair, replacement, or upgrade.

Figure 5-2 presents a simplified disassembly graph, indicating exemplary disassembly depth obtained through Giudice's approach. At the highest level, parts are listed and positioned. This indicates that to reach modules or parts at a deeper disassembly level, they must be dismantled first. Following the disassembly depth, modules and parts are depicted within their respective components. The disassembly depth is calculated based on the product design in advance. For example, to reach Part 3-A, nine parts and one module need to be disassembled ($n_d = 10$). Two different types of fasteners are involved. The difficulty of disassembling the first type of fastener is evaluated as $\alpha_1 = 0.5$, and the second type as $\alpha_2 = 0.8$. Twelve type 1 fasteners and ten type 2 fasteners need to be removed, which makes $f_{d_1} = 12$ and $f_{d_2} = 10$. β is defined as 1 in this case. Based on the disassembly graph, the disassembly depth of Part 3-A can be calculated as follows:

$$dd = \frac{1 + 10}{25} + 1 \cdot \frac{0.5 * 12 + 0.8 * 10}{80} = 0.615$$

The calculation result indicates that Part 3-A lies on the level with the disassembly depth $0.6 < dd < 0.9$.

Modules on different depths of disassembly are linked with each other through corresponding parts, which generates a pathway to reach specific modules or parts. In a complete disassembly plan, all parts and modules must be extracted from the product, encompassing all pathways in the disassembly graph. Conversely, only pertinent pathways are considered when selective disassembly is implemented, and the disassembly graph

In the “work instruction” sector, ERP and PLM provide basic work information through rough work instructions, which MES can then expand on. Instructional data, such as process flow and associated steps, can be housed in MES, thereby supporting operational guidance and process documentation. Additional contextual information linked to specific process steps, including resources, context, and objects, as discussed in Chapter 4, can be accessed from ERP and PLM. Object-relevant information is associated with PLM. These objects are identified within the alternative catalogue and allocated in the disassembly graph for a chosen disassembly scenario. Regarding resource- and context-relevant information, ERP facilitates high-level management across all perspectives within a manufacturing system. Specifically, sub-modules in ERP provide corresponding information management, such as the tool management module, which oversees information, including usage, maintenance, specifications, and security guidance.

In this framework, MES bridges the shop floor and high-level management, where ERP and PLM are situated. The information flow commences with selecting a scenario from the alternative catalogue, where the user chooses a specific disassembly scenario based on order or batch information assigned in MES. This action initiates the identification of the pertinent modules to be disassembled. The selected modules are then used as input to query the disassembly graph, which determines the optimal disassembly pathway, including the sequence of actions and the required disassembly depth. Once the disassembly pathway is established, the framework retrieves work instructions corresponding to each step in the pathway. These instructions are filtered to ensure they align with the scenario, thereby maintaining relevance to specific product variations or operator expertise, and they include details such as required tools and safety precautions. The retrieved instructions can guide the operator throughout the disassembly process. Feedback from this execution phase, including deviations, errors, or optimizations, is recorded and utilized to refine and improve the alternative catalogue, disassembly graph, and work instructions, thereby fostering a continuous improvement cycle within the framework.

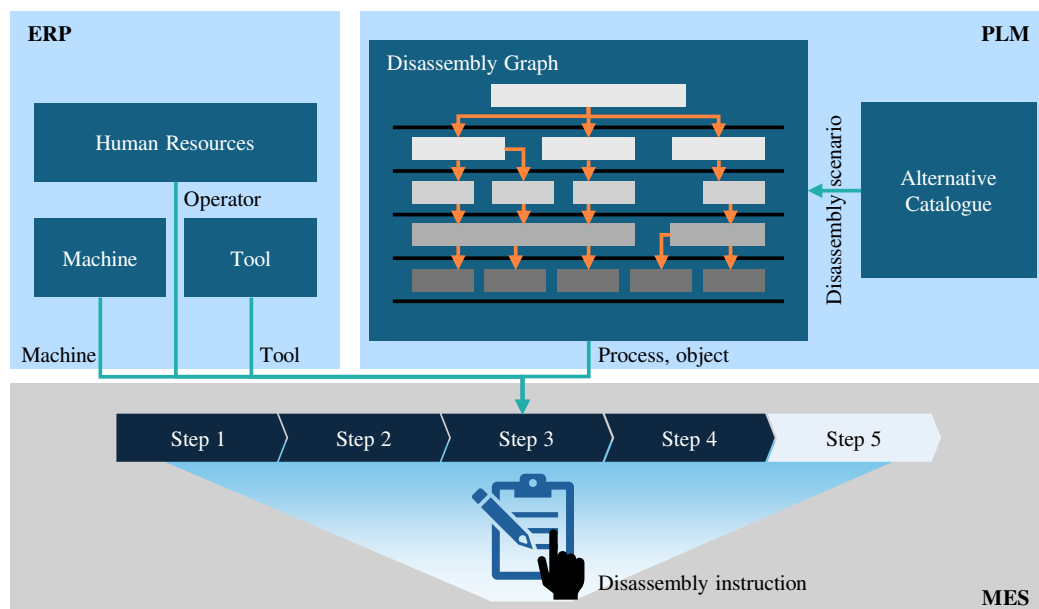


Figure 5-3 – Conception of the framework

5.2 Conception validation

The validation is conducted by a case study in the circular economy for washing machines, cooperating with a leading home appliance manufacturer in a public-funded

research project. In this case study, the manufacturer develops business strategies towards the circular economy to make their products more sustainable. Therefore, based on their products' usage conditions, corresponding scenarios are generated, partially illustrated in Figure 5-1. The disassembly graph for the respective washing machines is also generated, as demonstrated in Figure 5-2.

The first validation is oriented toward the scenario “repair.” In this scenario, the operator needs to reach Module I and repair its optical damage. After that, the washing machine can be reassembled and prepared for reentering the retails. According to the disassembly graph, Module I is located on the second level of disassembly depth. Therefore, to reach Module I, Part 1-E and 1-F need to be removed. In this context, the pathway can be generated as shown in Figure 5-4. Hence, the process steps can be established in sequential order as follows:

1. Preparation of necessary resources
2. Disassemble Part 1-E and 1-F using the assigned tools
3. Repair optical damage on Module I
4. Reassemble Part 1-E and 1-F using the assigned tools
5. Completion and documentation

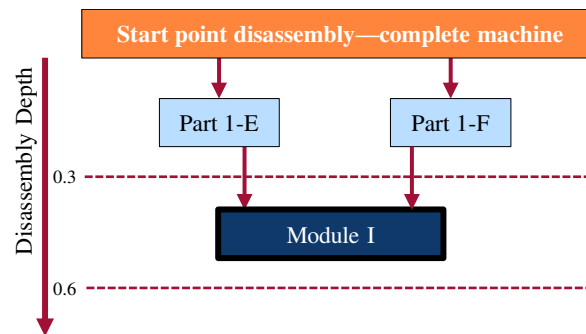


Figure 5-4 – Pathway for scenario “repair”

The scenario “refurbishment” is applied in the second case study. In this scenario, Module III needs to be replaced with a new one. According to the disassembly graph, Module III is located at a deeper disassembly depth compared to Module I. To reach Module III, it is necessary to remove Part 1-E and 1-F to reach Part 2-C and Module I, which need to be removed in the upcoming step to reach Part 3-B. In the end, by removing Part 3-B, Module III is reached. Based on the pathway illustrated in Figure 5-5, the process steps can be generated in sequential order:

1. Preparation of necessary resources
2. Disassemble Part 1-E and 1-F using the assigned tools
3. Disassemble Part 2-C and Module I using the assigned tools
4. Disassemble Part 3-B using the assigned tools
5. Replace Module III
6. Reassemble Part 3-B using the assigned tools
7. Reassemble...
8. Completion and documentation

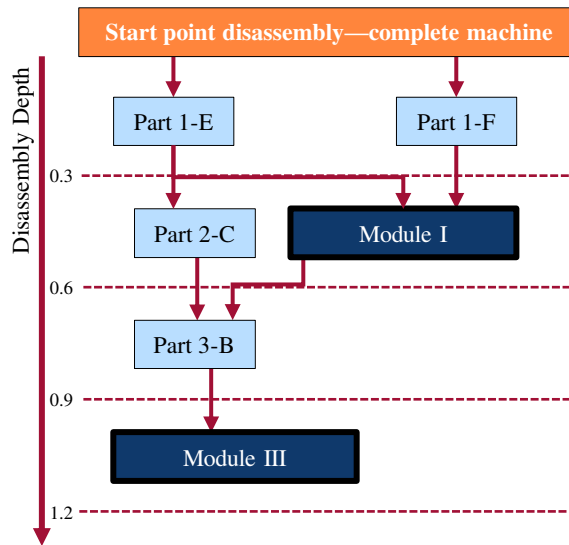


Figure 5-5 – Pathway for scenario “refurbishment”

The generated pathway is the foundation for instantiation, drawing upon the data model to derive corresponding work instructions. Figure 5-6 illustrates the data model for process step 2. In this step, Part 1-E and Part 1-F must be disassembled, necessitating the extraction of their information from the category object. This information encompasses part specifications, dimensions, and associated fasteners. For each process step, a corresponding data model is generated, and by aggregating these data models, an overall data model can be constructed, indicating the derivation of the work instructions to execute the selected scenario.

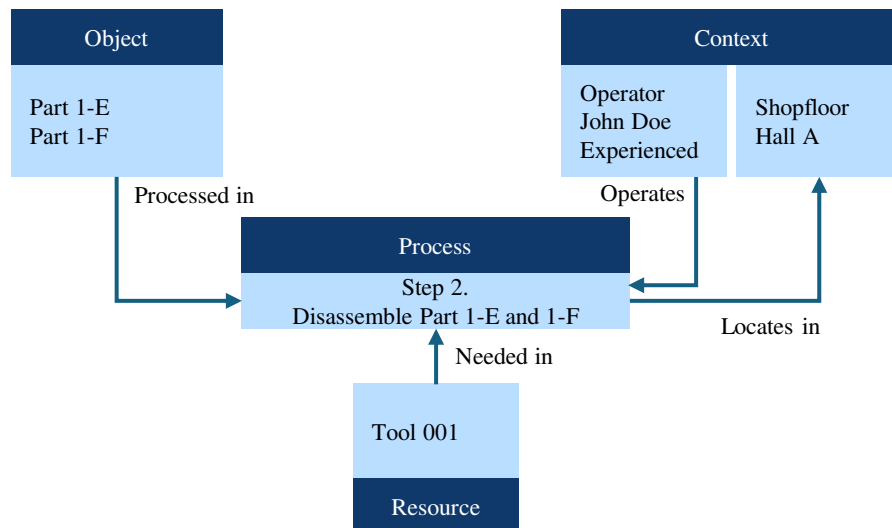


Figure 5-6 – Instantiated data model of process step 2 in the scenario “refurbishment”

The contextual information can be determined after the overall data model is generated. The next step is to retrieve all contextual information from its respective data sources. For instance, personal attributes such as the required certification for execution can be assigned to various scenarios and subsequently compared to the operator’s credentials stored in the ERP. Furthermore, object information, including part and module specifications, can be obtained from the PLM. Additionally, the necessary tools to execute each corresponding process step can be extracted from the tool management system within the ERP. Ultimately, all the retrieved information is linked to the respective process step and transmitted to the

MES. In MES, operators are furnished with context-specific disassembly instructions, facilitating informed decision support during their disassembly activities in the circular economy context. A computerized solution with data extraction pipelines and interface design still needs to be developed and validated in the future.

5.3 Discussion

As discussed in previous sections, the proposed framework addresses the challenge of applying R-strategies within the circular economy in a dynamic environment. This framework includes an alternative catalogue that offers predefined scenarios based on the manufacturer's business strategy, thereby reducing the decision-making burden on workers executing the disassembly process. The alternative catalogue also allows for new scenarios when product variants change. The relevant parts and modules provide a structural foundation, enabling workers to have an overview of the anticipated disassembly process.

Context-specific work instructions are delivered according to the location of relevant parts and modules in the disassembly graph, which is a critical interface between production planning and the shop floor. Cognitive worker assistance can be realized in this context, as workers receive tailored information based on their assigned tasks, such as conducting repairs or refurbishments.

Furthermore, applying the data model for work instructions introduced in Chapter 4 facilitates variable information provision during worker assistance. During validation, a washing machine manufacturer noted that experienced factory workers do not need detailed contextual information like tool information, as they are well-trained and can select tools proactively. Providing all contextual information in the data model increases their cognitive workload due to its high granularity. This practical perspective suggests simplifying the association between data classes in the data model based on the worker's experience. For example, when a worker is "experienced", the association between "resource" and "process" can be neglected, while if the worker is "amateur," it needs to be maintained. This reveals a variable worker assistance approach. Further consideration was expressed regarding the implementation of information systems. For small- and medium-sized companies, applying information systems proposed in the framework, such as PLM, can be cost- and resource-intensive, which brings additional economic burden. Therefore, a systematic solution is necessary for practical application in industrial environments that involves an applied information system based on the actual situation.

6. Conclusion and outlook

This work proposes a comprehensive framework for a worker assistance system designed to facilitate circular economy processes. The framework aims to provide informed decision support for workers and stakeholders involved in disassembly scenarios by applying various R-strategies. The implementation of this framework seeks to deliver comprehensive worker assistance through context-specific information presented in a digital format. This digital approach enables interconnectivity with diverse data sources within a manufacturing system, ensuring the data is collected according to the selected R-strategy.

Furthermore, the digital work instructions generated from this framework allow for dynamic information provision. Context-specific information within these work instructions is retrieved based on different scenarios, eliminating the need to rewrite and update the entire document each time, as traditional paper-based instructions require. The information presented to workers will be limited to relevant details about the specific process, reducing their cognitive workload and facilitating seamless integration with digital devices during manufacturing for fully digitalized worker assistance.

The next step in developing this framework involves practical implementation in an industrial environment. This necessitates the computerized modeling of the framework and connectivity to the relevant databases. The framework identifies ERP, MES, and PLM as potential sources of information from which all necessary data can be obtained. Interfaces or APIs for data extraction from these systems to the predefined data model are crucial for further development. Moreover, because data sources may vary depending on the specific circumstances in an industrial setting, standardized data formats and interfaces are essential to ensure the applicability and transferability of the proposed framework. Achieving prototypical implementation is both feasible and desirable in the next stage of this research.

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