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Data-assimilated lifecycle simulation for adaptive product lifecycle management

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ABSTRACT

This paper proposes a data-assimilated lifecycle simulation (DA-LCS) system. Data assimilation (DA) is a self-adjustment method for decreasing differences between a simulation and observation data from an actual-system by conforming the simulation model parameters to the observation at appropriate time intervals. The proposed system applies DA to LCS for adaptive operations in product lifecycle management. A case study of the lifecycle of a photovoltaic panel reuse business shows that DA-LCS successfully merges measurement data acquired from actual business operations into the LCS model, and sequentially revises the simulation estimations through DA.

1. Introduction

Sustainable development requires constructing sustainable product lifecycle systems that minimise resource consumption and environmental load while providing sufficient functionality to society [1]. To that end, designing an entire lifecycle as a network of various processes—such as manufacturing, logistics, use, maintenance, and recycling—is an effective approach. Lifecycle design is a process of planning and modelling the lifecycle beyond the product, and evaluating and optimising it from a holistic viewpoint [2]. This design stage clarifies specifications and requirements for the next stage, namely, implementation and management of the lifecycle (Fig. 1).

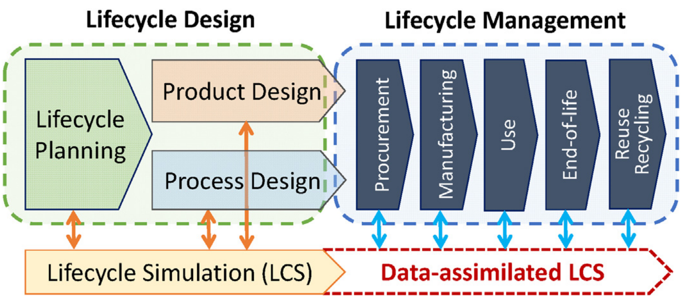

Fig. 1. Product lifecycle design and management framework.

Lifecycle simulation (LCS) is a promising method among technologies for lifecycle evaluation [3], as it can simulate the dynamic flow of materials and money in the lifecycle model based on discrete event simulation techniques, and it evaluates the total performance from environmental and economic aspects. In the left part of Fig. 1, the bidirectional arrows between the lifecycle design and simulation represent data feeding from design information and evaluation feedback by LCS. Although many studies have addressed LCS and its applications [4–6], they generally focus on support for the lifecycle design stage, not for decision-making at the management stage.

Because lifecycle models are constructed at the earlier design stage based on many assumptions made from the lifecycle information of previous product generations, differences between the simulations and actual conditions after implementation increase over time. For example, the external environment may deviate from the assumptions, if there are changes in the market, technology, or regulations. Furthermore, because the timing of malfunction and disposal of individual products is affected by the intensity of use, installation environment, and differences among users, it is difficult to estimate at the design stage the condition of end-of-life products collected for reuse. LCS should incorporate such changes of situation into the lifecycle model to support forecasting at the lifecycle management stage. To this end, this study attempts to apply the concept of data assimilation (DA) [7] to LCS to incorporate up-to-date information into the simulation.

DA is a self-adjustment method for decreasing differences between simulations and observation data from actual systems by modifying model status parameters at appropriate time intervals. DA has mainly been applied to numerical simulations in the geosciences, such as weather forecasting and tidal current predictions. In meteorological simulations for example, fixed-point field observations such as

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temperature, atmospheric pressure, and humidity are used to modify the simulation's initial parameters, status parameters, and boundary conditions to improve consistency with actual data, thereby increasing forecasting accuracy.

Although DA has been implemented in continuous simulations of various physical phenomena, no applications to discrete systems including product lifecycles have been established, owing to considerable differences in model formulation. This paper proposes a data-assimilated lifecycle simulation (DA-LCS) system implementing novel mechanisms to integrate DA into LCS. DA-LCS reuses a lifecycle model created at the design stage, and modifies the model status by importing the latest information from the actual lifecycle system at the management stage. In the right part of Fig. 1, the bidirectional arrows between DA-LCS and each process in the lifecycle management block represent data supply from process observations and decision supports by DA-LCS. This relationship forms a cyber-physical system which integrates sensor data from an actual product lifecycle with its simulation.

The rest of this paper is organised as follows: Section 2 defines DA-LCS and outlines a prototype simulation system. Section 3 presents a case study of the lifecycle of a photovoltaic panel reuse business. After discussion of the case study in Section 4, Section 5 concludes the paper.

2. Data-assimilated lifecycle simulation

2.1. Product lifecycle model for LCS

This section briefly describes LCS applied in this study and the simulation model. An LCS model is a network of processes in a product lifecycle, in which network links represent entity pathways between processes. The behaviour of each process is described in the process node, which holds a set of operational functions for the process. Based on the functions, LCS simulates the dynamic behaviour of each process at each time step. Entities are delivered from process to process in the network model. An entity represents an individual artefact including a product, its subassembly, and constituent materials. Interactions between probabilistic functions (e.g. failure rate distribution functions) described in a process and the attributes of individual entities (e.g. duration of the artefact) change the state and destination of the entities in the lifecycle model at each time step of the simulation.The number of occurrences in each process is multiplied by the unit material consumption, energy usage, and money flow. Finally, LCS predicts the performance of the product lifecycle from environmental and economic aspects, such as resource and energy consumption, environmental load, and lifecycle cost and stakeholder profit.

2.2. DA mechanisms for LCS

DA methods proposed in the past decades are generally classified into two types, data analysis and data replacement [8]. The data analysis is an adjustment process of differential equations in a simulation model. In most cases, the equations are adjusted by regression curve fitting through statistical analysis of observation data. The data replacement is a distinctive process of DA, in which model status parameters are replaced with observation data and the simulation is restarted from the renewed status.

To incorporate both DA processes, DA-LCS implements two mechanisms of 'behavioural analysis' and 'redistribution' for discrete system simulations. The behavioural analysis is a means of conforming process behaviours to observations by modifying functions described in the process nodes in a product lifecycle model. Examples include modifying a failure-rate function described in a use process through curvilinear regression of the function curve toward the actual failure distribution during an assimilation period. In this study, the period is defined as a time span over which observation data are analysed, and an 'observation' is a datum acquired from an actual lifecycle, such as the monthly number of disposed products. This analytical mechanism uses traditional techniques for data analysis—including regression analysis, discriminant analysis, machine learning, and curve fitting—and changes the coefficients of behavioural functions to fit the process behaviour to the actual lifecycle. In the example of the failure-rate function, the average value and standard deviation of the probabilistic function are changed to fit the function to the failure distribution histogram. A limitation of the proposed method is that the DA mechanism neither changes base principles nor replaces functions themselves, and thus the results of DA-LCS do not perfectly match actual data.

The redistribution is a complementary mechanism which changes the amount of entities in each process to incorporate observed amounts into the model status. This is a major extension from conventional DA in the application to LCS. In the conventional case of weather forecasting, the model status is represented as a set of continuous variables in differential equations. In discrete systems including LCS, the distribution of entities among processes represent the entire model status. For instance, the number of products and components located in each process at a particular time step determines the lifecycle model status in LCS. The delivery of entities from process to process forms a flow of materials. The redistribution mechanism reduces differences between LCS and observations regarding the entity flow.

In many cases, the number of observations from an actual system available for analysis is smaller than the number of parameters required to specify the overall model status. The distribution of entities among all processes in a lifecycle model therefore cannot be determined from available observation data alone. To complement the entire model status, we introduce a propagation algorithm in the redistribution mechanism, which changes the distribution of entities based on observed processes. DA-LCS transfers entities between processes in a lifecycle model to make them consistent with the observed process during an assimilation period in the simulation. In other words, the mechanism resolves contradictions among observations and the model status. Fig. 2 shows an example of redistribution by DA-LCS. In this case, observation from the process P_0 is used to modify the number of entities in other processes. The network links are used to transfer the entities.

The total mass of entities in a lifecycle model should be preserved during DA. Basically, the difference between the amount of entities entering a lifecycle model (e.g. total production volume) and those leaving it (e.g. materials sent to a thermal recovery process) is the total mass preserved. The amount $\Delta M_i(t)$ of entities redistributed to a process i (=0, 1, 2, ... N) at time t is determined as

$$\Delta M_i(t) = \zeta(i)\Delta M_0(t), \tag{1}$$

where $\Delta M_0(t)$ is the difference in the number of entities in an observed process P_0 between the simulation and observation at t. DA-LCS delivers the entities to process P_i from connected processes at each time step during the assimilation period. The counter i represents the distance (number of processes) from P_0

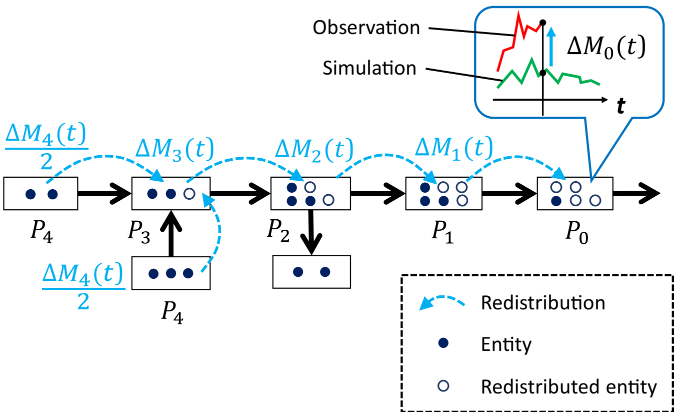

Fig. 2. Assimilation of observation data into lifecycle model status.