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PROPOSAL OF LIFE CYCLE DESIGN SUPPORT METHOD USING DISPOSAL CAUSE ANALYSIS MATRIX

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Abstract

This paper proposes a decision support method for determining life cycle scenarios in environmentally conscious product design. Here, decision of life cycle scenarios includes decision of objectives of design modification and selection of appropriate life cycle options, such as upgrading, remanufacturing, maintenance, and reuse. Since main objectives of this research include offering a simple and convenient tool to designers, quality function deployment is employed. The basic idea of this methodology is to analyze main disposal causes of a product by using “disposal cause analysis matrix,” which is proposed here, and to modify design of the product so as to reduce analyzed disposal causes. This will results in extension of product life and long-term usage of components. The method consists of four steps; namely, analysis of disposal causes of a product, selection of life cycle options and components to be replaced and reused, modularization of the product, and determination of life cycle scenarios. This paper also illustrates result of a case study using a cellular phone in order to show how the proposed method supports the decision process of life cycle scenarios.

Keywords: design for the environment, life cycle design, life cycle options, disposal cause analysis matrix

1. Introduction

In order to support environmentally conscious design, various concepts (e.g.,[1]) and DfX methodologies (e.g.,[2][3]) have been proposed. The aim of this research is to propose a design method for sustainable closed-loop life cycle systems of products, which reduce environmental impacts and increase functionality and services the product provides (let us call it “life cycle design”). In life cycle design, a designer should design not only a product, but also a product life cycle so as to make the product life cycle environmentally conscious. Therefore, it is not enough to simply apply DfX methodologies such as LCA [7], DfDA, and DfR. Rather, as many researches pointed out (*e.g.,* [4]), it is important to clarify appropriate life cycle options to a design object, including longer life, maintenance, upgrading, reuse, recycling, dumping, at the early stage of life cycle design. This choice affects on application strategy of DfX methodologies. For example, in designing a life cycle of a ballpoint pen, on one hand, maintenance centered life cycle by replacing ink cartridges repeatedly (like expensive ballpoint pens) is a good candidate, and, on the other hand, rapid take back and reuse life cycle [4] (like single use cameras) is another good candidate. Such choice affects on, for instance, design for disassembly of the ballpoint pen; the former requires disassemblability for replacing cartridges and the latter for reusing components. However, methodologies for determining such life cycle scenarios have not been clarified enough and, therefore, this issue results in one of the bottlenecks for supporting life cycle design. We here assume that a life cycle scenario includes business strategy, environmental performances to be achieved, life cycle options and targets of product design (*e.g.,* components to be reused).

The objective of this research is to propose a decision support method for determining the life cycle scenario; especially, selection of life cycle options and targets of design modification. We try to make the method simple and tiny so that designers can easily use it.

2. Decision support of life cycle scenario

The basic idea of the method is that if a designer analyzes main disposal causes of a product and modifies design of the product so as to mitigate analyzed disposal causes, this will results in extension of product life and long-term usage of components. For example, material and thermal recycling is promoted and practiced widely in Japan. But, such recycling costs manufactures a lot and it might be difficult to achieve the sustainability by such simple combination of mass production and mass recycling. Rather, it is important to develop additional services and business opportunities throughout a product life cycle by appropriately designing and managing a product life cycle [16]. In this context, extension of product life and long-term usage of components (including reuse and upgrading) is essential.

The proposed method consists of four steps; namely, analysis of disposal causes, selection of life cycle options, modularization of the product, and determination of life cycle scenarios.

2.1 Analysis of disposal causes

The first step is to find out main disposal causes of an existing target product by using the disposal cause analysis matrix. “Disposal cause” is the reason why users throw the target product away. Disposal causes can be classified into two types. One is because of the lifetime in the traditional sense; in other words, when a product breaks down or heavily deteriorates, it is thrown away. Let us call it *physical lifetime*. On the other hand, a product is thrown away when its performance, functionality, size, or appearance cannot satisfy customer’s needs any more, although the product itself might work perfectly. Let us call it *value lifetime*. Nowadays, lifetime of many consumer products (such as computers, digital cameras, and cars) is determined by their value lifetimes rather than their physical lifetimes and this fact is one of the main causes of the environmental issues under the mass production paradigm. For example, a report [15] reveals that 60 % of reasons for consumers’ replacement of PCs is covered by value lifetime of old PCs. In other words, an objective of life cycle design is to use up artifacts until their physical lifetimes, while extending their value lifetimes by keeping or upgrading their value. We further classify disposal causes into the following five categories. We assume that this classification is general and applicable to various kinds of products.

- Physical lifetime
  - *Function Consumption*: In some products such as photo films and drinks, main functions are inevitably consumed. This is the main reason for disposal in such a product.
  - *Failure*: If a product fails or is too deteriorated physically, it will be disposed.
- Value lifetime

Table 1. Disposal cause analysis matrix

Disposal Causes (*di*)	Importance (*ri*)	Functions (*fj*): Transfer ink	Store ink	Grasp	Carry						
Function consumption	9	*Wij*	9								
Appearance	1			9	3						
Capacity & Size											
Failure	3	9	3	1	1						
Value deterioration											
Importance of functions (*rfj*)		1.93	9.64	0.96	0.46						
	Top holder	0.5		0.1		0	0.99	0	0.08	0	1.06
	Body	*Wjk*		0.8	0.5	0	0.28	0	0.73	0	1.00
	Bottom holder			0.1		0	0.02	0	0.08	0	0.10
	Ink cartridge		0.9			0	0.58	0	0	8.10	8.68
	Tip	0.5	0.1			0	1.03	0	0	0.90	1.93
	Cap				0.5	0	0.11	0	0.13	0	0.23
	Components (*ck*)					Cause-Component Matrix (*Mik*)					total (*Mk*)

- *Appearance*: Products like sports cars and dresses will be disposed, when appearance is old-fashioned.
- *Capacity & Size*: Some products like refrigerators and children's shoes will be disposed, when their capacity and/or size become too small.
- *Value Deterioration*: Products like computers and digital cameras are disposed mainly because of their value lifetime owing to very fast technological innovations.

In order to support analyzing disposal causes, we here propose "disposal cause analysis matrix." Table 1 is an example of the matrix for a ballpoint pen. This matrix is based on quality function deployment (QFD) technique [8], since QFD is one of the most popular tools to designers. The matrix consists of three sub-matrices; namely, disposal cause-function matrix, function-component matrix, and cause-component matrix. The procedure of disposal cause analysis using this matrix is shown as follows:

1. First of all, a designer assigns importance (r_i) of each disposal cause by collecting voice of customers for existing products (for instance, by using user questionnaires). Here, disposal causes are classified into the five categories described above.
2. The designer determines correlations between functions and disposal causes in the disposal cause-function sub-matrix (w_{ij}). In other words, this sub-matrix denotes how much a function (j) is related to a disposal cause (i).
3. Importance (rf_j) of each function to the product disposal is calculated by using Equations (1) and (2). If the value of rf_j is high, the function j is critical to the disposal and, therefore, such functions are selected as objectives of design modification.

$$rf_j = \sum_i (r_i \times w'_{ij}) \tag{1}$$

$$w'_{ij} = \frac{w_{ij}}{\sum_j w_{ij}} \tag{2}$$

4. The function-component sub-matrix (w_{jk}) denotes correlations between components and functions; in other words, how much a component (k) contributes to a function (j). For example, in Table 1, the function "Transfer ink" is performed by the components "Top holder" and "Tip," and their contributions are equal. In this research, we assume that the product designer knows the correlations between components and functions well and,

therefore, it is easy to describe this sub-matrix.

5. With the above-mentioned data, the cause-component sub-matrix (M_{ik}) is calculated by using Equation (3). This sub-matrix represents importance (m_{ik}) of each pair of a disposal cause and a component to overall disposal of the target product.

$$m_{ik} = r_i \times \sum_j (w'_{ij} \times w_{jk}) \qquad (3)$$

In this way, the designer can easily understand important and unimportant pairs of disposal causes and components by constructing the disposal cause analysis matrix. In the example of the ballpoint pen, Table 1 denotes that the main cause of the ballpoint pen is "function consumption" as shown in r_i, and the main design target is the pair of "function consumption & ink cartridge" as shown in M_{jk}.

2.2 Selection of life cycle options

In this second step, a designer picks up important pairs of disposal causes and components from the disposal cause analysis matrix and selects appropriate life cycle options.

First, by using the cause-component sub-matrix (M_{ik}), the designer selects the important pairs that have higher m'_{ik} values in Equation (4), so as to satisfy Equation (5). These selected pairs (R) are primary targets of design modification. Here, we assume that the threshold t_R is given by the designer.

$$m'_{ik} = \frac{m_{ik}}{\sum_{i,k} m_{ik}} \qquad (4)$$

$$\sum_{(i,k)\in R} m'_{ik} \geq t_R \qquad (5)$$

Table 2 represents result of the pair selection in the example with $t_R = 60\%$. As shown in this table, the pair of "function consumption & ink cartridge" is selected.

For each selected pair, the designer assigns one or more appropriate life cycle options. "Life cycle options" are circulation options of products and components including so-called end-of-life options [5], maintenance, and upgrading. In this paper, we set up basic rules for selecting life cycle options as follows:

1. If the disposal cause of the selected pair is physical lifetime (*viz.,* function consumption and failure), the component of the pair should be replaced or repaired in maintenance or remanufacturing processes.
2. If the cause is value lifetime (*viz.,* appearance, capacity & size, and value deterioration), appropriate life cycle options are upgrading maintenance or upgrading remanufacturing, because upgrading of the product value is indispensable.

Table 2. Main disposal causes and reuse candidates of ballpoint pen

Main disposal cause pairs

Disposal cause	Component	Importance	Accumulated importance
Function consumption	Ink cartridge	62%	62%
Failure	Tip	8%	70%
Failure	Top holder	8%	78%
Function consumption	Tip	7%	85%
Appearance	Body	6%	90%
Other reasons		10%	100%

Reuse candidates

Component	Importance	Accumulated importance
Bottom holder	1%	1%
Cap	2%	3%
Body	8%	10%
Top holder	8%	18%
Tip	15%	33%
Ink cartridge	67%	100%

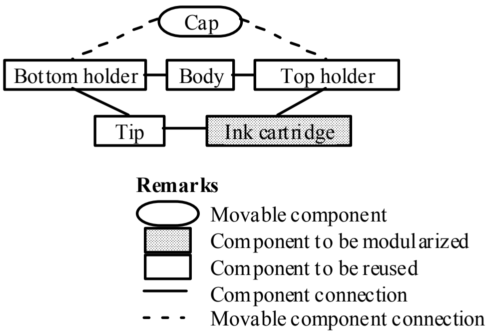

Figure 1. Component connectivity graph of ballpoint pen

Table 3. Function commonality of components in ballpoint pen

	Top holder	Body	Bottom holder	Ink cartridge	Tip	Cap
Top holder		0.47	0.29	0	0.83	0
Body	0.47		0.64	0	0	0.56
Bottom holder	0.29	0.64		0	0	0
Ink cartridge	0	0	0		0.67	0
Tip	0.83	0	0	0.67		0
Cap	0	0.56	0	0	0	

3. On the other hands, components that are not related to important disposal causes are good candidates for reuse, since quality of these components is not critical. This method represents them as components that have smaller values of m'_k defined in Equation (6).

$$m'_k = \frac{\sum_i m_{ik}}{\sum_{i,k} m_{ik}} \quad (6)$$

4. Finally, disposed products and components should be sent to material recycling, energy recovery, or appropriate dumping. Selection of these options is not the main target here.

In the example of the ballpoint pen, selected life cycle options include remanufacturing of the product with replacing ink cartridge and reuse of bottom holder, cap, body, and top holder.

2.3 Modularization of the product

Next, the method derives candidates of basic modular structure of the product in order to increase reusability and replaceability of components. While various approaches are proposed for modularization (*e.g.,* [6]), we here take a simple approach (note that this is only one of various approaches for encouraging the designer to consider modular structure of the product). Namely, 1) components related to each disposal cause are modularized for increasing replaceability and 2) components of reuse candidates are grouped from the viewpoint of functionality. The latter is based on our assumption that if two components perform a same function, they should put into the same module for making disassembly and inspection in reuse process easy. This commonality is calculated from the component-function sub-matrix (W_{jk}). Namely, we define functional commonality $CC(a,b)$ of components a, b as shown in Equation (7), where, j is a function and $w_{jk} \in W_{jk}$. And Equation (8) defines functional commonality of a set of components (P), where $n(P)$ denotes number of components in P. The designer determines basic modular structure of the product by using these indicators.

$$CC(a,b) = \frac{\sum_{j \in Z} w_{ja} + \sum_{j \in Z} w_{jb}}{\sum_j w_{ja} + \sum_j w_{jb}} \quad (Z = \{j \mid w_{ja} \neq 0 \wedge w_{jb} \neq 0\}) \quad (7)$$

$$CC(P) = \frac{\sum_{i,j \in P} CC(i,j)}{{}_{n(P)}C_2} \quad (8)$$

For example, Figure 1 and Table 3 denote a part connectivity graph of the ballpoint pen and functional commonality of two components, respectively.

Table 4. Candidates of life cycle scenarios of ballpoint pen

Main Disposal Cause Pairs	Cause	Component	Importance
A1	Function consumption	Ink cartridge	62%
A2	Failure	Tip	8%
A3	Failure	Top holder	8%
Life Cycle Options	Component	Option	
B1	Ink cartridge	Maintenance	
B2	Ink cartridge	Remanufacturing	
B3	Bottom holder, Cap, Body, Top holder	Reuse	
Component Replacement	Component set		commonality
C1	Ink cartridge (replace)		-
C2	Ink cartridge (refill ink)		-
C3	Ink cartridge, Tip (modularize)		0.67
Modularlization	Component set		commonality
D1	Tip, Top holder		0.83
D2	Tip, Top holder, Body		0.43
D3	Tip, Top holder, Body, Bottom holder		0.37
D4	Top holder, Body		0.47
D5	Top holder, Body, Bottom holder		0.47
D6	Body, Bottom holder		0.64

2.4 Determination of life cycle scenarios

As the result of this method, the designer achieves candidates of main disposal cause pairs, life cycle options, components to be replaced, components to be reused, and modular structure. Therefore, by choosing appropriate candidates, the designer can easily determine life cycle scenarios of the target product.

In the example of the ballpoint pen, the result of this method is summarized as shown in Table 4. In this table, while main disposal cause pairs and life cycle options are derived from the disposal cause analysis matrix, the designer should decide components to be replaced and basic modular structure based on the information given by this method. Nevertheless, this paper claims that it is very useful for supporting determination of life cycle scenarios to require designers to make tables like Table 4.

As the final step of the proposed method, the designer selects the most appropriate candidates from the table. In the case of the ballpoint pen, A1, B2, B3, C1, D1, and D6 are, for example, selected as a life cycle scenario.

3. Case Study

In order to clarify advantages and feasibility of the proposed method, we applied it to some examples including a ballpoint pen, a cellular phone, a camera, and a single use camera. Among them, this section describes a case study of a cellular phone. Note that the data shown in this section, including product data and importance of disposal causes, are hypothetical.

Table 5 shows the resulting disposal cause analysis matrix of the cellular phone. And Table 6 lists main disposal cause pairs and reuse candidates. As shown in Table 6, assuming $t_R = 60\%$, the main disposal causes are appearance of body and display and value deterioration of CPU board, display, and battery. On the other hand, candidates of reuse components are external connector, speaker, microphone, battery charger, antenna, and keypad. This result and functional commonality of components of the cellular phone (see Table 7) leaded the designer to candidates of life cycle scenarios shown in Table 8. Table 8 suggests two main life cycle

Table 5. Disposal cause analysis matrix of cellular phone

Disposal Causes	Importance	Functions																	
		Send/receive radio wave	Input sound	Output sound	Display info.	Type number	Memorize number	Search number	Set options	Connect to PC	Control	Store electricity	Form appearance						
Function consumption																			
Appearance	9				3								9						
Capacity & Size	3	3			3	3						9	3						
Failure	1					3					3	9	1						
Value Deterioration	9		1	1	9		3	3	9	1		9	9						
Importance of functions		0.43	0.20	0.20	4.48	0.62	0.60	0.60	1.80	0.20	0.19	3.65	9.04						
	Antenna	0.7											0.1	0.18	0.01	0.34	0.68	0	1.20
	Key pad					0.5	0.2	0.2	0.2				0.1	0.78	0.10	0.26	0.68	0	1.81
	Display				0.7	0.2	0.1	0.1	0.1				0.2	1.92	0.05	0.47	2.93	0	5.37
	Body												0.6	1.08	0.04	0.26	4.05	0	5.42
	Speaker			0.7										0.14	0	0	0	0	0.14
	Microphone		0.7											0.14	0	0	0	0	0.14
	Battery	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.7		1.80	0.43	1.03	0.23	0	3.48
	Batt. charger											0.3		0.54	0.17	0.39	0	0	1.09
	Ext. connector									0.6				0.12	0	0	0	0	0.12
	CPU board	0.2	0.2	0.2	0.2	0.2	0.6	0.6	0.6	0.3	0.9			2.30	0.21	0.26	0.45	0	3.21
	Components													Cause-Component Matrix					total

scenarios of this product. One is upgrading remanufacturing scenario in which display, CPU board, and body are replaced in a remanufacturing process and no modular structure is employed in order to increase upgradability. In this case, A1-A5, B1, B7, C6, and D4 are chosen from the table. The other is upgrading maintenance scenario in which display and CPU board are modularized and replaced at user sites. Modular structure is employed for increasing replaceability at user sites in this scenario: namely, A1-A5, B1, B7, C3, C6 and D3 are chosen in this case. Here, C6 implies that the body is decomposed into a frame that supports the whole product and a shell that makes appearance of the product in order to modularize reusable components (D3).

4. Discussions

Section 3 clarified how the proposed method supports the designer to determine life cycle scenarios. Advantages of the proposed method include: 1) designers can systematically derive candidates of life cycle scenarios and 2) objectives of design modification vary according to selected scenarios. Here, we conclude that five categories of disposal causes described in Section 2.1 are general enough, regardless of product kinds. And, this method suggests that, for encouraging designers to examine life cycle scenarios at the early stage of life cycle design, it might be useful to describe disposal causes in the form of the disposal cause

Table 6. Main disposal causes and reuse candidates of cellular phone

Main disposal cause pairs

Disposal cause	Component	Importance	Accumulated importance
Appearance	Body	18%	18%
Appearance	Display	13%	32%
Value Deterioration	CPU board	10%	42%
Value Deterioration	Display	9%	51%
Value Deterioration	Battery	8%	59%
Value Deterioration	Body	5%	64%
Capacity & Size	Battery	5%	69%
Value Deterioration	Key pad	4%	72%
Appearance	Antenna	3%	75%
Appearance	Key pad	3%	78%
Other reasons		22%	100%

Reuse candidates

Component	Importance	Accumulated importance
Ext. connector	1%	1%
Speaker	1%	1%
Microphone	1%	2%
Batt. charger	5%	7%
Antenna	5%	12%
Key pad	8%	21%
CPU board	15%	35%
Battery	16%	51%
Display	24%	75%
Body	25%	100%

Table 7. Functional commonality of cellular phone

	Antenna	Key pad	Display	Body	Speaker	Microphone	Battery	Batt. charger	Ext. connector	CPU board
Antenna		0.10	0.14	0.50	0	0	0.32	0	0	0.19
Key pad	0.10		0.73	0.39	0	0	0.52	0	0	0.60
Display	0.14	0.73		0.40	0	0	0.55	0	0	0.63
Body	0.50	0.39	0.40		0	0	0	0	0	0
Speaker	0	0	0	0		0	0.33	0	0	0.19
Microphone	0	0	0	0	0		0.33	0	0	0.19
Battery	0.32	0.52	0.55	0	0.33	0.33		0.50	0.30	0.88
Batt. charger	0	0	0	0	0	0	0.50		0	0
Ext. connector	0	0	0	0	0	0	0.30	0		0.20
CPU board	0.19	0.60	0.63	0	0.19	0.19	0.88	0	0.20	

Table 8. Candidates of life cycle scenarios of cellular phone

Main Disposal Cause Pairs	Cause	Component	Importance
A1	Appearance	Body	18%
A2	Appearance	Display	13%
A3	Value Deterioration	CPU board	10%
A4	Value Deterioration	Display	9%
A5	Value Deterioration	Battery	8%
Life Cycle Options	Component	Option	
B1	Body, Display, CPU board, Battery	Upgrading	
B2	Body, Display, CPU board, Battery	Upgrade remanufacturing	
B3	Body, Display, CPU board	Upgrading	
B4	Body, Display, CPU board	Upgrade remanufacturing	
B5	Body, Display	Upgrading	
B6	Body, Display	Upgrade remanufacturing	
B7	Ext. connector, Speaker, Microphone, Batt. Charger, Antenna, Key pad	Reuse	
Component Replacement	Component Set		Correlation
C1	Body, Display, CPU board, Battery (modularize)		0.41
C2	Body, Display, CPU board (modularize)		0.34
C3	Display, CPU board (modularize)		0.63
C4	Body, Display (modularize)		0.4
C5	Body (Add cover on Body)		-
C6	Body (Decompose Body into Frame and Shell)		-
Modularlization	Component Set		Correlation
D1	Antenna, Key pad, Frame		0.33
D2	Speaker, Microphone, Frame		0.00
D3	Antenna, Key pad, Speaker, Microphone, Ext. connector, Frame		0.07
D4	No modularization		-

analysis matrix and candidates of life cycle scenarios in the form of the tables like Table 8. Finally, the designer can use this method easily since it is very simple. Indeed, some design researchers of different companies evaluated that this method is feasible enough and very useful to achieve a consensus among project members at the planning stage of product design. Moreover, a company started to use this method in their life cycle planning process [10].

There exist several research efforts related to this work. Masui *et al.* [9] proposed a QFD based environmentally conscious design support tool called QFDE. This tool is useful for clarifying and weighting elemental requirements for environmental consciousness. Wimmer [11] proposed a checklist-based tool for ecodesign. Ishii [5] clarified relationship between product characteristics and appropriate life cycle options. Kobayashi [10] also proposed a similar relationship and a decision support tool for life cycle planning. Our approach has some similarity to these approaches (namely, Ishii and Kobayashi) in terms of classification of life cycle options, but our distinctive features include: 1) our approach focuses on "disposal causes" of existing products and 2) the proposed method provides designers a simple but systematic tool for determining life cycle scenarios based on the disposal causes. However, since our approach aimed at developing a *simple* tool, it has some issues to be solved:

- Modularization
  While the proposed method suggests some hints to modularization, it is very simple and does not show concrete modular structure. There exist research efforts on modularization including Fujita *et al.* [12] and Ishii [6]. We have also proposed an approach based on genetic algorithm [13]. Designers should use these approaches in order to derive more concrete modular structure from various perspectives.
- Bottom-up approach vs. top-down approach
  Since we employed a bottom-up approach starting from analysis of existing products, it might be difficult for designers to find out *very* innovative design solutions with the proposed method, such as "Service Oriented Products" [14]. This might be essential limitation of this method and designers should use both of this method and some top-down approaches that can find out innovative solutions.
- Arbitrariness in disposal cause analysis matrix
  Like the traditional QFD methodology, results of the method are affected by intuitiveness and arbitrariness in disposal causes analysis matrix, more specifically, weights of disposal causes, correlation between disposal causes and functions, and correlation between functions and components. Nevertheless, this issue is not very critical, because the primary goal of the method is to provide a tool for designers to examine life cycle scenarios at the early stage of life cycle design by trial and errors.
- Lifetime of components
  While physical and value lifetimes of components are important disposal causes, they are not considered in determining life cycle options. For example, a component that has a short physical lifetime cannot be reused even if it is selected as a reuse candidate in the method. Incorporating the aspect of lifetime is one of our future issues.
- Evaluation of selected life cycle scenarios
  One of main issues of our method is that it does not evaluate the final life cycle scenario generated by the designer. Merits can be evaluated by comparing a new disposal cause analysis matrix with the initial one. This is also one of our future issues.

5. Conclusions

This paper proposed a decision support method for determining life cycle scenarios using disposal cause analysis matrix. The basic idea is that if a designer modifies design of a product so as to mitigate disposal causes, this will results in extension of product life and long-term usage of components. By formalizing this idea as the disposal cause analysis matrix, this method offers a simple and easy tool to designers. Case studies clarified feasibility of this method and design researchers positively evaluate this method. Future issues include practical usage of the method, usage of lifetime information, and development of evaluation methods for selected life cycle scenarios.

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