

7.4 Part agent that proposes maintenance actions for a part considering its life cycle

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Abstract

The transition from a consumption-oriented society to a reuse-based society is needed for the effective use of resources and environmental protection. However, it is difficult for a user to make appropriate decisions for maintenance of his/her parts because of the wide range of choices of action and the huge amount of information required. To support the user's decision and to promote the reuse of parts, we have developed a part agent system that manages information about individual parts throughout their life cycle. A part agent is a network agent that contains the information of its corresponding part and follows the movement of the part via the network throughout its life cycle. This paper describes a new mechanism of a part agent that proposes appropriate maintenance actions for the corresponding part by estimating its expected value, cost, and environmental load based on the predicted information about its life cycle.

Keywords:

Part agent; Life Cycle of Parts; Reuse; Life Cycle Simulation; Proposal of Maintenance Actions

1 INTRODUCTION

The effective reuse of mechanical parts is important for the development of a sustainable society [1]. To realize effective part reuse, it is essential to manage individual parts over their entire life cycle because each individual part has a different reuse history.

For reuse-based production, manufacturers need to capture the quantity and quality of the parts returned for reuse. However, with the exception of leased products such as photocopiers [2], most products, once sold, are not under the manufacturer's control, which makes it difficult for manufacturers to predict the quantity and quality of returned parts. They may be reused in markets that are beyond the manufacturer's control. The uncontrollable and unpredictable diversity of user behavior hinders the management of parts by manufacturers.

On the other hand, it is difficult for product users to manage and carry out appropriate maintenance of the large number and variety of parts in the manufactured products they own. The difficulty in managing all these parts—not to mention the inaccessibility of appropriate maintenance information—impedes management by users, in spite of the fact that more environmentally friendly actions are required from users if they are to reuse parts effectively.

On the basis of these considerations, we propose a scheme whereby a part 'manages' itself and supports user maintenance activities. For this purpose, we propose a management system that includes network agents and radio-frequency identification (RFID) tags [3] [4]. A network agent is assigned to an individual part of a product to which an RFID tag is attached. It is programmed to follow its real-life counterpart throughout its life cycle. We refer to this network agent as a 'part agent' [5].

The part agent provides users with appropriate advice on the reuse of parts and promotes the circulation of reused parts. Using this mechanism, consumers can also be advised about

environmentally friendly ways of product use and predicted product failures.

Researchers have proposed methods to design the life cycle of products where designers select appropriate life cycle options for a product by evaluating various values throughout its life cycle [6]. The importance of the life cycle scenario and aspects of product-service systems have been recognized [7]. The evaluation of life cycle options can be made using life cycle simulations [8], most of which are based on the calculation of product flow among life cycle stages. An agent-based approach is employed when the life cycle simulation concerns an individual part [9].

However, the life cycle expected in the design phase may not be achieved, particularly in the case of parts or products with a long life cycle. Changes in economic circumstances, the development of new products and technologies, and other factors may undermine the life cycle options chosen in the design phase. We consider that robustness and an adaptive nature is important in life cycle design and execution. We believe that the part agent of our proposal can be used for this purpose.

In this paper, we propose a system for a part agent to generate advice in order to support the reuse of parts based on life cycle information. To select a life cycle path appropriate for the situation, the part agent compares possible paths by estimating their values and considering predicted behavior within the near future. This system will be applied to various estimations of the life cycle for which the part agent generates advice for the user.

The concept of the part agent system is described in Section 2. In Section 3, the proposed framework for the part agent to generate advice based on life cycle information is described. Implementation of the part agent is described in Section 4. Details and results of the life cycle simulation using the part agent are described in Section 5. Discussions and remaining

issues are presented in Section 6, and the paper is summarized in Section 7.

2 CONCEPTUAL SCHEME OF THE PART AGENT

The proposed part agent system is based on the following usage scenario. The system uses the part agent to manage all information about an individual part throughout its life cycle. The proposal assumes the spread of networks and high-precision RFID technology.

The part agent is generated at the manufacturing phase of the main parts, when an RFID tag is attached to its corresponding part. The part agent identifies the ID of the RFID tag throughout the part's life cycle, tracking the part's progression through the network. We chose an RFID tag for identification because RFIDs have a higher resistance to environmental stress than printed codes such as bar codes, which may deteriorate or be covered by dirt over the long period of a part's life cycle. Moreover, you can read, write and store an amount of data in RFID. These functions are not feasible by other print-based identification methods.

For a related research, Product Embedded Identifier (PEID) [10] has been developed which involves a small computing chip, an RFID tag, and sensors to support the middle and end of life of the products. In contrast to PEID system, our system aims to promote multiple reuses of individual parts that may go beyond the manufacturer's management. This requires a 'lightweight' system that can be used repeatedly without maintenance of sophisticated hardware.

Figure 1 shows the conceptual scheme of the part agent. The part agent collects the information needed to manage its corresponding part by communicating with various functions within the network. These functions may involve a product database that provides product design information, an application that predicts the deterioration of parts, one that provides logistic information, or one that provides market information. Furthermore, the part agent communicates with local functions on-site, such as sensory functions that detect the state of the part, storage functions for individual part data, and management and control functions of the product. Communication is established using information agents that are subordinate network agents generated by the part agents.

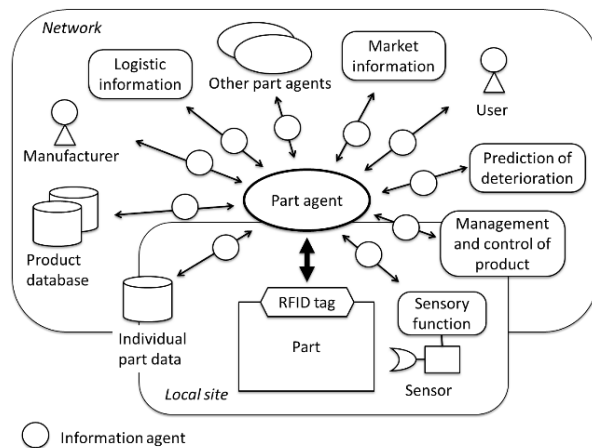


Figure 1: Conceptual scheme of the part agent.

On the basis of the collected information, the part agent provides users with appropriate advice on managing the corresponding part. Based on the advice from the part agent, the user makes a decision concerning product usage. Then, the part agent provides the necessary directions with regard to product management and control functions in accordance with the user's decision. The agent also contacts the part manufacturer regarding the repair of the part when it predicts part failure.

3 AGENT ADVICE BASED ON LIFE CYCLE INFORMATION

3.1 Framework for the part agent

It is difficult to determine the life cycle of a product in detail because one cannot predict what will happen in the future. To overcome this problem, we believe that the life cycle should be designed to allow for possible changes. As the design of robust life cycles is not a topic addressed in this paper, we simply assume that a life cycle stage in the model has multiple life cycle paths connecting to its next stages in order for the part agent to be able to select an appropriate path at the time of execution. For example, 'use' stage may have four optional paths: one leads to 'repair' stage, one to 'refurbish' stage, one to 'dispose' stage and one back to 'use' stage.

We propose, as shown in Figure 2, a basic framework for the part agent to appropriately advise the user based on the life cycle model and other related information. At each time step, the part agent performs the following procedure. First, the part agent identifies all the candidate paths from the current life cycle stage and then checks each path to see if it is 'active' or not. For example, if the part fails, then the path back to the 'use' stage (meaning that the part will continue to be used) cannot be followed and should be marked as 'inactive.'

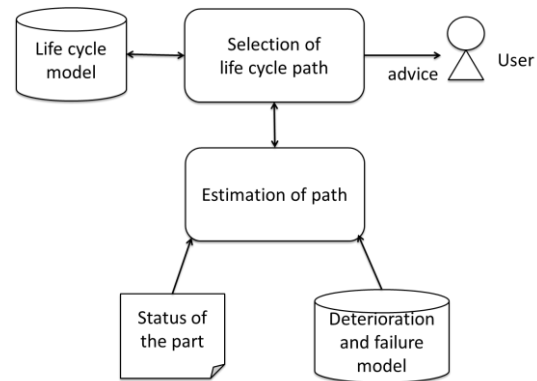


Figure 2: Framework for part agent advice generation.

3.2 Life cycle model

The part agent has information on the life cycle of the part consisting of a network of life cycle stages connected by life cycle paths. The information of the life cycle is created during the design phase of the part and is provided to the corresponding part agent. The life cycle differs depending on the type of the part.

Based on the information given in this life cycle, the part agent estimates each option of the life cycle by performing a simulation and then selects an appropriate route for the part.

3.3 Expanded life cycle model

Figure 3 illustrates our expanded life cycle model derived from the life cycle model of the part. The expanded life cycle path represents a transfer in one time step from an expanded life cycle stage to another stage. The expanded stage has values required or generated there for the step, such as cost, environmental load, and value. Multiple expanded paths may exist starting from an expanded stage as described above.

The part agent decides at every time step which path should be followed. For that purpose, the part agent estimates future possible actions. The probability assigned to each expanded life cycle path represents an estimated probability that the part agent takes that path.

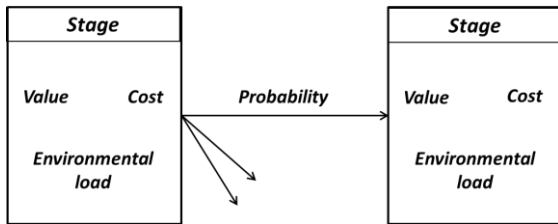


Figure 3: Expanded life cycle model.

The part agent evaluates each active expanded path. The evaluation is based on an estimation of the expanded path using information that includes the current status of the part and information about its deterioration and failure. The evaluation is made based not only on the current state but also on the predicted state of the near future.

As measures to estimate the path, the environmental load, value, and cost are provided for each stage based on the degradation model of the part as described below.

The probability that the part will take a certain path is also provided. The probability of following a path in the expanded life cycle is derived based on user preference. We assume that the user has certain preferences for the management of parts. Some may prefer lower cost options, some may prefer higher value options, and others may prefer to maintain a low environmental load. Based on these user preferences, probability is assigned to each path.

The derivation method of these probabilities is still to be developed. The probabilities should be determined both by user's preference and degradation of the part. The user's preference may be estimated through the declaration made by the users as well as through their captured behavior.

Based on these measures, the total performance index (TPI) [11] is derived for the evaluation of a stage. TPI provides a proper evaluation of the performance of a part throughout its life cycle by balancing its value, environmental load and costs and is given in the following equation.

$$TPI = \frac{value}{\sqrt{cost \times environmental\ load}} \quad (1)$$

A large TPI indicates that the value is high compared to the environmental load and cost. The expected TPI of the stage is calculated using equation (1) based on the expected value, the expected cost and the expected environmental load. A part agent can then propose to the user a choice of life cycle with the highest expected value.

3.4 Degradation of a part

To create a simulation to estimate the future state of a part, we assume that a part deteriorates with operational time. Our degradation model of the part is shown in Figure 4. The value of the part decreases with the time spent in use. When the part is repaired, some value is recovered. When the value dips below a threshold, disposal is recommended for the part.

In our simulation, described in Section 4, the maximum value is given to a part when it is newly produced. The value is reduced in the 'use' stage. It is increased in the 'repair' stage by a certain percentage (or to the maximum if the increase exceeds the maximum). Any part is sent to the 'dispose' stage when its value drops below a threshold.

We assume that the degradation of the value of the part affects its cost and environmental load as shown in equations (2) and (3) respectively.

$$cost = f_{cost}(value) \quad (2)$$

$$environmental\ load = f_{env}(value) \quad (3)$$

Functions $f_{cost}()$ and $f_{env}()$ may differ depending on the part type and may have additional parameters relating to usage and environment. In this paper, we assume simple linear functions as shown in equations (4) and (5).

$$f_{cost}(value) = -A_{cost} \times value + B_{cost} \quad (4)$$

$$f_{env}(value) = -A_{env} \times value + B_{env} \quad (5)$$

where A_{cost} , B_{cost} , A_{env} , and B_{env} are positive coefficients depending on the type of part.

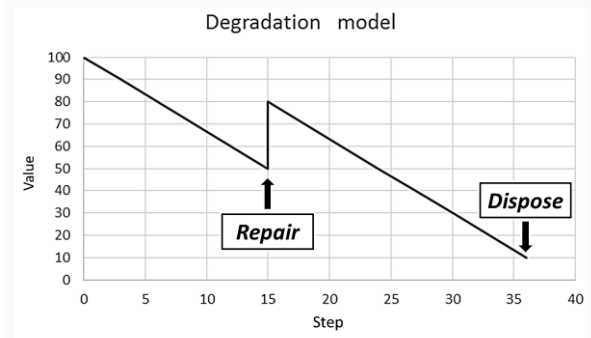


Figure 4: Degradation model.

3.5 Estimation of a path

Based on the equations derived from the models described above, expected value, cost, and environmental load are calculated as shown in equation (6) to estimate life cycle paths. The expected value of an expanded path is obtained by multiplying the probability of the path $Prob(ExPath)$ and the expected value of the expanded stage connected from the expanded path $ExpVal(ExStage|From(ExPath))$. The expected value of an expanded stage $ExpVal(ExStage)$ is calculated by summing up the expected values of all expanded paths starting from the expanded stage.

$$ExpVal(ExStage) = \sum_{ExPath|From(ExStage)} \{Prob(ExPath) \cdot ExpVal(ExStage|From(ExPath))\} \quad (6)$$

Note that the probabilities of all expanded paths starting from an expanded stage sums to one. These probabilities are derived from user's preference as described in 3.3. Further, note that equation (6) is recursively defined. In other words, to obtain the expected value of an expanded stage, it is necessary to calculate the expected value of other expanded stages. To avoid an infinite series of calculations, a maximum depth of calculation is given for the system. For the expected value of an expanded stage at the termination level, the value of the expanded stage is used instead of calculating the expected value obtained from equation (6).

The part agent performs this simulation at each time step in order to decide the appropriate path to take.

4 IMPLEMENTATION OF THE SYSTEM

Figure 5 shows how a part agent decides the appropriate actions for a corresponding part. The part agent has life cycle information of the part and its current state, including the life cycle stage. The part agent expands the life cycle to compose an expanded life cycle, starting at the current stage for a specified time step. Detailed information on expanded stages and paths such as deterioration, cost, and environmental load are calculated using the corresponding models described in the earlier and current states. Simulation is performed using this expanded life cycle. The part agent generates advice to the user based on the simulation result.

A prototype system of a part agent performing this process at each time step was implemented using the object-oriented programming language Java.

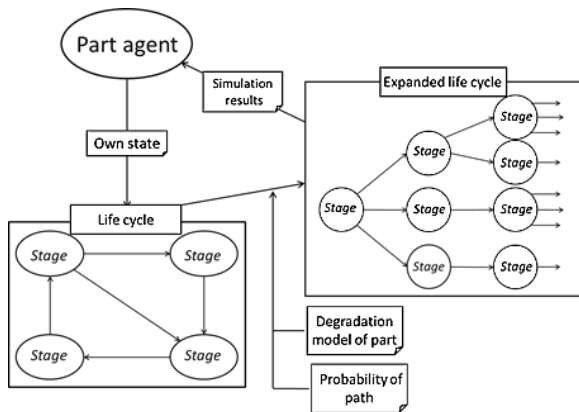


Figure 5: The part agent process used to decide appropriate actions for the corresponding part.

5 LIFE CYCLE SIMULATION

5.1 Simulation process

We developed a prototype simulation for the estimation of candidate paths.

A simple life cycle, shown in Figure 6, is defined for the simulation consisting of six stages: the 'produce' stage, 'sell' stage, 'use' stage, 'repair' stage, 'refurbish' stage, and 'dispose' stage. Paths connecting these stages are also defined: 'produce to sell,' 'sell to use,' 'use to repair,' 'repair to use,' 'use to refurbish,' 'refurbish to sell,' 'use to dispose,' 'produce to produce,' 'sell to sell,' 'use to use,' 'repair to repair,' and 'refurbish to refurbish.'

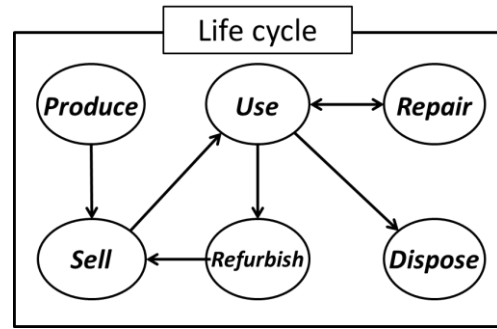


Figure 6: A simple life cycle.

Figure 7 shows the expanded life cycle generated from the simple life cycle in Figure 6 when the part is in the 'use' stage.

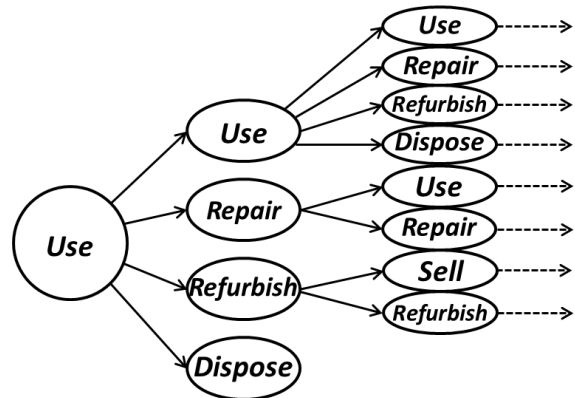


Figure 7: Expanded life cycle.

The properties of parts are updated in the stages as shown in Table 1. Note that we took a simple assumption where the cost and the environmental load depend on the value that degrades with time. When the part is in 'use' stage, its value decreases to 90% of the value of the former time step as shown in the table. The value is assumed as 100 when it is newly produced. We also assume that the probability of paths from 'use' stage to 'repair' stage, 'refurbish' stage and 'dispose' stage changes as the degradation of the value as shown in Table 2. We provide other paths to different stages with probability of 1.0 and those back to own stages with 0.0.

Table 1: Properties of stages

	Value	Cost	Environmental load
Produce	100	100	50
Sell	value	50	20
Use	$0.9 \times \text{value}$	$11 - 0.1 \times \text{value}$	$11 - 0.1 \times \text{value}$
Repair	$1.2 \times \text{value}$	$50 - 0.19 \times \text{value}$	30
Refurbish	$1.1 \times \text{value}$	$50 - 0.1 \times \text{value}$	20
Dispose	$0.3 \times \text{value}$	30	150

Table 2: Probabilities of paths from 'use' stage

To From	Use	Repair	Refurbish	Dispose
Use	$\frac{value - 1}{100}$	$\frac{100 - value}{200}$	$\frac{100 - value}{200}$	0.01

As an example, Figure 8 shows a result of the expected cost calculated with our method of simulation. Circles represent the stages and squares represent the paths. The number in a circle shows the cost of the stage itself calculated based on the parameters in Table 1 with the expected cost of all the branches starting from that stage shown in parentheses. The number in a square shows the probability the path will be selected. Dotted arrows starting from Use (Start) show the options at the stage.

In this simple example, the simulation is run for only one step to confirm the calculation process. For example, the expected cost of the 'use' stage in the middle is calculated using only the costs of the four stages that branch from it. The cost of the 'use' stage in the middle is calculated as 1.0 using Table 1 with the current value of 100. For the stages in the right of the middle 'use' stage, the value of the middle 'use' stage decreases to 90 and hence, the cost in right 'use' stage is estimated as 2.0, the cost in right 'repair' stage as 32.9, and so on, using the similar calculation. Using these estimated costs and taking into account the probabilities of the corresponding paths, the total expected cost for all the branches starting this 'use' stage is calculated as shown in the following equation.

$$ExpC(Middle Use) = 1.0 + (2.0 \times 0.89) + (32.9 \times 0.05) + (41.0 \times 0.05) + (30.0 \times 0.01) = 1.0 + (5.72) = 6.72 \quad (7)$$

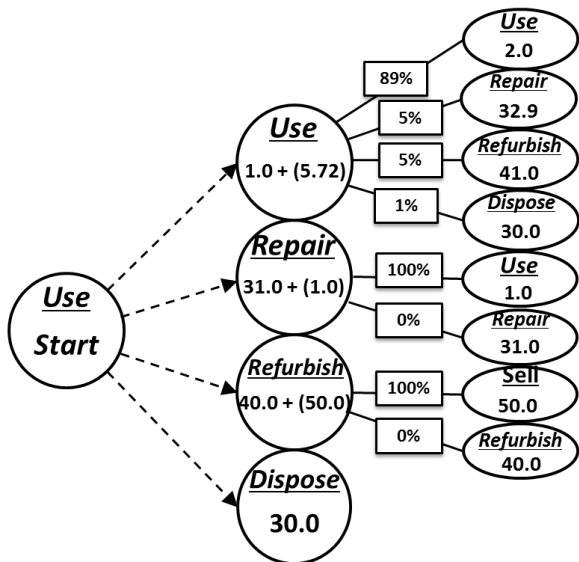


Figure 8: Calculated results of the expected cost.

Similarly, the expected environmental loads and value are also calculated. The expected TPI is calculated based on the estimation of the expected value, cost and environmental load as described in 3.3.

5.2 Simulation results

To evaluate our method of prediction, a part agent was run for 10 steps choosing an appropriate stage in each step.

As described above, the part agent calculates expected value, cost, environmental value and TPI for each candidate stage. It takes the path to the stage with the best expectation that is the highest value, the lowest cost, the lowest environmental value or the highest TPI according to the user's preference. The user is assumed to accept every advice from the part agent in this simulation.

We compared two cases of the simulation, one using our method and the other with randomly selected path. The results are shown in Figure 9 and 10. The black lines show the interested values for the paths selected by the part agent and the gray lines show those for the paths randomly selected. Figure 9 shows the value of the part and the stages its part agent has selected when the agent selects the paths with the highest expected value. In contrast to the case where the path was selected randomly, the selections by the part agent mostly result in higher value.

Figure 10 shows the TPI when the part agent chose stages with the highest TPI. The fluctuation is due to the part agent behavior based on its prediction. It foresees the higher TPI of future stages after the lower TPI of next stage.

The average TPI in 8 steps for the parts using our method and for the parts selected randomly were 28.50 and 26.16, respectively. In other words, the average TPI for our method was 108% of that obtained by random selection. Furthermore, the part following the part agent selection survived 10 steps whereas the part in random selection reached 'dispose' stage and terminated its life in 8 steps.

We believe that, though still premature, the results show potential for the effectiveness of our system.

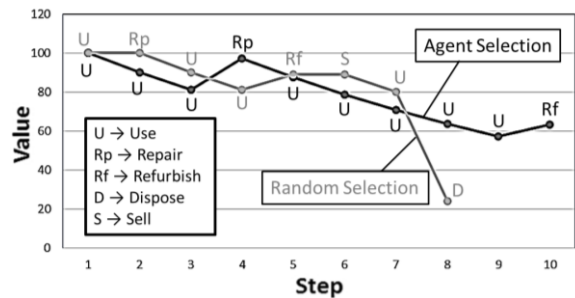


Figure 9: Simulation result when the part agent chose the path with the highest value.

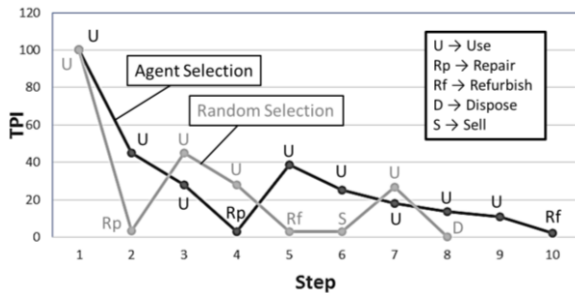


Figure 10: Simulation result when the part agent chose the path with the highest TPI.

6 DISCUSSION

The simulation result shows that the estimation of values in the near future would be an effective tool for generating advice.

The remaining issues and future prospects include

- creating a more realistic degradation model for parts,
- estimating the probability of paths,
- communicating with multiple agents, and
- performing simulations for assembly consisting of part agents.

As we described in Section 3.4, the degradation model for parts would not be as simple as given in Figure 4. Parts may deteriorate suddenly after exceeding a certain usage time, or may not significantly degrade for a long period. We need to create a deterioration model that considers the characteristics of each part.

The probability a path will be taken depends on the preference of the user, and the deterioration model of the part must also be considered. We need to calculate the probability of a path based on this information.

A single part is dealt with in this paper. However, required information may change because of the mutual effects of other parts and part agents. To solve this issue, appropriate communication will be required among part agents.

A product is composed of multiple parts. Therefore the simulation should deal with multiple part agents. Deterioration of a part affects other parts in the same assembly. Parts are not only repaired but also replaced. These issues need to be solved when assemblies are considered.

7 CONCLUSION

In this paper, we proposed a part agent to promote the reuse of parts. To overcome the uncertainty that cannot be predicted in the design phase, a fundamental mechanism was proposed to select the best life cycle path based on life cycle information. Future work is also discussed.

8 ACKNOWLEDGEMENTS

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