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Digital product passport enabled production control in the context of circular economy

Yannik Hermann*,[a], Christian Patlakis[a], Moritz Hörger[a], Marvin Carl May[a], Gisela Lanza[a]

[a]*wbk Institute of Production Science, Karlsruhe Institute of Technology (KIT), Kaiserstr. 12, 76131 Karlsruhe, Germany*

* Corresponding author. Tel.: +49 1523 9502593. *E-mail address:* yannik.hermann@kit.edu

Abstract

Digital Product Passports (DPP) are seen as a key technology to overcome the lack of transparency of products in context of circular economy and allow a simplified derivation of quality conditions. In this paper, a production control model is presented, that generates remanufacturing, recycle and reuse strategies within a linear production system based on information from the DPP. The quality condition, derived from the DPP, and the system utilization serve as the basis for the reinforcement learning (RL) model, which optimally integrates used parts into the linear production flow. In addition to optimizing throughput, the aim of the model is also to save material and energy, which can be achieved by reusing or remanufacturing used products. The integration of used products into the linear production was tested using a production system from the water meter industry. It was shown by simulation that with the developed RL model the material consumption of the production of water meters could be significantly reduced by finding optimal circular strategies.

Keywords: Circular Economy; Digital Product Passport; Production Control; Reinforcement Learning

1. Introduction

Increasing market demands for cost, quality and sustainability are shaping the production environment of companies [1]. Sustainability has gained importance due to resource shortage and population growth [2]. Companies need to design production systems that are efficient and sustainable. Traditional linear production systems, which follow the "take, make, dispose" principle, are unsustainable and resource-intensive [3]. Therefore, transforming production processes to enhance sustainability and efficiency is essential. The circular economy, characterized by closed material loops, presents a promising solution to minimize resource consumption, waste generation, and environmental impact [4]. Compared to linear systems, circular production can reduce resource use by up to 90% and cut material and energy costs by up to 30% [5], offering both ecological benefits and increased competitiveness. However, transitioning to a circular economy poses challenges such as complex supply chains, lack of transparency and uncertain product quality [6].

The DPP addresses these challenges by providing lifecycle product information and enhancing transparency. This simplifies quality assessment of used products, supporting sustainable and efficient production processes.

This paper presents a concept that uses the DPP as the basis for RL-based production control. This concept is simulative validated using a production system from the water meter industry. Here, it is possible to both assemble and reassemble the batteries and brass housings of water meters at the same stations. The focus is on the comparison between a purely linear production and a combined production consisting of linear and remanufacturing processes. It was shown that intelligent control of the used water meters does not have to result in a loss of throughput and WIP and that a significant amount of material can be saved at the same time.

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2. State of the art

2.1. Data spaces

Data spaces are platforms that enable data exchange between companies [7]. They are defined as federated, open infrastructures for sovereign data exchange, based on common agreements, rules, and standards [8]. Data spaces exist at various maturity levels, covering both industry-specific and cross-industry applications. These data spaces, each serving different purposes and at different stages of development, are tracked and represented in the Data Space Radar [9]. Initiatives like International Data Spaces Association (IDSA) and Gaia-X drive their development. IDSA provides a standardized architecture for secure data exchange, known as IDS RAM, while Gaia-X creates a trusted digital ecosystem for data and service availability [7].

2.2. Digital product passport

The DPP is essential for a climate-friendly and resource-efficient economy as part of the European Green Deal and Circular Economy Act [10]. The DPP supports the digitalization of product lifecycles and has significant potential for implementing and scaling the circular economy [11]. It is defined as a dataset containing information about a product's origin, composition and repair and disassembly possibilities. It also includes handling instructions for the end of the product's lifecycle, detailing how components can be recycled or disposed of environmentally [10]. The DPP can be accessed electronically, facilitating the capture, processing, and sharing of product information among actors in the supply chain. Technically, the DPP can be implemented using the Asset Administration Shell, which acts as a digital twin for products, enabling data capture and storage throughout the product lifecycle and providing targeted access to authorized groups [12].

2.3. Production control in remanufacturing

A RL approach for order control in hybrid disassembly systems was developed by [13]. This approach assigns products to either manual or autonomous stations based on their condition, optimizing resource usage and reducing emissions by leveraging the strengths of both station types. An approach on material flow control in flow shop systems using RL is presented by [14]. The agent determines the optimal timing for releasing parts for reprocessing, which effectively reduces work in progress and enhances throughput by dynamically adapting to changing conditions. A two-agent system in which a maintenance agent and a production agent work together to manage a circular production system is introduced by [15]. The maintenance agent plans and executes frequent maintenance activities to minimize downtime, while the production agent ensures efficient production, thereby maximizing overall profitability. A DQN algorithm to tackle the job shop scheduling problem in reprocessing systems is presented by [16]. Their approach aims to minimize total production time by developing an efficient scheduling strategy that adapts to the variable quality of input materials and differing production requirements. RL to the disassembly line balancing problem is applied by [17]. They use a Q-learning algorithm to assign tasks to various stations with the goal of minimizing carbon emissions and maximizing productivity, considering the distribution of tasks and the current emission levels.

3. Methodology

End-of-Life (EOL) products are prone to a high degree of uncertainty in terms of product quantity and quality. The uncertainty regarding product quality results in very complex and expensive diagnostic processes to determine the quality status of products. In combination with a lack of knowledge about the number of EOL products, these two factors present the industry with major challenges when dealing with EOL products. To increase the knowledge about quality and quantity, the product passport can be used as a promising tool.

The following section presents a methodology that firstly addresses data exchange via the DPP from a content-related and technical perspective. It is then shown how the data from remanufacturing companies can be used for the scheduling of EOL products in form of RL agent, while considering the linear production. The aim of the RL model is first to derive a suitable circular economy strategy based on the product quality status and then to determine the optimum time for scheduling the EOL product. The optimization objectives of the RL agent are of an economic nature, in that it weighs up the material savings from the circular strategy against the increased process times of the EOL products and thus lower throughput. On this basis, a decision is then made as to whether an EOL product or a new product is put into production.

3.1. Realization of the DPP ecosystem

The DPP is seen as part of a digital ecosystem that connects the various players who have relevant information for remanufacturing purposes as visualized in Figure 1.

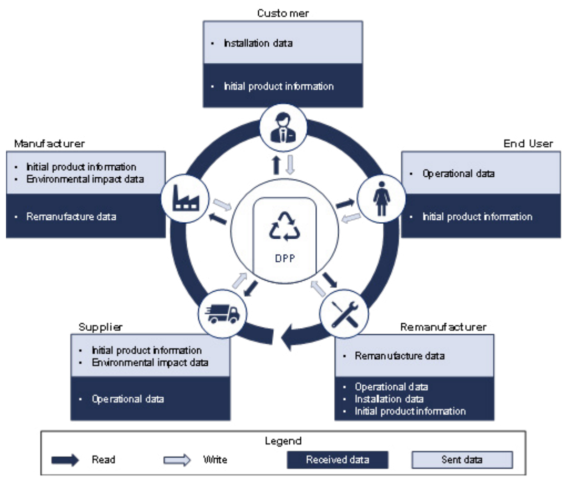

Figure 1: Actors and data streams along the product life cycle contributing to DPPs

By providing cross-company and cross-sector information along the life cycle, interaction between the various players in the digital ecosystem is facilitated. Core concepts for Industry 4.0 and data spaces offer great potential in the realization of the DPP system [10].

The actors along the product life cycle can be divided into supplier, manufacturer, customer, end user and remanufacturer, whereby a company can represent several actors at the same time. Each actor provides specific data about the respective product on the one hand and receives relevant data from the product passport from other actors on the other. Figure 1 lists the data that is relevant for the production control of EOL products. On the other hand, environmental impact data can be used to track the PCF of the product throughout its life cycle.

The primary aim of the data is to provide the remanufacturer with information about the quality status, the work steps to be carried out and the materials included in product. The assignment of the data to the respective information elements is shown in Table 1.

Table 1. Relevant data from DPP for production control of EOL products

Meta data	Data	Information for EOL production control at Remanufacturer
initial product information	product name, model number, product ID, technical data, bill of material, assembly plan	material, work plan for remanufacturing
environmental impact data	carbon footprint, energy intensity in production	not directly necessary for production control
remanufacture data	disassembly plan, life cycle count,	data sent by remanufacturer
installation data	special incidents during installation	quality of product
operational data	data while product in operation	quality of product

It should be noted here that the list in Table 1 is not to be seen as a complete list of data for the DPP, but contains the data for production control presented in the sections 3.2 and 4.2. It is also assumed that information for the disassembly plan can be derived from the combination of the bill of materials and the routing from linear production. In addition, the installation data can, for example, be error messages from a B2B customer who is installing the product. The operating data can also be linked to the DPP manually or automatically with suitable sensors. Which data is explicitly relevant for remanufacturing varies from product to product and must be clarified individually between the players.

Figure 2 visualizes how this cross-company data exchange with the DPP can look technically. The focus here is particularly on the property of interoperability. To ensure this, technically standardized and secure access to the product passport should be possible. The basis for this is the EU's sovereign data space Gaia-X [18]. The product passport can be stored in the cloud environment in a standardized manner in the form of administration shells. The asset administration shell is a universally valid, standardized representation of data. The standardization of the data format is a critical success factor, as this is the only way to ensure interoperable access to the DPP data. So-called Eclipse Data Space connectors are used to enable companies to exchange data in a sovereign manner [19]. These enable the transfer of meta and contract data and thus form the link between the DPP and the actors. As an example of interfaces for retrieving administration shells via the Eclipse Data Space connectors after a contract has been concluded, endpoints can be implemented via Restful API that reference individual DPPs using their IDs. An example of such an endpoint for a DPP with the ID 0, which is located on a cloud instance with the IP address 0.0.0.1, would be: *https://0.0.0.1/product/0*. The endpoint is therefore made up of the IP address of the respective cloud instance, the path */product/* and the ID of the administration shell of the DPP being searched for. The endpoints are implemented using the aas2openapi package [20].

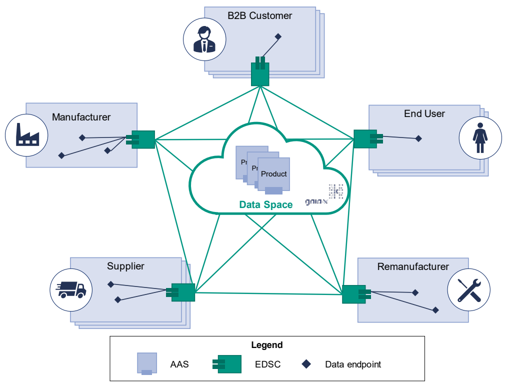

Figure 2: Digital ecosystem and central components which allow data transfers between the different actors

3.2. Scheduling of used products in linear production system using reinforcement learning

The RL agent presented in the following sections represents a solution for the efficient integration of water meters into a linear production system that has hybrid stations. Hybrid stations are those that can carry out both processing steps for used products and processing steps for new products. A decision must therefore be made at these stations as to whether a used product is to be remanufactured and reconditioned or a new product manufactured. The goal of the agent is to decide when it makes sense to remanufacture a used product, primarily from an economic point of view. The conflicting objective here is that the process times for used products are longer than for new production due to more complex work processes and quality fluctuations and therefore lead to a lower throughput. However, a considerable amount of raw material can be saved, which leads to a reduction in costs. In addition to throughput and material consumption, the target variables that the agent uses for optimization are the work in progress (WIP) and the demand for used and new products.

First, it is given a status that contains the current system load and the data from the product pass for which a decision is to be made on whether to feed it into the system. The agent in the form of a neural network then decides within the framework of the action whether the used product should be sent for reprocessing and, if so, which work steps are necessary for this. The selected action is carried out in the simulation and the reward is calculated based on the defined target values. This is passed to the agent and the neural network is adapted accordingly. The data that the agent needs for control is either taken from the product pass or relates to the current system utilization in production. This eliminates the need for time-consuming quality assessment operations. It should also be mentioned that the agent can be applied to companies that perform the tasks of both a manufacturer and a remanufacturer. This means that a product is sent back to the original manufacturing company at the end of its life cycle. New production and remanufacturing then takes place in the same production environment.

3.2.1. State space

The state space in this approach comprises the quality condition of the product, utilization of buffer storages, operational status of workstations and demand for new and used products. The quality condition of the product is derived from DPP and determines its processing path and times. This quality condition can be categorized into quality classes. The utilization of buffer storages is measured as the percentage of total capacity used in all intermediate and buffer storages, both for linear production and remanufacturing. The operational status of workstations indicates whether each workstation is “working” or “idle” affecting the system's processing capabilities. The demand for new and used products reflects current market needs.

3.2.2. Action space

The action space of the agent is based on the possible circular strategies within a production system. In this approach, these strategies include remanufacture, reuse, and recycle. In each time interval, the agent decides whether to release a product in the production system or not. This means the agent makes decisions about waiting, remanufacture, reuse, and recycle. The appropriate circular strategy and the corresponding path in the production system are determined based on the quality condition of the product derived from DPP.

3.2.3. Reward function

The reward function aims to incentivize or penalize the agent based on defined objectives for its chosen actions. The total reward R_{total} is defined as follows:

$$R_{total} = R_{TP} + R_{WIP} + R_{Material} - M * E$$

The throughput reward R_{TP} rewards the agent for the throughput in both linear and circular production, weighted by their respective demands. In this formula, d_l describes the demand for new products and d_{ce} for used products. The throughput of new products within the linear production system is formulated as tp_l, while the throughput of remanufactured products is written as tp_{ce}. The weighting factors w_1, w_2 and w_3 adjust the importance of each component.

$$R_{TP} = w_1 * \left(\left(\frac{d_l}{d_t} \right) * tp_l + \left(\frac{d_{ce}}{d_t} \right) * tp_{ce} \right)$$

The work-in-progress penalty R_{WIP} penalizes the agent for high levels of work-in-progress, encouraging the minimization of WIP, and is defined as:

$$R_{WIP} = w_2 * WIP$$

The material consumption penalty $R_{Material}$ penalizes the agent for high material consumption, with circular options remanufacture and reuse consuming less material than new production. This is represented by the formula:

$$R_{Material} = w_3 * material\ consumption$$

The penalty component $M * E$ ensures that products with insufficient quality are not inappropriately reused, with M being a high constant and E representing the error condition which is formulated as:

$$E = \begin{cases} 1, if\ reuse\ is\ used\ instead\ of\ recycling \\ 0, else \end{cases}$$

4. Case Study

4.1. Case description

The production system in Figure 3 is a linear process involving multiple operations, where a simple product moves sequentially through different production stages. Within each stage, there are multiple stations, and buffer storages are placed between these stages. Additionally, the system integrates circular strategies such as remanufacture, reuse and recycle.

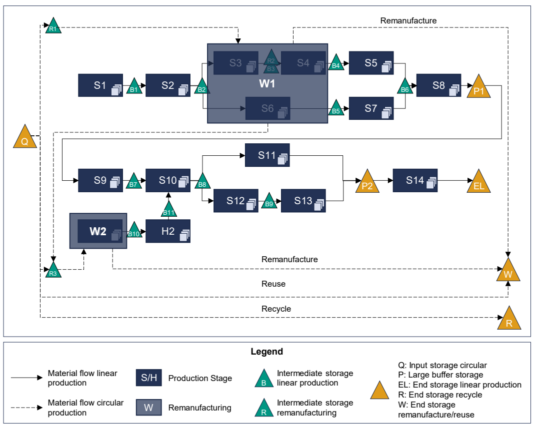

Figure 3: Exemplary production system including stages with remanufacturing and linear operation capabilities

Used products are returned to the manufacturer and placed into the input storage. The system includes two remanufacturing options: W1 and W2, with additional buffer storages for remanufacturing. Within these stations, linear processes as well as remanufacturing and reconditioning in the sense of reassembly can be carried out. The battery of used water meters can be replaced in W1 and the brass housings can be reconditioned in W2. As the water meters are very easy to dismantle, it is possible to have the remanufacturing carried out by employees from linear production with short process times. The system supports reuse by directly transferring parts from the input storage for used products to the end storage for remanufacture and reuse. For recycling, parts are directly routed from the input storage to the end storage designated for recycling.

A RL agent uses data from the DPP to control the production system. This agent makes decisions on routing the returned products through the appropriate stations and determining when production orders should be released, optimizing predefined target metrics from section 3.2.3. It should also be mentioned that the process times in the simulation for reprocessing were adjusted by corresponding factors of the quality condition. For very good quality states, the process time was slightly reduced compared to linear production and otherwise increased. This is due to the fact that the number of process steps for the reprocessing of used water meters in good condition is lower than in the linear process of new production. However, the exact process times cannot be specified due to confidentiality.

4.1.1. State Space

In the addressed case, the state space is made up of the order state, the system state and an external state.

The order state is defined by the quality status of the returned products. The quality status of a returned product determines the path in the circular system, the process times at the reprocessing stations and thus also influences the target values of throughput and WIP. This quality state can be modeled as a p-dimensional state vector q in the use case under consideration.

$$q = (q_1, q_2, q_3, q_4)^T$$

The $p = 4$ dimensions of this vector correspond to the meta data *Operational data* from table 1. For deriving the quality status of this exemplary product, the acceleration data (q_1), temperature data (q_2), humidity data (q_3) and battery voltage data (q_4) over the life cycle was tracked in the DPP and given to the remanufacturer.

Using this data, the battery condition and the condition of the brass housing can be expressed as a decimal number between 0 and 1 by a neural network, for example.

The system utilization is recorded for all intermediate storage stations for linear production (B1 to B11) and reprocessing (R1 to R3) as well as the buffer storage stations (P1 and P2) and can be expressed as a percentage of the total capacity. The operating status is recorded for all stations within the operations (S1 to S14 and H1 to H2). The operating status for each workstation can be defined as "in operation" or "inactive". It can also be marked as "defective" in the event of failures. The external status is recorded in the form of the requirements for new and reconditioned water meters, as they have a direct influence on the agent's reward. For example, the scheduling of orders for used products is rewarded more if the demand for them is greater than for new products.

The order status, the system status and the external status are determined at fixed time intervals and passed to the agent. A time interval of ten seconds is proposed for this approach. This decision is based on an assumed throughput of 2920 products per shift in the linear case, which means that on average one product leaves the system every ten seconds.

4.1.2. Action Space

The agent's action space is based on the possible paths in the circular production system visualized in Figure 4. In addition to control via the corresponding reprocessing stations, the agent also has the option of not submitting an order and waiting.

The action a_0 corresponds to waiting. This means that no order is submitted in this time interval. This may be the case if, for example, the system is busy or there is no demand for treated water meters. If the agent decides to submit an order, actions a_1 to a_5 are available for selection. Actions a_1 to a_3 relate to reprocessing. In contrast to the five reprocessing paths shown in Figure 4, there are only three actions for scheduling in the action space. This is due to the fact that the path is selected automatically in the production system, which means that the order is processed by the first available station. Analogous to Figure 4, actions a_4 and a_5 correspond to reuse and recycling.

The reward function is formed in the context of the analysed use case analogous to section 3.2.3 and is therefore not explained further.

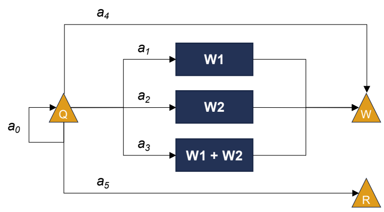

Figure 4: Action space of the implemented RL agent

4.1.3. Results

Table 2 shows the results of the implemented RL agent compared to an optimal throughput for linear production.

Table 2. Results of the production control compared to linear production only

	Me-thod	Throughput new products	Throughput used products	Total throughput
Linear	DoE	2920	0	2920
Linear + Circular	RL	2680	223	2903

The optimal throughput of linear production results from the best allocation of employees to the respective stations and was analysed using a Design of Experiments (DoE) with a Latin

Hypercube Design. For that, 9639 experiments were simulated. The results show that the used products were fed into the production system by the RL agent in such a way that the total throughput was only reduced by 17 water meters. The WIP was also maintained at a comparable level of around 350 water meters. As an average cost saving of 50 % can be assumed for the used water meters in terms of material, a successful cost reduction has been achieved through the RL-based production control of used water meters.

4.2. Limitations

The approach presented is linked to a number of conditions, which are listed below.

The digital product passport is essential and should be maintained in collaboration across company boundaries. From a technical perspective, the components must always be easy and quick to disassemble and reprocess. Employees who work at stations that are used for both remanufacturing processes and linear production processes must have the appropriate qualifications. From a hardware point of view, these stations must also be highly flexible so that they can carry out both linear processes and remanufacturing steps.

5. Discussion and outlook

In order to leverage the information of the DPP, the presented paper introduces a novel approach for controlling linear production systems in the presence of remanufactured components based on data stored in DPPs. Therefore, relevant information to be collected along the product life cycle are identified and categorized in terms of their applicability for an efficient remanufacturing process. Based on these information, remanufacturing components are to be reintroduced into linear production. Due to the resulting complexity, this paper proposes a novel of order scheduling based on RL optimizing throughput, work-in-progress and material consumption. The methodology has been successfully tested against the use case of the production system of a water meter manufacturer.

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