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Building Interoperable System Enabling Failure Information Knowledge Sharing between Designing/Manufacturing and Maintenance Departments Focusing on Information Architecture Differences

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ABSTRACT

Recent years have seen a shortening of product lifecycles and a trend toward product optimization for individual customers, but at the same time, development and maintenance departments have become increasingly global in scope making it difficult to improve product quality in the market. Against this background, the need has been felt for a system that can make efficient use of failure information knowledge accumulated for different products and by different departments to improve maintenance response and prevent reoccurring failures. Although advances in information processing technology have driven the evolution of practical information -storage and information -retrieval systems, the search performance of an interoperable system handling failure information knowledge across different products and departments suffers from many problems in terms of effectiveness and efficiency if using the standard keyword search method. This paper proposes a new information retrieval system focusing on information architecture differences between departments and presents the results of evaluating an actual failure information system using this system.

KEYWORDS

information architecture, FMEA, information foraging, failure information, knowledge sharing

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1. Introduction

Advances in information processing technology have enabled the storage and application of much information, and many information retrieval systems for efficiently accessing this information have come into use. The Internet has contributed greatly to the development of society through the storage and use of massive amounts of information. Nevertheless, there are many information retrieval systems that do not necessarily function well, such as systems used by design and manufacturing departments to access failure information stored in a maintenance department (referred to below as "failure information retrieval system"). In many companies, failure information obtained from users and stored in the maintenance department can be extremely valuable to the design and manufacturing departments at the time of product development since it can help in preventing failures from reoccurring in the market. Problems have arisen, however, in achieving efficient use of this information.

Denoting a group of information created for some purpose as "content," these problems originate in the mechanism used for propagating such content from one person to another. Each site on the Internet can be treated as content, as can a customer's report of a failure in a failure information retrieval system. Two issues, in particular, arise in the process of propagating information in content form from one person to another: comprehension of information expressions in content and search performance of content that expresses information. For the first issue, it is thought that comprehension comes down to the abilities of the content creators and content users, and for the second issue, that search performance greatly depends on the information retrieval system itself. The focus of our research is not on improving comprehension by creating contents in a certain manner but on achieving effective use of contents that has already been created through an appropriate information retrieval system.

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Why is it that successful information retrieval systems such as the Internet exist while there are some systems such as for failure information retrieval that do not necessarily function well? We consider the difference between such successful and unsuccessful systems to lie in the extent to which the information architecture of the content provider differs from that of the user. On the Internet, content is generally created with user needs in mind with the result that differences in information architecture between the provider and user are small. A defect information retrieval system, in contrast, consists of content that places priority on responding to customer -reported failures. As a result, differences in information architecture between the provider and user can be significant.

What kind of Human Centered Design should be used as a cornerstone to improve search efficiency in an information retrieval system in which information architecture differences between the content provider and user are great? In this study, we first analyze the reasons as to why efficient searches cannot be performed by standard keyword searching specifically in a failure information system. Then, with the aim of improving search efficiency in an information retrieval system in which information architecture differences between the provider and user are great, we seek to answer the above question from the viewpoint of information foraging theory[1][2].

This paper is organized as follows. Section 2 analyzes the problems with the keyword search method in information retrieval having major information architecture differences. Section 3 models the search process and proposes a search method based on abstract concepts. Section 4 evaluates and discusses the search performance of a defect information retrieval system using both methods. Finally, Section 5 summarizes the findings of this study.

2. Problems with the Keyword Search Method in Information Retrieval having Major Information Architecture Differences

2.1. Differences in information architecture

Failure Mode and Effect Analysis (FMEA) is a technique commonly used in design and manufacturing processes in the manufacturing industry. An example of a record in a FMEA system as commonly used in design departments is shown in Fig. 1. Please see Ref. [7] for more details on FMEA. In actuality, a FMEA record also includes items such as failure mode impact and frequency, but since these items are not used at the time of searching, we omit them in this study. Here, each FMEA record is referred to as "content." An example of a defect report as issued by the maintenance department is shown in Fig. 1(b). Although format and item descriptions may differ between companies and departments due to the lack of common specifications, the items making up a failure report are commonly "phenomenon," "cause," "countermeasure," and "details."

	Part	**Failure Mode**	**Cause**	**Countermeasure**
Content X	LED	burned out	error in rated design	revise design standard
Content Y	S3D2	measurement error	calibration error	Revise Standard operation Procedure

(a) Typical FMEA records

	Content A	**Content B**	**Content C**	**Content D**
Phenomenon:	Abnormal operation in measuring part	LED on main unit not flashing	Problem in oscillating -circuit display	Power -supply problem in LED strip
Cause:	Design error in cam mechanism	Damage due to poor design	LED damaged	Installation error; LED is OK
Countermeasure:	Replace part	Replace board	Redesign board	Repair
Details:	*Numerical data*	*Pictures, text*	*Text*	*Illustrations*

(b) Example of Failure Reports

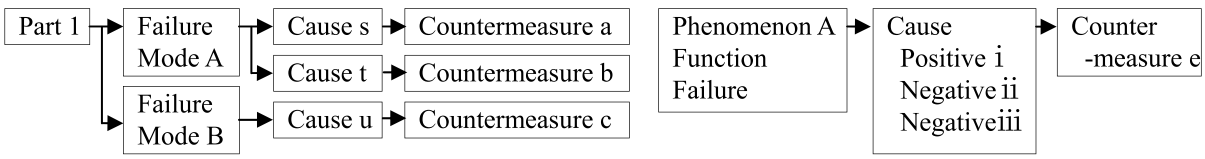
Fig. 1. Information architecture of FMEA and failure report

The FMEA process seeks to assign a relationship between each record and previously generated failure information. The ability to efficiently search for cases related to each FMEA record in maintenance department failure reports is therefore of great importance. In Fig. 1, Content B and Content C in the failure report are related to Content X in FMEA records in Fig. 1 (a), but since information architecture differences between the two are significant, correct search results may not be obtained by the standard keyword search method. We therefore decided to analyze the differences between the information architectures of FMEA records and failure reports and to analyze the problems with the standard keyword search method in information retrieval systems in which information architecture differences are great.

There are six main elements that form the information architecture of content: item, description, format, perspective, viewpoint, and fluctuation. There are various types of items, such as explicit and implicit, depending on how the content is configured. There are also various types of relationships between items, such as parallel, hierarchical, and supplementary. A description provides more detailed information on an item, and restrictions on the form that descriptions can take depend on the type of content. Format refers to the method of expressing a description, and in addition to media like texts, figures and tables, graphics, audio, and video, there are also bullets, word lists, detailed explanations, etc. Perspective is the scope of expressing a description. It may be explicit, implicit, or not indicated at all. Viewpoint, meanwhile, pertains to the person conveying the description, and includes standpoint, stature, and competence. Fluctuation refers to variety in expression and notation and to the level of description.

2.1.1. Differences in items

A FMEA record centers about a particular part and includes failure mode, cause, and countermeasure as described above. A number of failure modes can exist for the part in question, and each failure mode may be accompanied by more than one cause and countermeasure. In a failure report, a record centers about a phenomenon and includes causes, countermeasures, and detailed descriptions.

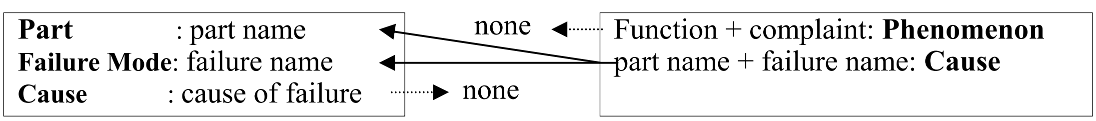


(a) FMEA items **(b) Failure Report items**

Fig. 2. Differences in FMEA and Failure Report items

2.1.2. Differences in description

In a FMEA record, the cause field describes what caused the failure to occur. A record in a failure report, on the other hand, frequently describes a complaint about functional failure as a phenomenon, and in the cause field, describes the part failure that caused that functional failure to occur. It is not uncommon for “cause” in a failure report to span multiple FMEA items. Furthermore, as shown in Fig. 2(b), “cause” in a failure report can include not only positive causes but also negative causes as a result of investigating causes that may give rise to the phenomenon in question.



(a) FMEA description **(b) Failure Report description**

Fig. 3. Differences in FMEA and Failure Report description

2.1.3. Differences in format

A FMEA record is usually described in short, concise sentences consisting of words and numerical data, while a failure report is often described in a relatively free format using figures, tables, and other media.

2.1.4. Differences in perspective

In FMEA, a record is commonly described taking all related products into account as reflected by the entry "revise design standard," while a record in a failure report is often limited to just the part in which the failure occurred as reflected by the entry "replace part."

2.1.5. Differences in viewpoint

A FMEA record is commonly described using specialized terminology from the viewpoint of a designer. A defect report, in contrast, is often described using simple and highly abstract expressions focusing on functional complaints from the viewpoint of the customer.

2.1.6. Differences in fluctuation

Fluctuation in expressions and notation exist in both FMEA and defect reports, and in either case, there is a strong tendency to use compact expressions, but regularity varies with the individual. Description level is also non -uniform; regularity here is often difficult to find.

2.2. Problems with the keyword search method

When searching for content having major differences in information architecture as in the case of FMEA and failure reports as described above, three problems with the keyword search method can significantly degrade search performance.

The first problem is keyword context mismatch that results from the fact that the same keyword can be used in various contexts. When a certain keyword is used in an unessential section of content, many instances of content with low equivalency will appear in the list of results generated by that keyword. In Fig. 4, the list of results generated by the keyword "LED" includes Content D in which this keyword is used in the unessential context of "power -supply of LED strip." In addition, the description of negative causes, which reflects differences in description among other differences in information architecture, is a major factor behind the problem of keyword context mismatch.

"LED" = { Content B : LED on main unit not flashing, Content D : Power -supply problem in LED strip}

Fig. 4. Example of keyword context mismatch

The second problem is keyword expression mismatch in which instances of content with high equivalency are expressed by different keywords. It cannot be denied that contents with high equivalency can exist outside a generated list of contents, which is a major factor behind failed searches. In Fig. 5, the expression "burned out" is used in Content X in Fig. 1(a), but in Content B and Content C, the expression "damaged" is used. This mismatch results in a failed search. The source of this problem often lies in the specialized and abstract terminology that is used, which reflects differences in viewpoint among other differences in information architecture.

"burned out" = Φ

Fig. 5. Example of keyword expression mismatch

The third problem is the compound keyword, which, as the name implies, originates in the use of a compound term as keyword. In Fig. 6, the compound term “design error” will generally be broken down into two words in the manner of “design ∨ error”, “∨” is OR operation. This results in the retrieval of Content D having the expression “installation error,” which is totally irrelevant. On the other hand, if “design ∧ error”, “∧” is AND operation, were to be intentionally specified, Content B and Content C would fail to be retrieved. There is a great tendency for search performance to drop as a result of such differences in fluctuation between FMEA and defect reports.

“design error” → “*design*” ∨ ”*error*” = {
Content A：*design error*,
Content B：poor *design*,
Content C：re*design* board,
Content D：installation *error*
}

Fig. 6. Example of compound keyword problem

3. Search Technique Taking Information Architecture Differences into Account

In the previous section, we showed why the standard keyword search method is not very good at retrieving information in a system having major information architecture differences. Information foraging theory[3][4][5][6] suggest that more efficient searching can be performed by treating the target search space as an aggregate of many partial sets rather than one total set. In our study, we propose a technique that, instead of directly performing a keyword search on the target search space, performs searching only after comprehensively examining and classifying that space with the aim of improving search performance.

3.1. Model of search process

In the following, contents obtained by searching is called “target contents” and information used to judge whether retrieved target contents are actually the contents needed is called “a base content.” In addition, the set of contents belonging to conceptual space expressed by some concept is called “content set based on a concept mark.” In Fig. 1, Content X in FMEA records is a base content and Content A, Content B, Content C, and Content D are a content set based on the concept mark “failure report in a department”. Furthermore, if a content set based on a newly formed concept mark should be generated within an existing content set based on a concept mark, the latter is called a total set and the former a partial set. The list of results produced by a search is a partial set generated from the total set of target contents. Analyzing information in multiple instances of contents and evaluating its equivalency in terms of meaning is called analytical discrimination, and evaluating the equivalency of concept marks in contents is called comprehensive discrimination.

The contents search process can be modeled by the following sequence of actions. The process begins by generating concept marks through concept formation based on information in a base content. It then generates partial sets of target contents having high conceptual equivalency as determined by comprehensive discrimination applied to the total set of target contents. The process then performs analytical discrimination against each instance of target contents included in these partial sets to find as much target contents as possible having high equivalency with the base content.

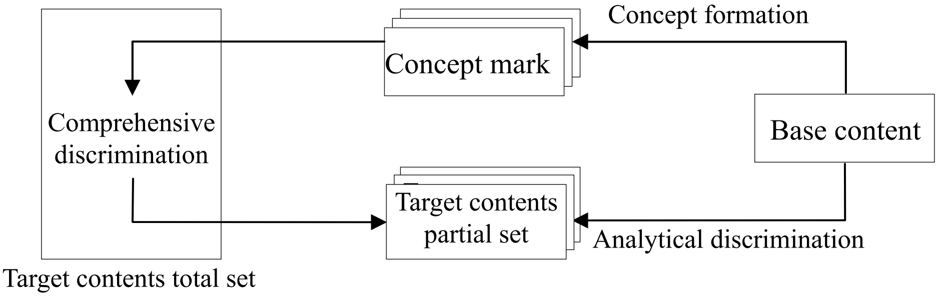


Fig. 7. Model of search process

Here, contents search time is the sum of concept -formation time, comprehensive -discrimination time, and analytical discrimination time.

$$ST = CT + GT + AT = \sum_{i=1}^{N} (ct_i + gt_i + \sum_{j=1}^{mi} at_{ij})$$

ST: Contents Search Time
CT: Total Concept -formation Time
GT: Total Comprehensive Discrimination Time
AT: Total analytical Discrimination Time
ct_i : Concept -formation Time per Repetition
gt_i : Comprehensive Discrimination Time per Repetition
at_j : Analytical Discrimination Time per One Instance of Contents
m_i : Number of Instances of Contents to be Subjected to Analytical Discrimination among the Partial Sets of Target Contents with Respect to a Certain concept
N : Number of Repetitions

In the above, concept formation takes up a relatively short time (CT is small). Comprehensive discrimination, meanwhile, is a principal function provided by search systems, and in many cases, it is automated as the main function of an information retrieval system. Analytical discrimination, in contrast, depends on the objectives, knowledge, and experience of users, and is rarely automated. To do so requires many man -hours. We therefore consider a strategy for minimizing as much as possible AT, the dominant element of ST.

3.2. Search by classification based on abstract concept formation

We apply information foraging theory as proposed by Pirolli et al.[5][6][7] as a strategy to minimize total analytical discrimination time in the search process model. Information foraging theory applies the ideas of optimal foraging theory in biology to information retrieval behavior in humans. It consists of the following three models:

- Information Patch Model
  Should a searcher continue foraging in the current information site or move on to the next one?
- Information Scent Model
  How does a searcher obtain cues or hints for foraging?
- Information Diet Model
  Which foraging candidate out of many should be selected?

In this study, we apply the idea behind IP to information retrieval systems, propose a search -by -classification system based on abstract concept formation, and analyze the effectiveness of this system. Here, the process of forming concepts by the abstraction of descriptions included in contents is called “abstract concept formation.” Instead of performing a search on the total set of target contents straight away by keywords, we first classify information patches by abstract concepts and then search within those patches.

In this way, the base content and total set of target contents in Fig. 1 can be classified as shown in Table 1.

Table 1 Classification of defect reports by abstract concept formation

	Design induced	Assembly induced
Electrical performance	Content X Content B Content C	Content D
Mechanical performance	Content A	

Referring to the table, Content B, Content C, and Content D, while not equivalent by analytical discrimination, are equivalent by comprehensive discrimination in terms of the concept mark [electrical performance] by abstract concept formation. Similarly, Content A, Content B, and Content C are equivalent by comprehensive discrimination in terms of the concept mark [design induced] by abstract concept formation.

concept mark: [electrical performance] = { Content B, Content C, Content D }

(a) Partial set generated by concept mark [electrical performance]

concept mark: [design induced] = { Content A, Content B, Content C }

(b) Partial set generated by concept mark [design induced]

Fig. 8. Examples of concept marks by abstract concept formation

Partial sets of target content generated by concept marks through abstract concept formation can result in many items of contents with high equivalency when subjected to analytical discrimination with a base content. On the other hand, when performing analytical discrimination among a base content and target contents outside of the generated partial sets, the probability of finding contents with high equivalency is low. Abstract concept formation enables target search space to be limited. Lowering the level of abstraction in a stepwise manner and combining abstract concepts enables target content with high equivalency to be isolated with a low miss rate.

concept mark: [electrical circuit $\wedge$ design induced] = {Content B, Content C}

Fig. 9. Example of isolating target contents by abstract concept formation

3.3. Comparison of keyword search and search by classification based on abstract concept formation

The process of keyword concept formation typically examines a base content in an analytical manner and extracts keywords. Keyword extraction itself is relatively easy, and search performance by keyword searching is high when searching against sets of contents having small differences in information architecture. On the other hand, search performance is low between sets of contents having large differences in information architecture in which the problems of keyword context mismatch and keyword expression mismatch can easily occur. In this case, the number of attempts at keyword extraction in a trial -and -error process increases and the probability of finding correct results decreases.

Abstract concept formation comprehensively recognizes the total target set including a base content and generates partial sets that are conceptually close to the base content before commencing a search. If a search returns results (“food” in foraging theory), the user can now select the partial set ("feeding area" in foraging theory) corresponding to one of those results and do a detailed search. If the user is not satisfied with the information in that partial set, the user can then move to another partial set to investigate further. This behavior is analogous to foraging theory. Please see "Quality Feedback Model for Trouble Recurrence Prevention" for details on a method for conceptualizing and automatically classifying words extracted from documents using a semantic network [8][9][10][11][12].

4. Evaluation and Discussion of Proposed Search Technique

4.1. Data used in experiment

In this experiment, we used a claim information system (CIS) storing defect information on more than 100 types of industrial electronic equipment as a maintenance department's defect information system, and took 200 defect entries from this system as a total set of target content. We also used FMEA on certain industrial electronic equipment as a design department's FMEA system, and treated 6 records from this system as search -base content. These FMEA records are shown in Table 2. Note that only the record items "Part," "Failure Mode," and "Cause" used in actual searches are included in this table.

Table 2 FMEA records used in experiment

Task No.	Part		Failure Mode	Cause
T1	Display circuit		Mishandling	Not described
T2	Switch		Lifetime	Not described
T3	Label	Name plate	Assembly error	Not described
T4	Power circuit	IC	Mishandling	Damaged by thermal stress
T5	Switch		Other	Low design margin
T6	Signal –line	Connector	Manufacturing failure	Wrong part

Table 3 shows the classification based on abstract concept formation. There are 2 large classifications which are "Cause" and "Phenomenon" and they are not mutually exclusive. The large classification "Cause" is classified into "Manufacturing", "Design", "Part", "Transporting" and "Usage", which are mutually exclusive within the large classification "Cause". The large classification "Phenomenon" is classified into "Unstable behavior", "Operation error", "Display failure", "External failure" and "Structural failure", which are also mutually exclusive within the large classification "Phenomenon". Table 3 is given to subjects in experiments.

We classified automatically the 200 items of CIS into the ten concept marks with a software we developed. In the software, the method described in 3.3 was implemented. It took about 20 minutes to classify the 200 items.

Table 3 Classification based on abstract concept formation

Large Classification	Small Classification	Description
Cause	Manufacturing	Defects occurred in manufacturing process
	Design	Defects occurred in design process
	Part	Defects of parts
	Transporting	Defects occurred in packaging/transporting process
	Usage	Errors in operation by users
Phenomenon	Unstable behavior	Unstable behaviors of the products
	Operation error	Incorrect results
	Display failure	Displayed incorrectly
	External failure	Defects such as scratches on product surfaces
	Structural failure	Missing and/or incorrectly assembled parts

4.2. Experimental method

Four technicians from a design department were selected as subjects based on the following conditions:

1) Subject is not familiar with CIS content
2) Subject has enough domain knowledge to assess the suitability of search results

Using each row of Table 2 as search -base content, the objective of each task was to retrieve related examples from the 200 items of CIS data using the keyword search method and classification search method based on abstract concept formation. To evaluate a learning effect in the second search performed by a subject, subjects A and B perform search tasks T1, T2, and T3 by the keyword search method and the second time by the classification search method based on abstract concept formation, and search tasks T4, T5, and T6 are each performed in reverse order. Subjects C and D perform search tasks T4, T5, and T6 by the keyword search method and the second time by the classification search method based on abstract concept formation, and search tasks T1, T2, and T3 are each performed in reverse order.

4.3. Experimental environment

The experiment was performed in a standalone environment. All subjects used the same personal computer, which was equipped with a search system incorporating modules for keyword searching and search -by -classification based on abstract concept formation, 200 items of CIS data, and a stopwatch tool for measurement purposes. All other applications on the computer were disabled.

4.4. Experiment results and discussion

Experimental results for the six tasks are shown in Figs. 10 to 15 and Tables 4 to 9. Search times are shown in Figs. 10 to 15 Results for the keyword search method are shown in gray and those for the classification search method based on abstract concept formation in white. Results in black indicate incorrect search results. While there were several cases of incorrect search results for the keyword search method, all search results for the classification search method were correct. Examining only correct results, it can be seen that search time by the classification search method was shorter than that by the keyword search method in all cases.

Tables 4 to 9 show a history of the search formulas used. The letters on the left of a table identify the subjects. Each cell in a table shows a concept mark generated by concept formation and the number of partial -set elements. The number of columns represents the number of times that comprehensive judgment and analytical judgment were repeated. The numeral within ( ) signifies the number of partial -set elements in concept -formation results, the numeral within [ ] the number of elements requiring analytical judgment, and the numeral within { } the number of correct results found. Non -hatched type in the table indicates classification by keyword and hatched type indicates classification by abstract concept formation. Italic type in the table indicates partial sets for which correct results were found.

Experimental results for each task are summarized in sections 4.4.1 to 4.4.6. The results show that the number of analytical discrimination has a significant impact on overall length of search time.

4.4.1. Analysis of Task T1

For Task T1, there was only one correct case. All subjects obtained good results in terms of accuracy and search time by the classification search method. As a compound term, the part name “display circuit” resulted in many hits of unrelated examples. In addition, narrowing down the search to the keyword “display” still resulted in 56 hits requiring much analytical discrimination time. In an attempt to prevent so many hits, Subject D specified the search formula “display $\wedge$ circuit” and was able to narrow down the number of hits to 15, but still failed in retrieving a correct result. This was an example of a failed search due to compound terms in contents. In the classification search method, three subjects selected the abstract concept “usage ∧ unstable behavior” as the first search formula based on the failure mode “mishandled”, and while this selection ended in failure, the number of instances of analytical discrimination was 6 at most thereby shortening search time.

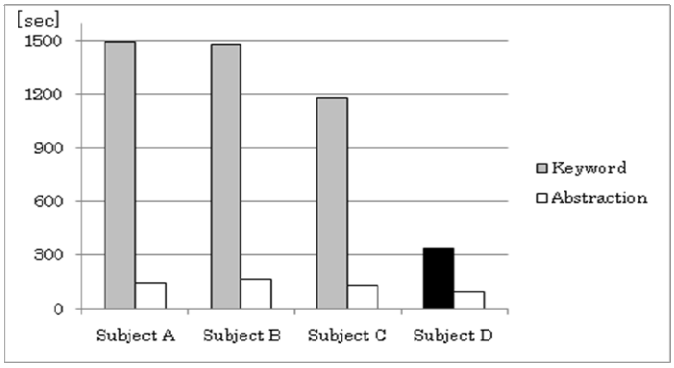


Fig. 10. Task T1 search times

Table 4 History of Task T1 search formulas

(a) Keyword search method

	1st search formula	2nd search formula	3rd search formula
A	display circuit (106)	display ∧ mistake (2)	*display[56]{1}*
B	error[9]	display circuit (106)	*display[56]{1}*
C	display circuit (106)	display ∧ mistake (2)	*display[56]{1}*
D	display circuit (106)	display ∧ circuit [15]{0}	-

(b) Classification search method

	1st search formula	2nd search formula	3rd search formula
A	usage ∧ unstable behavior [3]	*usage ∧ display failure [3]{1}*	-
B	usage ∧ unstable behavior [3]	*usage ∧ display failure [3]{1}*	-
C	usage ∧ unstable behavior [3]	*usage ∧ display failure [3]{1}*	-
D	*usage ∧ display [3]{1}*	-	-

4.4.2. Analysis of Task T2

Next, for Task T2, there was again only one correct case. Search times were good for all subjects by the classification search method. After selecting the abstract concept “part” in the classification search method, the search was narrowed by using the keyword “switch” thereby preventing the keyword context mismatch problem. The number of instances of analytical discrimination was 2 and search time was shortened.

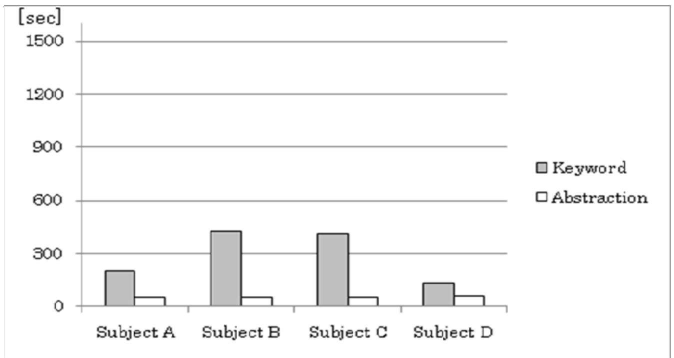


Fig. 11. Task T2 search times

Table 5 History of Task T2 search formulas

(a) Keyword search method

	1st search formula	2nd search formula
A	switch ∨ lifetime (42)	*switch ∧ lifetime [5]{1}*
B	*switch [20]{1}*	-
C	*switch [20]{1}*	-
D	*switch ∧ lifetime [5]{1}*	-

(b) Classification search method

	1st search formula	2nd search formula
A	*part(22)*	*switch [2]{1}*
B	*part (22)*	*switch [2]{1}*
C	*part (22)*	*switch [2]{1}*
D	*part (22)*	*switch [2]{1}*

4.4.3. Analysis of Task T3

For Task T3, there were two correct cases. Three subjects terminated the search after retrieving one correct case using the keyword "label" in the keyword search method. The other correct case was overlooked due to the keyword expression mismatch problem in which "name ∨ plate," another expression for "label," went unnoticed here. In the classification search method, selection of the abstract concept "manufacture ∧ external failure" resulted in 3 instances of analytical discrimination enabling retrieval of all two correct cases in a short time.

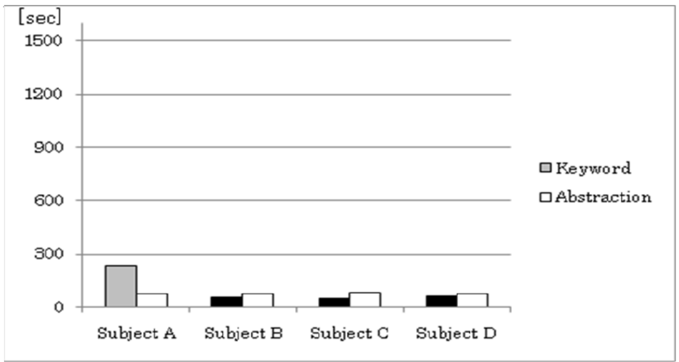


Fig. 12. Task T3 search times

Table 6 History of Task T3 search formulas

(a) Keyword search method

	1st search formula	2nd search formula
A	*label [2]{1}*	*name ∨ plate [3]{1}*
B	*label [2]{1}*	-
C	*label [2]{1}*	-
D	*label [2]{1}*	-

(b) Classification search method

	1st search formula	2nd search formula
A	*manufacturing ∧ external failure [3]{2}*	-
B	*manufacturing ∧ external failure [3]{2}*	-
C	*manufacturing ∧ external failure [3]{2}*	-
D	*manufacturing ∧ external failure [3]{2}*	-

4.4.4. Analysis of Task T4

For Task T4, there were three correct cases. Search times were good for all subjects by the classification search method. With the keyword search method, there were 12 instances of analytical discrimination by the search formula "power circuit ∧ IC." However, after forming the abstract concept "usage ∧ operation error", the keyword context mismatch problem caused by the search formula "power circuit ∧ IC" was avoided resulting in only 5 instances of analytical discrimination and the shortening of search time.

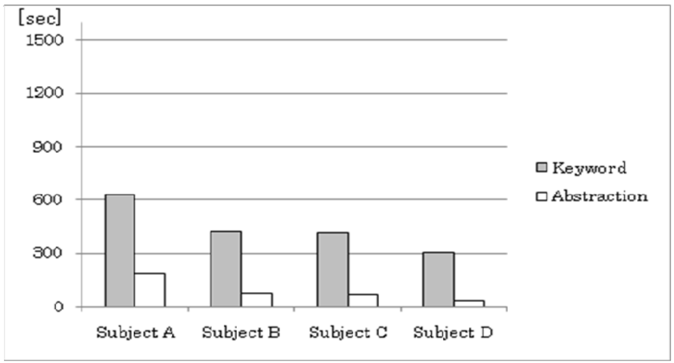


Fig. 13. Task T4 search times

Table 7 History of Task T4 search formulas

(a) Keyword search method

	1st search formula	2nd search formula	3rd search formula
A	power circuit (118)	*power circuit ∧ IC [12]{3}*	-
B	power circuit (118)	*power circuit ∧ IC [12]{3}*	-
C	power circuit (118)	*power circuit ∧ IC [12]{3}*	-
D	power circuit (118)	*power circuit ∧ IC [12]{3}*	-

(b) Classification search method

	1st search formula	2nd search formula	3rd search formula
A	usage ∧ operation error *(58)*	power circuit (32)	*IC [5]{3}*
B	usage ∧ operation error *(58)*	power circuit (32)	*IC [5]{3}*
C	usage ∧ operation error *(58)*	power circuit (32)	*IC [5]{3}*
D	usage ∧ operation error *(58)*	power circuit (32)	*IC [5]{3}*

4.4.5. Analysis of Task T5

For Task T5, there were no correct cases. Search times were good for all subjects by the classification search method. In the keyword search method, subject D was able to reduce the number of hits through use of the keyword expression "degree of margin," but all subjects, after much trial and error, were forced to analytically discriminate all examples related to the keyword "switch" and could not avoid the keyword context mismatch problem. In the classification search method, all subjects without exception searched by the keyword "switch" after forming the abstract concepts "design" and "part" thereby avoiding the keyword context mismatch problem and reaching a conclusion with very good efficiency.

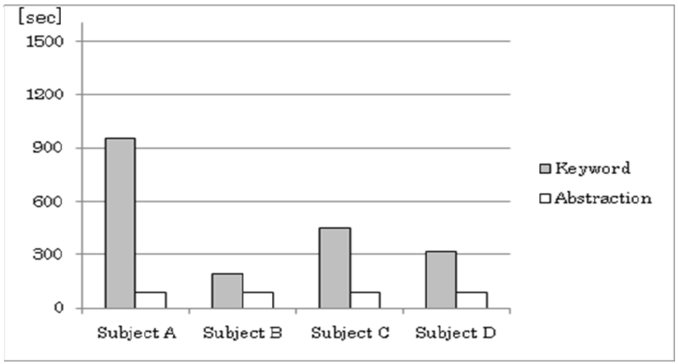


Fig. 14, Task T5 search times

Table 8 History of Task T5 search formulas

(a) Keyword search method

	1st search formula	2nd search formula	3rd search formula	4th search formula
A	switch (20)	switch ∧ design (0)	Margin (0)	Switch [20]
B	switch [20]	-	-	-
C	switch [20]	switch ∧ design (0)	-	-
D	switch (20)	switch ∧ margin (0)	switch ∧ degree of margin [11]	-

(b) Classification search method

	1st search formula	2nd search formula	3rd search formula	4th search formula
A	design [1]	part (22)	switch [2]	-
B	design [1]	part (22)	switch [2]	-
C	design [1]	part (22)	switch [2]	-
D	design [1]	part (22)	switch [2]	-

4.4.6. Analysis of Task T6

For Task T6, there were three correct cases. Search times were good for all subjects by the classification search method. In this example, any keywords like “signal line” “connector,” “manufacturing failure”, and “mistaken part” could easily cause the compound keyword problem and the keyword context mismatch problem to occur. All subjects, as a result, behaved in a perplexed manner when using the keyword search method. In the classification search method, on the other hand, all subjects formed the abstract concept “manufacturing ∧ structural failure” thereby avoiding the keyword context mismatch problem and retrieving the three correct cases in an efficient manner.

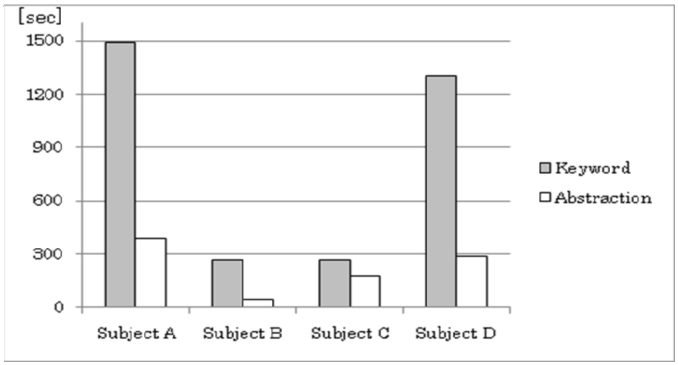


Fig. 15. Task T6 search times

Table 9 History of Task T6 search formulas

(a) Keyword search method

	1st search formula	2nd search formula	3rd search formula
A	connector (45)	*connector ∧ part [44]{3}*	-
B	line (37)	*line ∧ connector [8]{3}*	-
C	connector (45)	connector ∧ signal [8]	*signal line ∧ connector [13]{3}*
D	signal line (63)	*signal line ∧ connector [13]{3}*	-

(b) Classification search method

	1st search formula	2nd search formula	3rd search formula
A	*manufacturing ∧ structural failure [4]{3}*	-	-
B	*manufacturing ∧ structural failure [4]{3}*	-	-
C	*manufacturing ∧ structural failure [4]{3}*	-	-
D	*manufacturing ∧ structural failure [4]{3}*	-	-

5. Conclusion

This study focused on failure information retrieval systems used by design and manufacturing departments to access failure information in the maintenance department. We proposed an interoperable failure information knowledge system between design/manufacturing and maintenance departments based on a classification search method using abstract concept formation that takes information architecture differences into account. We also evaluated the proposed system comparing it with the standard keyword search method. We showed that our proposed classification search method based on abstract concept formation is superior to the keyword search method in both the accuracy and speed of information retrieval.

In this study, we use the technique described in 3.3 to classify items automatically. To apply our classification search method to various systems, it should be taken into account which technique is the most suitable from viewpoints such as differences of architectures.

In future research, with the above in mind, we aim to make the results of this study more general in scope and to develop interoperable systems that can deal effectively and efficiently with highly diverse sets of content having greatly different information architectures.

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