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# Simulation of a Cyber-Physical Lifecycle System Based on a Blockchain Platform

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**Abstract**

Product lifecycle management plays a crucial role in establishing resource circulation systems based on artifact stocks accumulated in society. However, given the involvement of diverse stakeholders, managing the complex circular systems of a product lifecycle requires advanced digital technologies. The concept of a cyber-physical lifecycle system (CPLS) is proposed in this paper. CPLS constructs the digital twin of a product lifecycle to be managed. The digital model in the cyberspace is used for analysis, simulation, and reconfiguration of the lifecycle based on real data acquired from the physical space of the CPLS. In this research, we introduce blockchain technology in the CPLS to aggregate information on target products and processes from each stakeholder involved in the lifecycle. To support decision-making in lifecycle management, a life cycle simulation (LCS) is conducted in the cyberspace of the CPLS based on the acquired data through blockchain. Subsequently, decisions are made based on the simulation results to increase the profit of each stakeholder and minimize the environmental loads of the entire lifecycle. In a case study focusing on the life cycle management of electric motors, we conducted a simulation-based analysis on the prototype of CPLS. A twin-experiment for the case showed the effectiveness of production management using the CPLS from economic and environmental perspectives.

*Keywords:* life cycle management, cyber-physical system, life cycle simulation, blockchain, circular production ;

## 1. Introduction

Economic and social activities based on mass production, mass consumption, and mass disposal lead to various environmental problems such as climate change, depletion of natural resources, and biodiversity loss. There is a need for a shift from such a one-way economy to a circular one in the manufacturing industry.

Circular production is a promising approach to maintaining the values of industrial products through their lifecycle through the effective utilization of resource stocks in society [1]. The ideal circular production system aims to circulate the resources of the products without distinguishing between new and remanufactured ones while minimizing resource input, consumption, and waste generation through services and other means.

Product lifecycle management plays a significant role in establishing a circular production system based on stocks such as end-of-life products. However, due to the involvement of various stakeholders in product lifecycle management, advanced digital technology is necessary for the management of complex circular systems.

In this study, we propose the concept of a Cyber-Physical Lifecycle System (CPLS). CPLS constructs the digital twin model of a product lifecycle to be managed. The digital model in the cyberspace is used for analysis, simulation, and reconfiguration of the lifecycle based on real data acquired from the physical space of the CPLS.

In this study, we introduce blockchain technology in the CPLS to aggregate information on target products and processes from each stakeholder involved in the lifecycle. To support decision-making in lifecycle management, a Life Cycle Simulation (LCS) is conducted in the cyberspace of the CPLS based on the acquired data through blockchain. Subsequently, decisions are made based on the simulation results to increase the profit of each stakeholder and minimize the environmental loads of the entire lifecycle.

## 2. Related works

A Cyber-Physical System (CPS) collects diverse data from the real world (physical space) using sensor networks, processes and analyzes the data using large-scale data processing techniques in cyberspace and converts it into knowledge. The information and value generated are utilized to revitalize industries and address societal problems [2]. In recent years, CPS has been positioned within the stage of industrial development known as

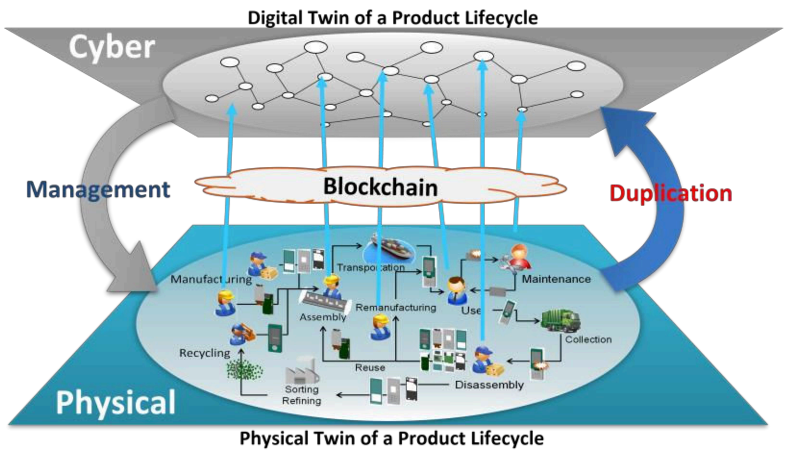


Fig.1. Concept of CPLS

Industrie 4.0. In this study, we aim to construct a CPS to collect data from the product lifecycle via blockchain technology, analyze the data using LCS, and make decisions for lifecycle management.

LCS is a simulation method for evaluating product lifecycles from economic and environmental perspectives by simulating a material flow in which a certain number of products and their components go through the processes of a life cycle for a certain period [3]. In this study, a digital twin of a product lifecycle is constructed as an LCS model in a CPLS. The LCS uses the data acquired from a product lifecycle in the real world through blockchain and the simulation results are used for managing the lifecycle.

Blockchain is a digital technology that connects data groups in block units, processes and records a series of transactions in a distributed manner within the same system. It achieves high availability and data integrity by using electronic signatures and hash pointers to easily detect tampering with data structures and by ensuring that the data is held by numerous nodes distributed across the network [4].

There has been an increasing number of cases where blockchain is utilized for data management not only in the financial sector but also as a platform for resource circulation. Liu et al. [5] proposed a platform leveraging blockchain technology, where multiple stakeholders can securely and openly store and exchange data for product lifecycle management in Industrie 4.0. Rolinck et al. [6] conceptualized an application system based on blockchain for efficiently conducting lifecycle assessments. Toneli et al. [7] demonstrated a practical example of a cyber-physical supply chain planning system applying CPS to supply chain management. Kumar et al. [8] proposed a cyber-physical production system applying CPS to production processes as a framework for conducting live lifecycle assessments. However, there are few studies working on circular management using CPS targeting the entire product lifecycle.

## 3. Proposed system

### *3.1. Overview of the proposed system*

The CPLS proposed in this study is a digital platform that reflects information acquired from a product lifecycle in the physical space into a lifecycle model in the cyberspace. It supports lifecycle management by conducting simulation and analysis using LCS in the cyberspace of the CPLS. The LCS model is a digital twin of the product lifecycle, which visualizes the holistic status of the lifecycle and provides the future prospects for optimal decisions in the management. The schematic picture of the CPLS is shown in Fig. 1.

The product lifecycle model consists of various processes such as resource procurement, part manufacturing, product assembly, transportation, sales, use, collection, reuse, and recycling. Therefore, it is difficult to obtain information on the products whose ownership is transferred to various stakeholders along with the processes and to grasp the status of the entire lifecycle. By using CPLS, information can be collected from each stakeholder via blockchain, enabling decision-making based on a wide view of the product lifecycle. In addition, since the cyberspace of CPLS is composed of simulation models, preliminary studies such as simulation, optimization, and redesign of the product lifecycle system can be conducted on the digital twin.

### *3.2. System configuration*

Each stakeholder, including material suppliers, manufacturers, and product users, registers data on the blockchain that records the individual status of the products and the transactions of the users. The LCS is executed using the data registered on the

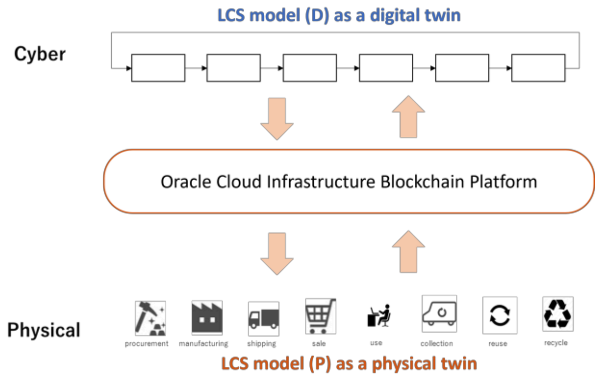


Fig. 2. Twin-experiment of a CPLS

blockchain as parameter values. Then, the manager of the product lifecycle makes decisions based on the simulation results.

### 3.3. System construction procedure

The following is a procedure for constructing the proposed system.

(1) First, an LCS model of a target product lifecycle is created. Then the status of the products and parts in the simulation is defined.

(2) A blockchain infrastructure is connected to the LCS model. The simulation model is adjusted to be a digital twin of the target product lifecycle by building a mechanism for collecting data from the real world using the blockchain.

(3) The simulation is executed under various scenarios. The scenarios are given according to the type of decision-making needed for the lifecycle management.

(4) Decisions are made based on the simulation results to control the flow of the resources in the product lifecycle.

## 4. Case study

### 4.1. Prototype of CPLS

We developed a prototype of CPLS for the experiment described below.

First, we created an LCS model of a product life cycle and defined products and components based on the products' information using AnyLogic [9]. In this case study, we replaced the physical space of CPLS with the LCS model instead of using the actual lifecycle in the real world. In other words, since both the cyberspace and physical space of CPLS are constructed with simulation models, two simulation models are created on the same platform, one for cyberspace and one for physical space to conduct a twin experiment [10]. The image of the prototype of CPLS is shown in Fig. 2.

We used the Oracle Cloud Infrastructure Blockchain Platform [11] to develop a system for collecting and matching information from the physical space. In this system, the information registered on the blockchain will be replicated in a

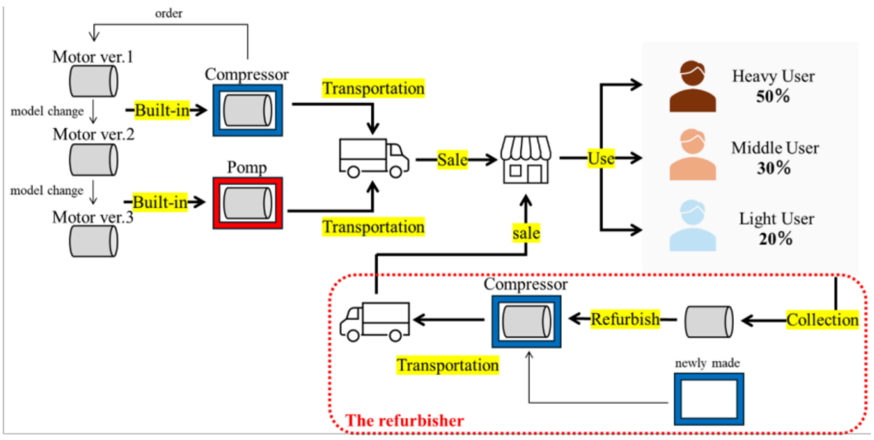


Fig. 3. LCS model of the motor lifecycle

cloud database. Using the database, required information about the product can be retrieved.

### *4.2. Target product*

The case study targeted medium-sized motors that are installed into industrial equipment such as compressors and vacuum pumps. Motors are highly versatile and incorporated with a variety of mechanical devices because they have a simple function and long lifetime. Therefore, we considered cascade reusing by installing motors taken from end-of-life products into other new products.

### *4.3. Experimental procedure*

First, we created an LCS model. A process flow model, simulating each process of the product lifecycle, was created and agents were defined based on individual product information. In addition, product information in the physical space is registered in the blockchain. Next, we prepared scenarios for the experiment. Finally, we used the search function to retrieve the information needed for simulation in cyberspace from the blockchain. Finally, the LCS was executed for the timeframe of 240 months starting from the beginning of 2023, as the digital twin of CPLS. The values of the evaluation indicators in each scenario for the experiment were calculated to demonstrate the effectiveness of lifecycle management using CPLS.

### *4.4. LCS model*

The LCS model of the motor lifecycle is shown in Fig. 3. Compressor and pump manufacturers order motors to be installed into their products from motor manufacturers according to each manufacturer's production plan. In addition, motor models are regularly changed to produce upgraded products. Each product will be transported by transporters to distributors nationwide, who will then sell the products to users. For the users of each product, there are three user groups with different intensities of use. The refurbisher collects 30% of the end-of-life products. Then, the motors are removed from the used products, and 80% of them are inspected to determine if they are good enough to be refurbished. The refurbisher manufactures only the main body of the compressor and incorporates the reused motor into the compressor. Compressors with reused motors are then traded again on the same market as new compressors.

### *4.5. Scenarios for the experiment*

The following scenarios were set up to compare lifecycle management using CPLS (A) and not using CPLS (B).

(1)-A The refurbisher uses CPLS to estimate the percentage of each user group and to predict the disposal quantity of used products.
(1)-B The refurbisher makes appropriate assumptions about the proportion of each user group and predicts the disposal quantity of end-of-life products.
(2)-A The refurbisher uses CPLS to search information registered on the blockchain and collect used products that meet the conditions.
(2)-B The refurbisher collects discarded used products indiscriminately in collection boxes located at various locations.
(3)-A The refurbisher searches the information registered on the blockchain using CPLS to estimate the residual value of the product. Then, based on the residual value, the product is refurbished with no upper limit on the number of times it can be reused.
(3)-B The refurbisher limits the number of times motors can be reused to one time.

The experiment was conducting using the blockchain platform of the CPLS prototype to register information about the motors on the blockchain and search for information about products that meet the criteria set by the refurbisher.

By using the system's API to execute smart contracts, we were able to record information such as the model type, specifications, start date of use, owners, and manufacturer of each motor. Based on this information, we confirmed that the refurbisher can search for motors suitable for reuse.

## 5. Discussions

The simulations in the cyberspace of the CPLS were executed for each scenario to calculate the total environmental impact, total profit of the refurbisher, and average reuse rate of the refurbished motors. The total environmental impact was calculated as the amount of carbon dioxide emissions generated throughout the product lifecycle.

Fig.4 shows the transition in the number of reused motors. There is no difference in the number of reuses between when CPLS is used and not used as shown in Fig. 4. Fig. 5 and 6 show the total environmental impact of the motor lifecycle and the total profit of the refurbisher, respectively. Fig. 7 shows the average reuse rate of the motors during the simulation period.

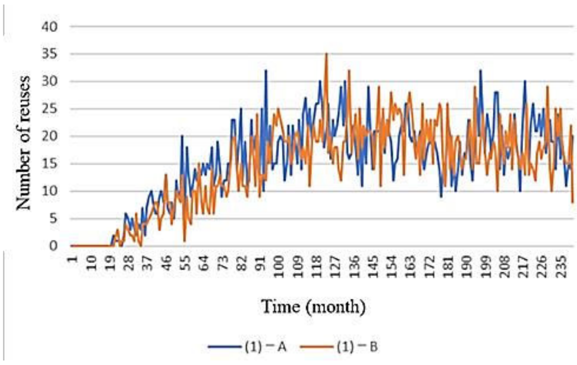


Fig. 4. Number of motor reuses in scenario (1)

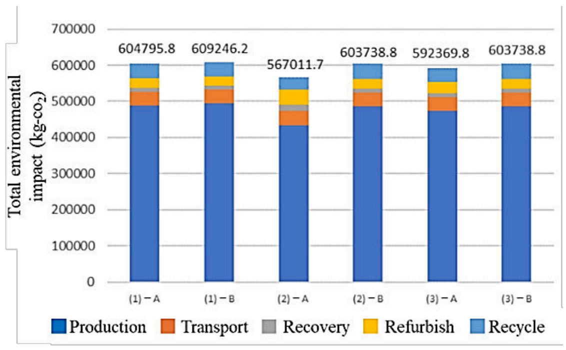


Fig. 5. Total environmental impact of the motor lifecycle

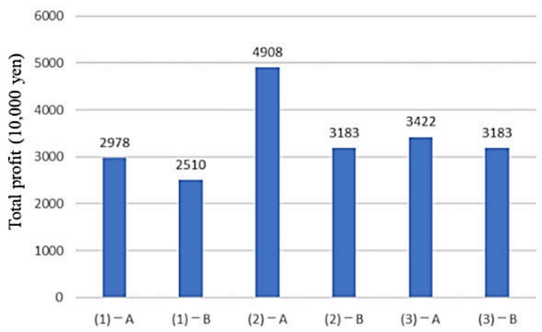


Fig. 6. Total profit of the refurbisher

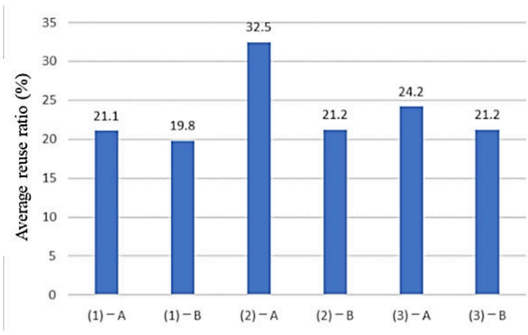


Fig. 7. Average reuse rate

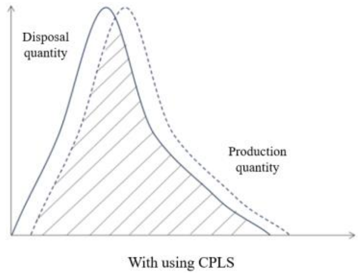


Fig. 8. Quantity of disposal and production with a CPLS

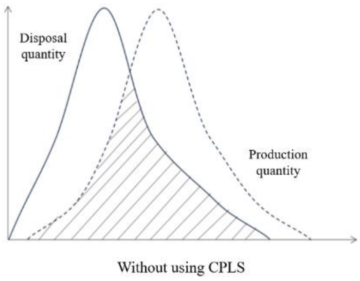


Fig. 9. Quantity of disposal and production without CPLS

For scenario (1), the total profit when using CPLS was increased compared to not using CPLS, even though the average reuse rate did not differ significantly. Fig. 8 and 9 show the quantity of end-of-life products disposed of and the quantity of the main bodies of compressors produced.

When the CPLS works, as shown in the Fig. 8, the graphs of disposal and production are almost the same shape, and many waste products can be directly reused (shaded area). As a result, the sales unit price will be higher, resulting in higher gross profit. On the other hand, when the CPLS is not used, as shown in Fig. 9, the waveforms of disposal quantity and production quantity differ slightly, and production quantity that can be directly reused from the disposed products is small. As a result, the sales unit price will be lower, resulting in smaller total profit.

However, since this study does not set a limit on the period during which disposed products can be reused, the surplus in disposal quantity in the first half can be covered by the surplus in production quantity in the second half. Therefore, there is not much difference in the average reuse rate.

For scenario (2), the use of CPLS exceeded the use of no CPLS in most of the evaluation indicators. Therefore, it is meaningful to use CPLS to obtain information on products from users and to strengthen the collection system.

For scenario (3), the number of reused products with CPLS exceeded that without CPLS from the middle to the latter half of the simulation period. This is because the quantity of products to be refurbished again increases and the quantity of products to be discarded decreases from the middle to the second half of the simulation period.

## 6. Conclusion

The concept of CPLS as a support system for lifecycle management is proposed. The system obtains information from a product lifecycle in the physical space, performs various verifications and analyses using LCS in the cyberspace and feed the results back into physical space. As an underlying technology for the CPLS, blockchain is introduced to collect information from various stakeholders in the product lifecycle and to use functions such as search, matching and traceback for system construction.

In the case study on the lifecycle management of industrial motors as the target products, we constructed an LCS model and conducted simulations based on various scenarios. A twin-experiment compared a production management of refurbished motors with CPLS and the management without the system based on economic and environmental indicators. The results showed that the "with CPLS" was superior in each of the evaluation indicators, indicating the effectiveness of the management using the CPLS.

Future work includes the construction of a CPLS that takes geographic and logistics information into account for a digital twin model combining discrete event and agent-based modeling. It is also necessary to execute LCSs that consider competitors in the product market, reproduce markets in the cyberspace of the CPLS, and simulate the occurrence of price competition.

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