11 Upgrade planning for upgradeable product design

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Abstract

The current mass production paradigm contributes significantly to environmental degradation. To solve these environmental problems, concepts involving the reuse and remanufacture of products and materials are being proposed. The design of upgradeable products, which could be used for longer than conventional products and encourage people to reuse artefacts, is one of the most promising approaches using these methodologies. In addition, they might provide new business opportunities in the later stages of their product life cycle. Achieving upgradeable design requires a proper plan, which must include information on the upgradeable design, including when a product should be upgraded, with regard to which function, and to what extent. The upgrade plan should also include a solution lineup for upgradeable design that satisfies these conditions. To devise such an upgrade plan, designers need to predict technological trends and user demands. This paper proposes a methodology for upgrade planning based on the prediction of user demand, and on the assumption that technological trends influence user demands. In addition, a methodology is proposed for changing upgrade plans after target products have been distributed, to meet possible fluctuations in technological trends or user demands.

G. Huppes and M. Ishikawa (eds.), Quantified Eco-Efficiency, 261–281.

11.1 Introduction

In order to reduce the environmental problems caused by excessive disposal of products in modern society, products with closed-loop life cycles need to be manufactured. Inverse Manufacturing is one of the most promising concepts to achieve such products (Umeda and Tomiyama 2000). Reuse and remanufacturing, the concepts related to Inverse Manufacturing, are effective means to extend the physical life of a product. However, product life means not only physical life but also value life, which is terminated when functions become insufficient. Many manufactured products, such as mobile phones, are abandoned at the end of their value life. This paper presents a method for extending the value life of products by upgrading them (Shimomura et al. 1999). Efficient upgrading of products requires an upgrade plan which includes the specifications of the products in every product generation. To make this upgrade plan realistic and flexible, it is necessary to predict future technological trends and user demands. Technological trends are assumed to generally influence consumer demands, and on the basis of this assumption, an upgrade plan which includes the prediction of technological trends could be effectively adapted to satisfy user demands. The objective of this paper is to propose a general upgrade planning method. In addition, a method is proposed to modify the upgrade plan to adjust to unpredicted events. Most future events in an upgrade plan can be expressed as changes in the product's components. Therefore, a database should be prepared that can manage the required information, such as product categories, performance and cost, for the purposes of managing and maintaining the information about a product's structure and components. This information could be used to devise a plan for the design of upgradeable products that could adjust flexibly to future events.

11.2 Upgrade design methodology

Upgrade design is the design of a product so that its performance can be adjusted to changeable user demands by replacing some of its components. Section 11.2 explains the fundamentals of upgrade design and its influence on the environment.

Basic principle of upgrade design

We assume that the performance of a product remains constant until deterioration or breakdown occurs. On the other hand, user demands for product performance generally increase over time, since users become aware of the new functions or better performance of new products in the same category. As time goes on, the gap between their demands and the performance of their own product widens. Thus, it can be assumed that consumers replace their products when the gap becomes wider than a certain threshold level. In such cases, it can be said that the value life of a product has terminated, at least for these users.

Upgradeable design methodology aims to improve product performance to meet user demands by replacing product components and extending the product's value life (see Figure 11.1).

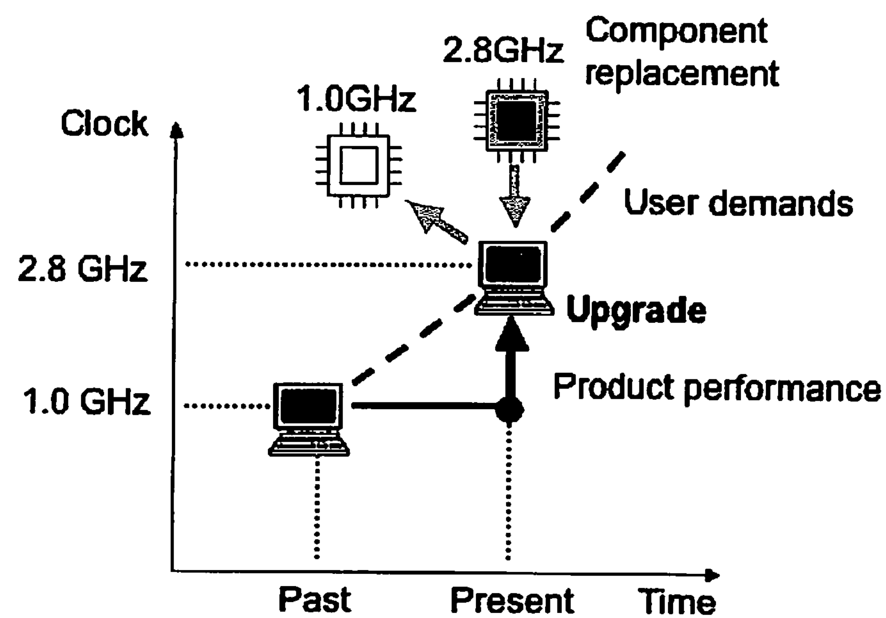


Figure 11.1 Concept of an upgradeable product

Eco-efficiency of upgrade design

Application of upgradeable design reduces the cost of the product's life cycle as well (Ishigami et al. 2002).

(1) Reduction of unnecessary production. The application of upgradeable design results in a reduction of the total amount of production, even though upgrade components must be supplied. This reduces the use of unnecessary materials and energy.

(2) Reduction of waste disposal. In addition to decreasing the number of products used, the replacement of components prolongs the value life of upgradeable products. This should also result in fewer products to be disposed of. Users of upgraded products should enjoy good functionality after component replacement. This important characteristic of upgrade design sets this system apart from other environmentally friendly products or systems.

Upgrade plan

An adequate upgrade of products requires a well-designed upgrade plan that would satisfy the changing user demands. This section explains the structure of such an upgrade plan.

Upgrade design process

Figure 11.2 shows the upgrade design process based on upgrade planning, including two sub-processes:

(1) Upgrade planning. As noted in section 11.1 upgradeable design aims to extend the value life of a target product. To this end, product designers should project future user demands on the target product at the start of the design process. On the basis of this prediction, they must develop a lineup of upgradeable design solutions for a certain period, called an 'upgrade span.' This process allows designers to develop a plan for upgrade design.

(2) Upgrade plan alteration. On the other hand, an unexpected event, called a 'disturbance,' may occur even after the production or sale of an upgradeable product. The designers should respond to such disturbances and change the upgrade plan based on new information. This process allows the upgrade plan to remain adequate.

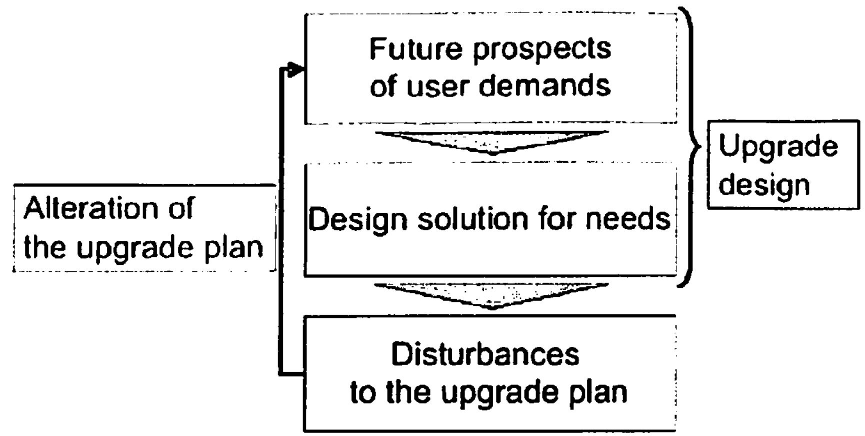


Figure 11.2 Upgrade design process

Design information for an upgrade plan

The upgrade plan contains the following information:

(1) Product performance. Product performance refers to changes in the performance of a target product resulting from technological trends and user demands. Product performance is described by means of parameters.

(2) User demands. User demands are described as parameters of various aspects of the product (such as function and price).

(3) Product structure. This structure is described as a set of components.

(4) Lineup schedule. This is a schedule for introducing a new product, namely a new set of components, to the market. Section 11.4: 'Searching for design solutions', explains how the upgrade schedule is to be determined.

11.3 Description of user demands

In upgrade design, product designers aim to match product performance and user demands. Hence, describing user demands is a very important aspect of upgradeable design. We propose the following two concepts for the description of user demands: (1) Matching user demands and technological trends; (2) Describing the diversity of user demands.

Matching user demands and technological trends

The relationship between a manufacturer of upgradeable products and a user of such products is depicted in Figure 11.3. First, the manufacturer produces products made of existing components. Next, he/she introduces such products into the market. Designers can project the trend of product performance on the basis of a roadmap for the components (see Figure 11.4 (a)). These roadmaps for components and products describe future variations in technological trends, and designers use them to develop an upgradeable product.

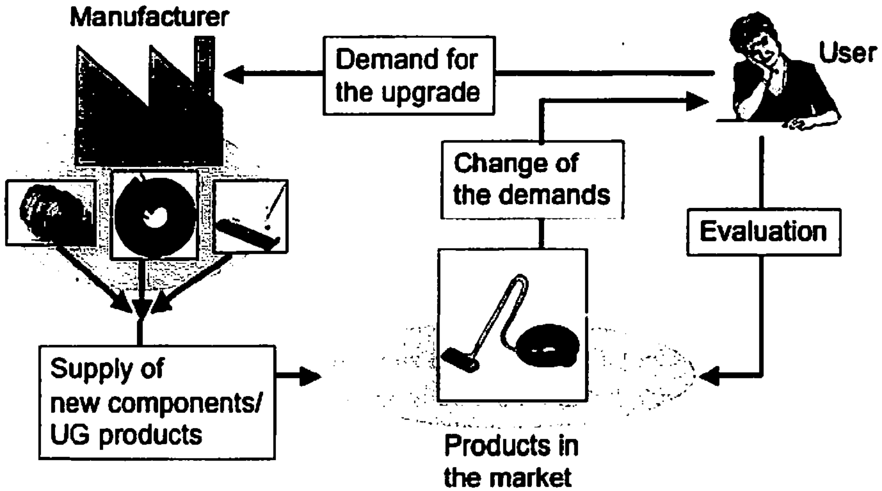


Figure 11.3 Relationship between users and a manufacturer

Consumers then purchase their favourite products after evaluating them on the basis of their own demands. The present study proposes a consumer behaviour model of purchasing products, which assumes that technological trends influence every user demand (see Figure 11.4 (b)). As time goes on, product lineups in the market are refreshed, and some products with higher quality or performance may come into the market. This may cause users to become dissatisfied with their own products. In other words, the gap

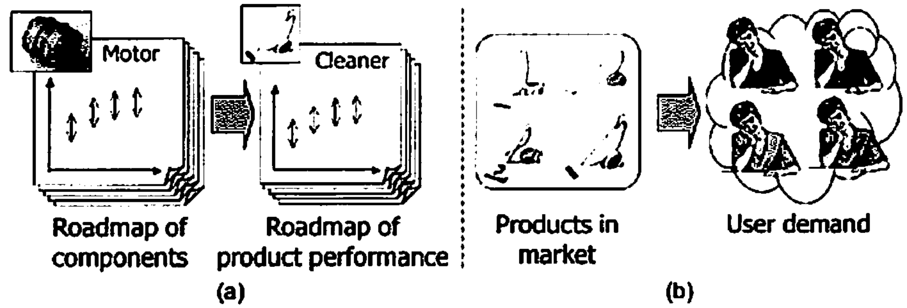


Figure 11.4 Technological trends and user demands

between their demands and the performance of their own product becomes wider. They replace the old product or demand an upgrade from the manufacturer when the gap becomes wider than a certain threshold level.

Describing the diversity of user demands

Since users of any product usually have a large variety of demands, designers have to consider the various demands. We address this issue by categorising user demands as plural patterns and making upgrade plans for every user-demand pattern.

Some patterns of user demands are shown in Figure 11.5. A user with higher threshold levels for product performance is referred to as a 'low-cost user' in this study. By contrast, a high-end user is one with a lower threshold. Using such threshold levels for product evaluation allows various user demands to be expressed. An explanation for the process is presented in 11.4: Setting user-demand patterns.

High-end users	Low-cost users	Professional users
•Demand the highest level of performance •Do not care about costs	•Do not care about performance •Do not buy expensive products	•Demand a high level of performance in some aspects •Do not care about the other aspects of performance •Require the lower price

Figure 11.5 Patterns of user demands

11.4 Upgrade planning

This section focuses on the upgrade planning mentioned in 11.2: Upgrade plan. Product designers can develop an upgrade plan by going through the following process:

(1) Developing a structure model.
(2) Building a component database.
(3) Developing a valuation parameter (VP) roadmap.
(4) Setting user-demand patterns.
(5) Searching for design solutions.
(6) Evaluating the upgrade plan.

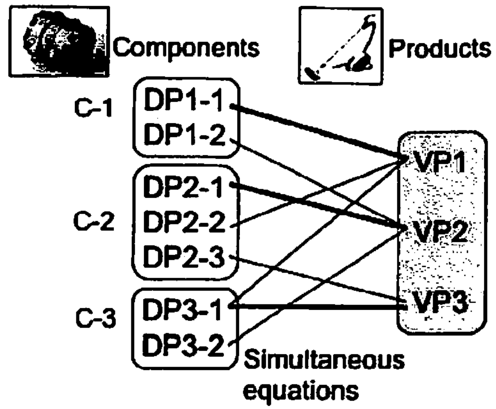
Developing a structure model

Designers first develop a structure model that shows the structural relationships between a product and its components. We assume that the specifications of a product and its components can be described by a set of parameters, which are explained below.

(1) Valuation parameter. When purchasing a product, users should check some parametric values of the product's performance. These may be functional parameters, such as suction power and number of revolutions in a vacuum cleaner, or attribute parameters, such as weight or price. The present study refers to such parameters as valuation parameters (VPs). These parameters can also express the user demands for a target product.

(2) Design parameter. To derive the VPs, a design parameter (DP) was defined to describe the specifications of each component. DPs describe the characteristics of each component, such as electric power and turbine radius (Umemori et al. 2001).

(3) Description of the upgrade. The designers describe the relationship between DPs and a VP of a target product using a set of simultaneous equations (see Figure 11.6), derived from information on the target product structure and its physical characteristics (Ishigami et al. 2002; Umemori et al. 2001). The designers can use the VPs of the target product to follow user demands by determining the values of a DP set and replacing some components. Some components may have strong links with a particular VP. These are the key components of the target VPs.



VP	Key components
1	C-1
2	C-2
3	C-3

Figure 11.6 Structure model

When a key component of a particular VP is not unique, or when one component is the key component of more than one VP, the designers should revise the structure model and solve the side effects caused by replacing the component for the upgrade (Shimomura et al. 1999).

Building a component database

Next, designers research the technological trends relating to the target product. They should examine both the current technology and the future fluctuations in the technological trend during the upgrade span. The result of this analysis is stored in the component database, which contains information about each component of the target product, including the category the product falls under (e.g., motor, fan), a DP set and a schedule for the component to enter and exit the market. A DP set for each component is described as a range of values. The designers express the future fluctuations of each DP as a roadmap on the basis of the information in the component database (see Figure 11.7).

Developing a VP roadmap

The previous step involved developing the DP roadmap, which expresses the fluctuations of future technological trends. In the present step, designers

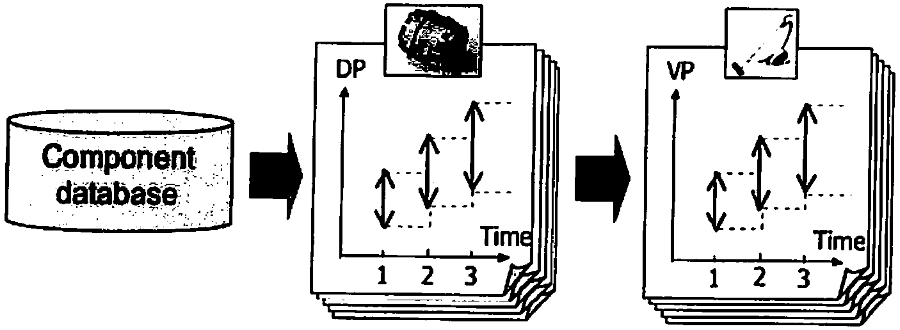


Figure 11.7 DP/VP roadmap

similarly derive the VP roadmap of a target product during the upgrade span.

A VP roadmap can be obtained by applying the simultaneous equations of VPs and DPs determined in the structure model (see Section 11.4 'Developing a structure model - (3)'). This VP roadmap expresses not only the future technological trends but also the upper and lower limits of the future level of user demand.

Setting user-demand patterns

In this part of the process, user-demand patterns are set using the following two operations on the basis of the information on future technological trends in the component database. First, the designers qualitatively classify various user demands as multiple patterns. Second, they divide each VP range into multiple ranges and make them correspond to each user-demand pattern.

Based on the results of these operations, they design the correspondence between user demands and VP range sets (e.g., a user whose user-demand pattern is 'high-end' requires a high-performance product). The present study expresses each user-demand pattern by a range set of VPs.

(1) Qualitative expression of user demands. The designers develop multiple user-demand patterns, such as 'high-end' and 'low-cost' (see Figure 11.5). Each demand pattern is characterised by a qualitative symbol set, such as the three-grade ranking 'H', 'M' and 'L'. Table 11.1 summarises

the user-demand patterns for a vacuum cleaner. For example, the high-end user presented in Table 11.1 requires a vacuum cleaner with suction power and clean emissions in the 'H' rank and noise in the 'L' rank.

(2) Quantification of user demands. Based on the VP roadmap and several user-demand patterns, the designers express the fluctuations in a VP range set for every user-demand pattern as time-series. Table 11.2 describes the correspondence between three user-demand patterns for the VP 'suction power of a vacuum cleaner' and the qualitative ranking and quantitative VP range set.

Designers can express user demands as a set of concrete and quantitative value ranges by describing the time-series information of a user-demand pattern. For example, as shown in Figure 11.8, a CPU with a speed of 2.4 GHz has been displaced from the 'H' rank at T_2 because of shifts in user demands. This time series behaviour of VP ranges can be used to determine a target value for the product upgrade.

Searching for design solutions

In this step, designers search for design solution lineups to satisfy each user-demand pattern. The VP range set of the quantified user-demand patterns is the target value of the design solution in each generation.

Table 11.1 Qualitative user-demand pattern

VP name / User demands	Suction	Noise	Emission
High-end	H	L	H
Low-cost	L	H	L
Professional	M	M	H

Table 11.2 Relationship between VP ranks and VP ranges

Suction user demands	VP rank	VP range [W]
High-end	H	[600-480]
Low-cost	L	[600-180]
Professional	M	[600-360]

Speed / Time	VP rank	VP range [GHz]
T_1 (Past)	H	2.4
T_2 (Present)	M	

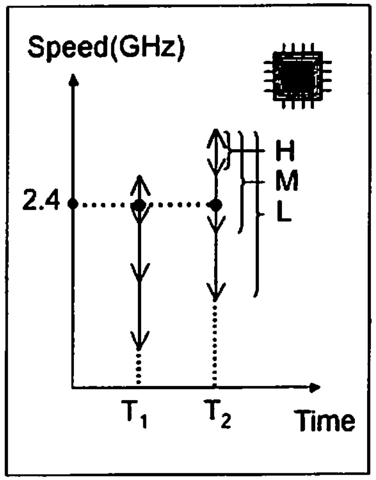


Figure 11.8 Shifts in VP rank and VP range

Process before the first upgrade. First, designers tentatively choose a design solution for the first generation. This solution may be modified afterwards. Next, they examine the basic specifications of a design solution for the next generation. This specification is derived from the design solution for the first generation. It contains the target VPs to be upgraded, a timing of the upgrade, and a set of VPs.

Timing of the upgrade. The product upgrade should be effected when any VP is displaced beyond the range of user demands. Figure 11.9(a) depicts two VP roadmaps (VP1, VP2) for a vacuum cleaner. In this case, VP1 is the first to exceed the range of user demands. Designers should perform an upgrade before TVP1, the first displacement point. In addition, designers must ensure that the timing of the second upgrade agrees with the adopted design solution. The displacement of two design solutions is shown in Figure 11.9(b). The displacement point of each solution is different, which influences the entire upgrade schedule.

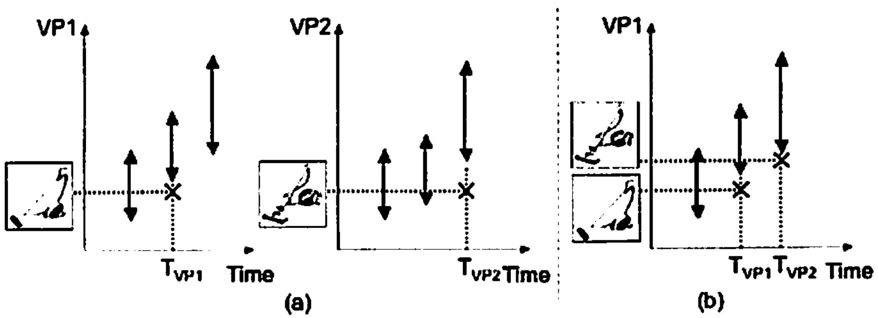


Figure 11.9 Determining which VP to upgrade and establishing upgrade timing

Determining the basic specification. After the VP to be upgraded and the upgrade timing have been determined, the designers search for the key components that are to be replaced. By changing these components, they can determine the basic specifications of the target product.

Searching for a design solution. In addition to the key components, designers also have to select the other components to be replaced. These are not the key components, but their replacement is indispensable when searching for design solutions. Designers explore the component database to identify these non-key components and define a design solution for the second generation that would satisfy the basic specifications given above. Designers can reject every design solution that is below the lower limits of the VP ranges. If they can obtain appropriate solutions, they search for solutions for the next generation. If they cannot, they correct the basic specification and design solution for the former generation and try again to find solutions (Shimomura et al. 1999). This operation is based on the methodology proposed by Umemori (Ishigami et al. 2002; Umemori et al. 2001). The designers should continue until every user-demand pattern is satisfied during the upgrade span.

Evaluating an upgrade plan

In this step, the designers make upgrade product lineups composed of design solutions that they have obtained in the previous steps. The product lineup information includes a list of upgraded VPs, the schedule for the upgrades and a list of replacement components.

If there are multiple upgrade product lineups for one user-demand pattern, designers evaluate them on the basis of their cost throughout the upgrade plan, as well as the components-sharing rate, that is, the rate of the components that are identical between generations, and their flexibility to meet future disturbances. They then choose one lineup for one user-demand pattern. The process of upgrade planning ends with the complete upgrade product lineups for each user-demand pattern.

11.5 Alterations to the upgrade plan

After the production or distribution of an upgradeable product, unexpected events may happen. Such events are called 'disturbances' in the present study. One such disturbance is fluctuations in future technological trends. We describe a disturbance as a change in the component database. On the basis of this change, designers alter the user-demand patterns and the upgrade plan in accordance with their assumptions about user demands. This section describes the procedure for upgrade plan alterations using two examples of disturbances: *case 1*, production stoppage of components, and *case 2*, emergence of new technology.

Figure 11.10 summarises the processes that take place when an upgrade plan is altered in these two cases.

(1) Description of disturbance. In this step, the designers adapt the component database to reflect the disturbance. In case 1, the designers

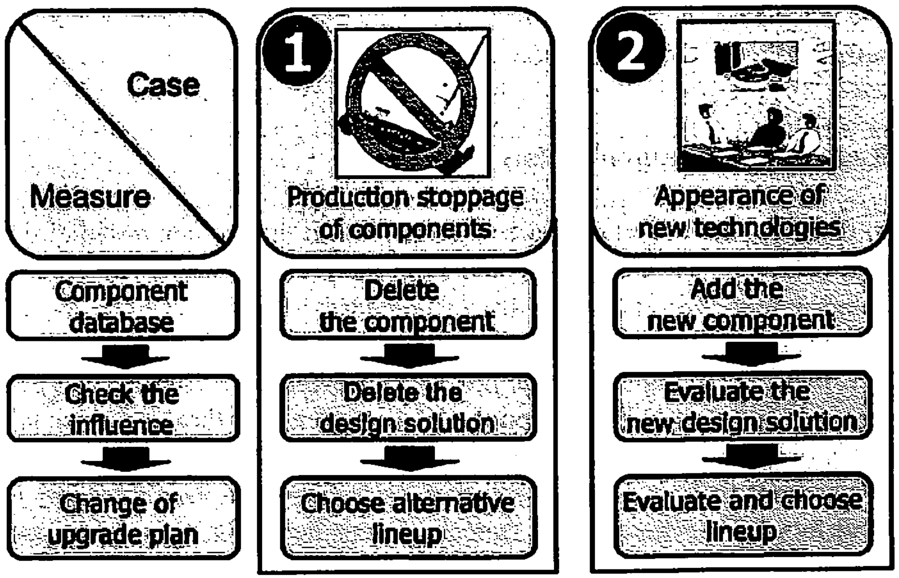


Figure 11.10 Alteration of upgrade plan

delete the pertinent components from the component database. In case 2, the designers add a new component with new technology to the database.

(2) Determining the influence of the disturbance. In this step, the designers determine the influence of a disturbance on every existing upgrade plan for each user-demand pattern. In case 1, the designers check whether any design solution with the pertinent component exists in the design solution lineup. In case 2, the designers determine whether the new design solution with the new component is a good replacement of the existing design solutions in the lineup. This judgment involves evaluating not just a single solution but the entire upgrade design solution lineup.

(3) Altering the upgrade plan. Finally, the designers alter the upgrade plan on the basis of the results of their assessment in the previous step. The alteration occurs in response to a disturbance caused by structural changes. In case 1, designers discard the related design solution, by correcting the upgrade plan and searching for alternative design solutions again. The alternative design solution must of course satisfy the required VP ranges for each user-demand pattern.

Furthermore, the solution must be consistent with the entire upgrade plan. In case 2, the designers replace an existing design solution with a new one only if that replacement improves the upgrade plan in terms of the evaluation described in 11.4: Evaluating an upgrade plan, i.e., in terms of the cost and the components-sharing rate throughout the upgrade plan.

11.6 Applying the upgrade design – a case study

This section presents and explains an example of the upgrade design based on the above-mentioned methodology.

Design conditions

The initial design conditions for upgrade design are summarised in Figure 11.11 and Tables 11.3, 11.4 and 11.5. The details of this condition are discussed below.

Structure model. The example of upgrade design used here is a simple vacuum cleaner model. Its structure model is shown in Figure 11.11. The model uses four VPs: 'Cleanliness', a positive parameter which stands for clean emissions; 'Noise', a negative parameter which stands for the noise

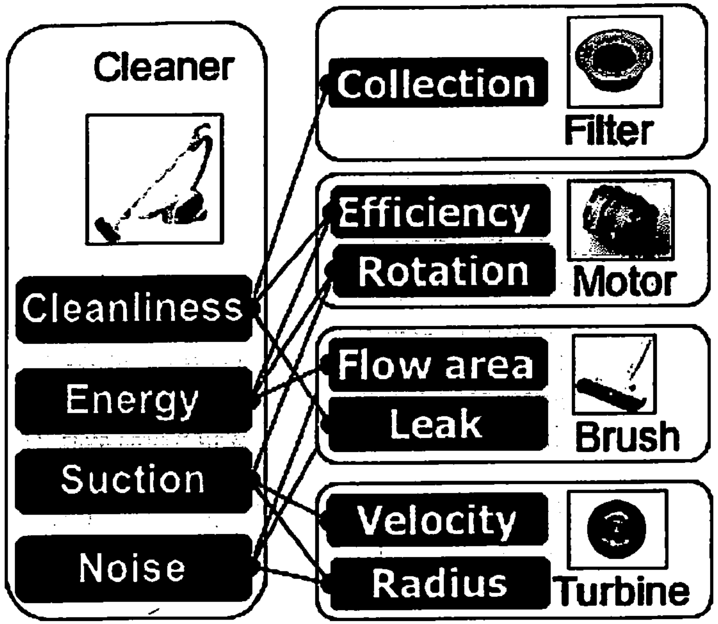


Figure 11.11 Structure model of a vacuum cleaner

generated when the vacuum cleaner is used; 'Suction power', a positive parameter which stands for the vacuuming power of the appliance; and 'Energy consumption', a negative parameter which refers to the power consumed by the vacuum cleaner.

Component database. Tables 11.3 and 11.4 show the design information for a 'Filter' and a 'Motor' in the structure model of the vacuum cleaner presented here. The filter has one DP, called the 'Collection rate', and the motor has two DPs, 'Rotation' and 'Efficiency'.

User-demand pattern. Table 11.5 presents three qualitative user-demand patterns: (1) Commercial users. This includes people who use high-performance vacuum cleaners, and require vacuum cleaners with high suction power and very clean emissions. The other parameters, such as noise and energy consumption, are unimportant. (2) Energy-saving users. This type of user requires machines that consume little energy. Such users demand low energy consumption and do not consider the other VPs. (3) Intermediate users. This pattern represents the middle-level user, who is interested in an upgrade. They require a middle-level performance for all VPs.

Table 11.3 Design parameters of a filter

Filter		F1	F2	F3	F4
DP	Collection rate	0.3	0.5	0.8	0.9
Existence span		[1-2]	[1-3]	[2-3]	[3-3]

Table 11.4 Design parameters of a motor

Motor		M1	M2	M3	M4	M5	M6
DP	Efficiency	0.5	0.7	0.5	0.7	0.5	0.7
	Rotation	120	130	150	150	180	180
Existence span		[1-2]	[2-3]	[1-3]	[2-3]	[2-3]	[3-3]

Table 11.5 User demand patterns for a vacuum cleaner

	Energy	Suction	Noise	Cleanliness
Commercial	H	H	H	H
Energy saving	L	L	H	L
Intermediate	M	M	M	M

Upgrade planning

Under the initial design conditions discussed in the section 'Design Conditions', an upgrade plan for a vacuum cleaner was developed, with an upgrade span of three years. Figure 11.12 depicts this upgrade plan, including the VP roadmap and the design solution lineups for each user-demand pattern in the roadmap view. Figure 11.12 (a) relates to suction power, while (b) is about energy consumption. Three narrow bands for each generation show the user demand ranges of the VP. The circles in the bands represent the values of upgrade design solutions for each. The large rectangles behind the user demand range bands show the VP ranges of all products in the market. Since the suction power is a positive VP, its value range gradually rises. On the other hand, the value range of the 'Energy consumption' VP declines annually.

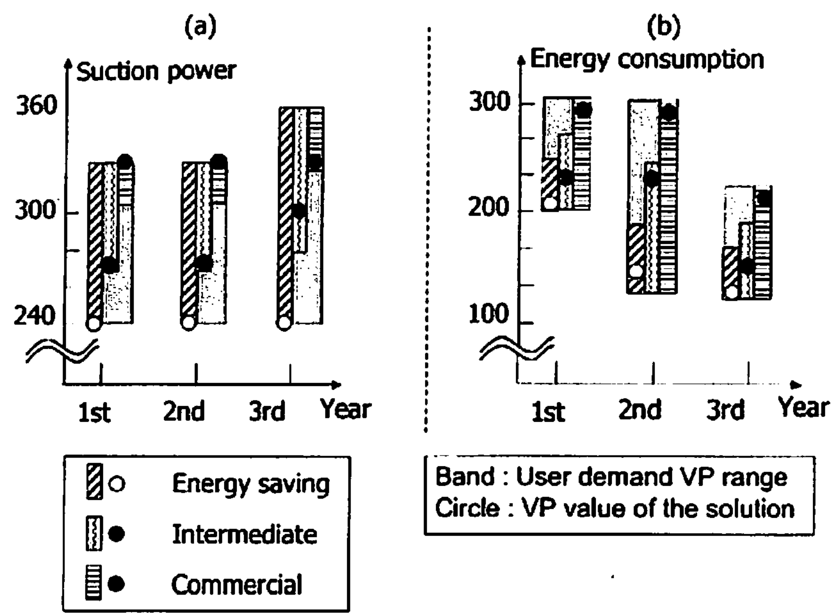


Figure 11.12 Upgrade plan for each user-demand pattern

As for suction power, 'Energy-saving' and 'Commercial' users do not require any upgrades during the upgrade span. This is because the suction power VP rises gradually, and the VP of a first-generation product is not displaced from the user demand range. Only the intermediate users require an upgrade in the third year.

The VP for energy consumption, the VP decreases annually. The lower limit of the range declines from the first to the second year, so 'Energy-saving' users require an upgrade in the second year. In addition, since the upper limit of the value range declines from the second to the third year, 'Commercial' and 'Middle' users require an upgrade in the third year.

11.7 Discussion

The outcome of the above case study shows that suitable components were selected for each type of customer on the basis of an upgradeable design

methodology. Based on these results, product designers can design a product structure that takes future upgrades into account.

The upgradeable design methodology is comparable to some other product design methods. For example, the quality function deployment (QFD) method shows some similarities with the upgrade design methodology, such as the use of a product structure model. However, one of the main differences between the two methods is that the upgrade design methodology includes a process to allow the demands of customers to be predicted on the basis of future technological trends. This provides product designers with greater insight into their customers' preferences.

The upgradeable design methodology can be evaluated by comparing it with some other environmentally conscious business models. The differences between them are shown in Table 11.6.

Table 11.6 Evaluation of environmentally conscious business models

	Environmental impact	**Efficiency**	**Satisfaction with functions**
Upgrade design	Good	Good	Very good
Remanufacturing	Very good	Not good	Not good
Function sales	Good	Good	Good
Material recycle	Not good	Not good	Not good

Conventional environmentally friendly business models, such as remanufacturing and materials recycling, encounter problems with the process of recovering the used products. In addition, recovery operations are expensive. The concept of functional sales, which is a lease service of the products with required functions, is attractive since its function can be replaced based on customer needs.

In comparison to these conventional models, upgrade design can reduce the environmental impact as well as upgrade a product's functionality, without having to deal with the recovery process. The concept of upgrade design is applicable to the functional sales service. Such a concept could result in further reduction of the environmental impact.

The current mass production paradigm contributes significantly to environmental degradation. To solve these environmental problems, concepts involving the reuse and remanufacture of products and materials are being proposed. The design of upgradeable products, which could be used for longer than conventional products and encourage people to reuse artefacts, is one of the most promising approaches using these methodologies. In addition, they might provide new business opportunities in the later stages of their product life cycle. Achieving upgradeable design requires a proper plan, which must include information on the upgradeable design, including when a product should be upgraded, with regard to which function, and to what extent. The upgrade plan should also include a solution lineup for upgradeable design that satisfies these conditions. To devise such an upgrade plan, designers need to predict technological trends and user demands. This paper proposes a methodology for upgrade planning based on the prediction of user demand, and on the assumption that technological trends influence user demands. In addition, a methodology is proposed for changing upgrade plans after target products have been distributed, to meet possible fluctuations in technological trends or user demands.

11.8 Conclusion

This paper proposes a method to design a realistic and feasible upgrade plan which includes predicting future technological trends and user demands by using roadmap information and a component database. A future sudden event (disturbance) is expressed as an alteration to the component database, and a method to effect corrective actions against such disturbances is proposed.

Future studies will focus on the implementation of an upgrade plan alteration system, involving 're-planning' of the upgrade plan based on the updated component database after a future disturbance.

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