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A Toulmin's Framework-Based Method for Design Argumentation of Cyber-Physical Systems

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Abstract

The design of cyber-physical systems (CPS) is a promising domain, where the data market is expected to soon penetrate. When engineers focus on only a particular part of data (whether intentionally or not) for establishing a design hypothesis, the design hypothesis may also be supported by data sets in the market. Therefore, the validity of such a design hypothesis cannot be evaluated by the data itself, and can only be accepted by the robustness of the logic behind the design argumentation. Although the validation of the design logic is significant, cognitive aspects (which people have spontaneously) disturb the design argumentation reasoning. Therefore, a design method that overcomes the cognitive aspects is indispensable for the CPS designers. This work proposes a CPS design method using the interaction between logic and data sets with a logic visualization tool, and applies the proposed method to the design of a diagnosis system for semiconductor manufacture. The capability of the proposed method is also discussed and analyzed in this paper.

Type of Paper and Keywords

Research paper: *Cyber-physical system, data market, system design, design logic, logic visualization tool, validation, Requirements for Development (RFD), Toulmin's argumentation framework*

1 Introduction

There is growing interest in creating data markets in which data sets are handled as "goods" available for buying and selling [8]. Cyber-physical systems (CPS), such as advanced electric power grids and extreme-yield agriculture, are becoming increasingly important in data markets because CPSs require various data sets from a wide variety of stakeholders in order to define the system requirements.

CPS designers establish their design hypotheses by combining data sets in the market with their own field/experiment data sets. Usually, these hypotheses are validated with indexes such as "confidence" and "support" in data mining tools [14]. However, a hypothesis derived from a combination of data sets cannot be validated with these indexes because the data sets are collected from independent statistical populations. Therefore, the validity of such hypotheses can only be evaluated by the robustness of the logic behind its design argumentation.

However, design argumentation can be misled on the basis of invalid hypotheses that are supported by data sets. This is because the data sets, especially the big ones, include various kinds of variables, which may mislead the reasoning behind the design [14]. In this way, any design hypothesis can be supported by data sets when engineers focus only on one particular part of the data. In this paper, we propose a design method for cyber-physical systems based on the interaction between logic and data sets. A logic visualization tool and inquiry set are developed to support the proposed method. We then apply the method to the design process of a diagnosis system for the manufacturing equipment of semiconductor devices.

The rest of this paper is organized as follows: Section 2 discusses related work and the issues in data system design. Section 3 describes the proposed design method and the logic visualization tool. Section 4 presents a case study in which the proposed method for designing cyber-physical systems is applied to a diagnosis system for semiconductor device manufacturing equipment. Section 5 concludes the paper.

2 RELATED WORK AND DESIGN ISSUES

In recent years, several approaches for validating the logic of a system design have been considered. These approaches can be classified into three categories: informal, semi-formal, and formal [11]. The informal approach uses free documentation written in unrestricted natural languages as a notation of system specifications. The semi-formal approach utilizes disciplined documentation written in either structured natural languages or diagrammatic notations such as SADT [18], UML [15], and SysML [4]. The formal approach uses a formal description such as B [1] and VDM++ [2].

In both informal and semi-formal approaches, the design logic is usually validated through inspections, desk checks, and walkthroughs [16], all of which are heuristic. The precision of the validation is heavily dependent on personal experiments and the capabilities of the reviewers. On the other hand, the formal approach verifies the design logic by descriptive and prescriptive statements that accompany the formal description. Such approaches are expected to achieve a higher degree of precision than both semi-formal and informal approaches.

However, the formal approach has a fatal defect: it excludes stakeholders from being review participants due to the low readability of formal description. During the early stages of system design, stakeholders are indispensable review participants because preliminary specifications contain omissions and ambiguities, which must be complemented by the stakeholders themselves. Visualization of the design logic is an effective method to urge both stakeholders and designers to discover omissions and ambiguities through design review.

Although the validation of the design logic is significant, the following cognitive aspects (which people have spontaneously) disturb reasoning [14] [5]:

- Eagerness to seek solutions before estimating the validity of the design logic.
- Proficiency in finding a plausible hypothesis.
- Inclination to change a hypothesis to a firm conviction.

The cognitive aspects listed above are common, and CPS engineers have especially a strong eagerness to realize useful systems based on data sets. Therefore, a design method, which overcomes these cognitive aspects, is indispensable.

3 DESIGN METHOD

The design method of cyber-physical systems is composed of two consecutive phases: the phase of requirement definition and the phase of requirement elaboration and validation.

3.1 Definition of Requirements

In the phase of requirement definition, designers first describe preliminary requirements in a document of Requirements for Development (RFD) using a natural language. The RFD document is converted into semi-formal descriptions and then into atomic propositions using the method of Rolland's notation [17] in order to collect orthographical variants. Each atomic proposition is connected with similar words by the logic visualization tool in order to clarify gaps in the logic. The atomic propositions are then assigned to Toulmin's argumentation framework [19] [20] in order to clarify the structure of the design logic. This assignment is carried out interactively in collaboration with stakeholders and designers. Through the collaborative work, designers and stakeholders clarify the role of each atomic proposition and discover omissions and ambiguities in the RFD documentation. Figure 1 outlines the phase of requirement definition.

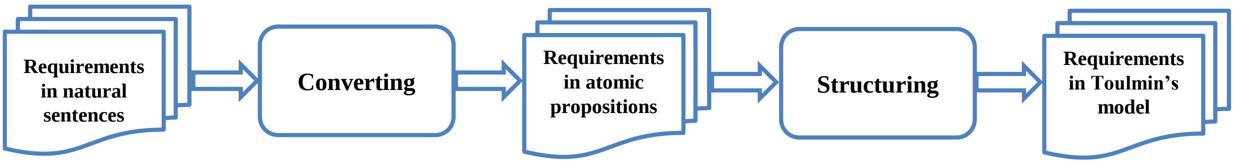

Figure 1: The phase of definition of requirements

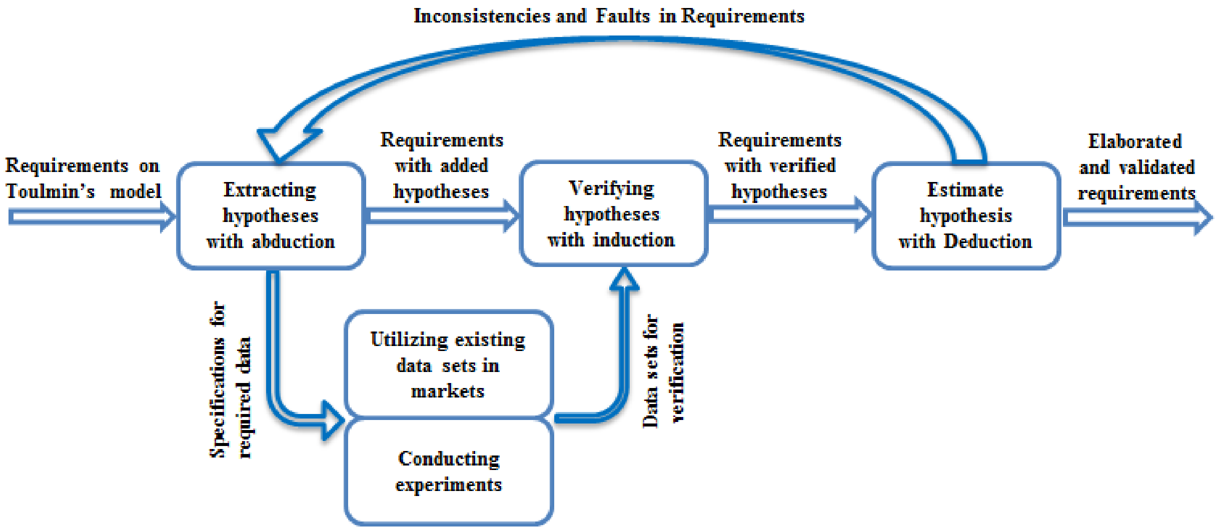

Figure 2: The phase of elaboration and verification of requirements

3.2 Elaboration and Validation of Requirements

Designers often formulate invalid hypotheses in system specifications during the early stages of the design process due to the cognitive aspects described in Section 2. Thus, specifications may be based on invalid hypotheses. To avoid this, hypotheses should be inductively validated on data sets, and the iterative validation consists of five processes: abductive, inductive, and deductive inferences [9]. Figure 2 describes the phase of requirement elaboration and validation.

4 IMPLEMENTATION

We have implemented our CPS design method as a logic visualization tool, which supports the design processes proposed in Section 4. The tool provides direct manipulation for iterative reasoning and for the cooperative work among designers and stakeholders in the phase of the elaboration and verification of requirements. The visualization tool consists of four functions: conversion, connection, assignment and verification. Table 1 outlines these functions, and they are discussed in detail in the following subsections. The tool is implemented as a Java application. Two screenshots of the tool are shown in Figure 3 and Figure 4.

Table 1: Functions of the logic visualization tool

Functions	Description
Conversion	Converting simple sentences in natural language into atomic propositions
Connection	Connecting atomic propositions with similar words and with propositional symbols
Assignment	Assigning atomic propositions to Toulmin's argumentation framework
Verification	Verifying the logic structure on the model with Tableau method

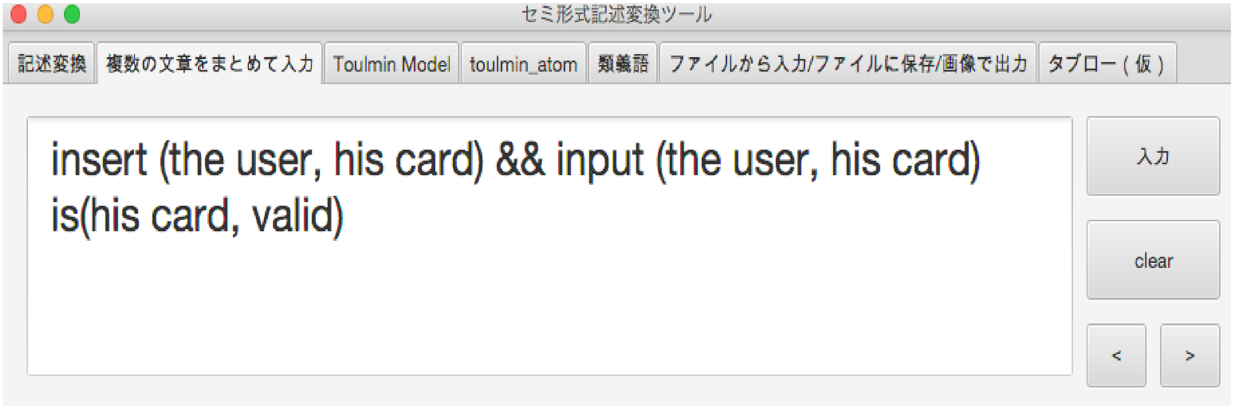

Figure 3: Screenshot of the visualization tool: Inputting simple sentence with Rolland's notation method

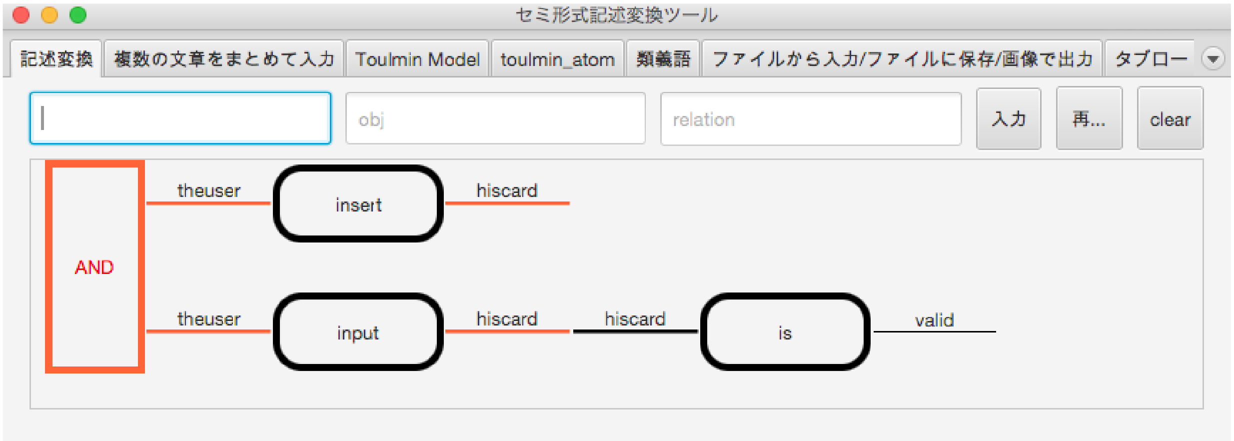

Figure 4: Screenshot of the visualization tool: visualizing atomic propositions

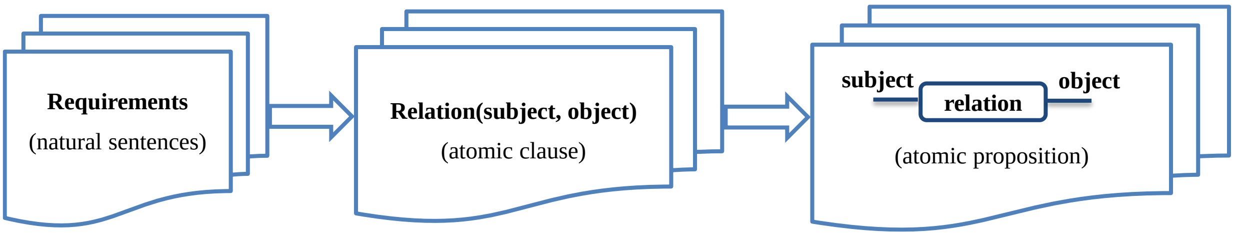

Figure 5: Conversion of requirements into atomic propositions

4.1 Converting requirements into Atomic Propositions

For the design argumentation of cyber-physical systems, it is important for the logic behind design argumentation to be unambiguous and processable. Therefore, we need to convert the system requirements described in the natural language into formal description. We first use Rolland's description method [17] to obtain a semi-formal description for the Requirements for Development (RFD). The core concept of Rolland's notation is that requirements are composed of *atomic clauses*, and *logic symbols*. An atomic clause expresses an action or status, and a logic symbol expresses a logical relationship between two atomic clauses. The atomic clauses are finally converted into atomic propositions. The conversion process is outlined in Figure 5.

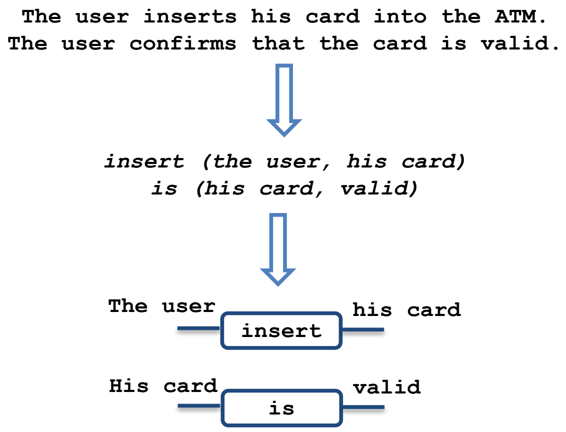

Figure 6: An example of converting requirements into atomic propositions

As an example, a description of requirements is: "*The user inserts his card into the ATM. The user confirms that the card is valid.*" In this example, there are two atomic clauses: "the user inserts his card," which is regarded as an action clause and provides the semantics of the atomic function; "the card is valid," which is regarded as a state clause and provides the semantics of the object's state. Using Rolland's notation method, these two atomic clauses are described as "*insert (the user, his card)*" and "*is (his card, valid)*". Each atomic clause is then converted into an atomic propositions. This example is illustrated in Figure 6.

4.2 Connecting Atomic Propositions

In general, the Requirements for Development (RDF) is composed of flows of atomic clauses. The connection function of the tool links each atomic clause with similar words. When there is no jump or gap in the logic among atomic clauses, atomic propositions are connected with similar words. In other words, we can find a jump or gap in the design logic by observing the linkages of atomic propositions on the tool. The tool has a user-definable dictionary and thesaurus and is able to handle synonyms in atomic clauses.

The relationships among atomic clauses can be notated explicitly with the following logical symbols: $\wedge$ (conjunction), $\vee$ (disjunction), $\neg$ (negation), and $\Rightarrow$ (implication). For example, the atomic clauses "the user inserts his card" and "the user inputs his password" imply that "the card is valid". This is notated as *insert (the user, his card) && input (the user, his password)* $\Rightarrow$ *is (his card, valid)*, and illustrated in Figure 7. The tool thus converts series of atomic clauses (including the logical symbols) into the linkages of atomic propositions.

4.3 Assigning Atomic Propositions to Toulmin's Argumentation Framework

Toulmin's graphical argument framework [19][20] is adopted to describe the reasoning scheme behind the design method. The Toulmin's framework is composed of six components: Data, Claim, Warrant, Backing, Rebuttal and Qualifier. The relation of these complements are illustrated in Figure 8.

Claim: the position or assertion being argued for. The claim is the main point of an argument. "Harry is a British subject" is an example of a claim. In the context of this paper, a claim is a consequent observation or a goal of requirements.

Data: facts or evidence used to prove the claim. "Harry was born in Bermuda" is an evidence, which supports the claim "Harry is a British subject".

Warrant: assumptions, general principles or conventions. The warrants are typically the general, hypothetical, logical statements, and ensure that the claim can be inferred form the data. According to the warrant "A man born in Bermuda is generally a British subject", one can validate the claim "Harry is a British subject" from the fact "Harry was born in Bermuda". The warrant is typically implicit (unstated) and this provides space to question the warrant or reveal rebuttals to the warrant. In the context of this work, a warrant is a logical step or a design rationale.

Backing: evidences or facts, which provide additional support to the warrant.

Rebuttal: counter-arguments. They are exceptions or limitations to the argument, and indicate circumstances or situations where the argument would not hold. In our work, rebuttal specifies exceptions to the design rationale.

Qualifier: words (e.g. 'most', 'usually', 'always' or 'sometimes'), indicating the strength of the inference from the data to the claim.

In order to avoid ambiguity, each component in the Toulmin's framework is described with an atomic proposition and/or linkages of atomic propositions instead of natural languages (see Figure 9). The assignment of atomic propositions to the framework is carried out interactively in collaboration with stakeholders and designers. Through this collaborative process, designers and stakeholders clarify the role of each atomic proposition and discover omissions and ambiguities in the logic behind the design argumentation. The Toulmin's argumentation framework always requires a Warrant and Backing. In the context of this work, Warrant is regarded as the design rationale. The framework acts efficiently for a

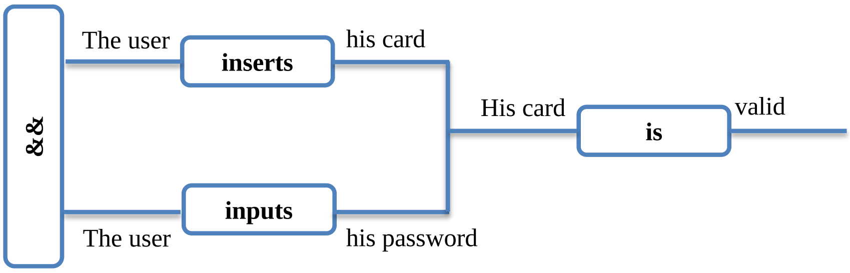

Figure 7: Rule for linking atomic propositions

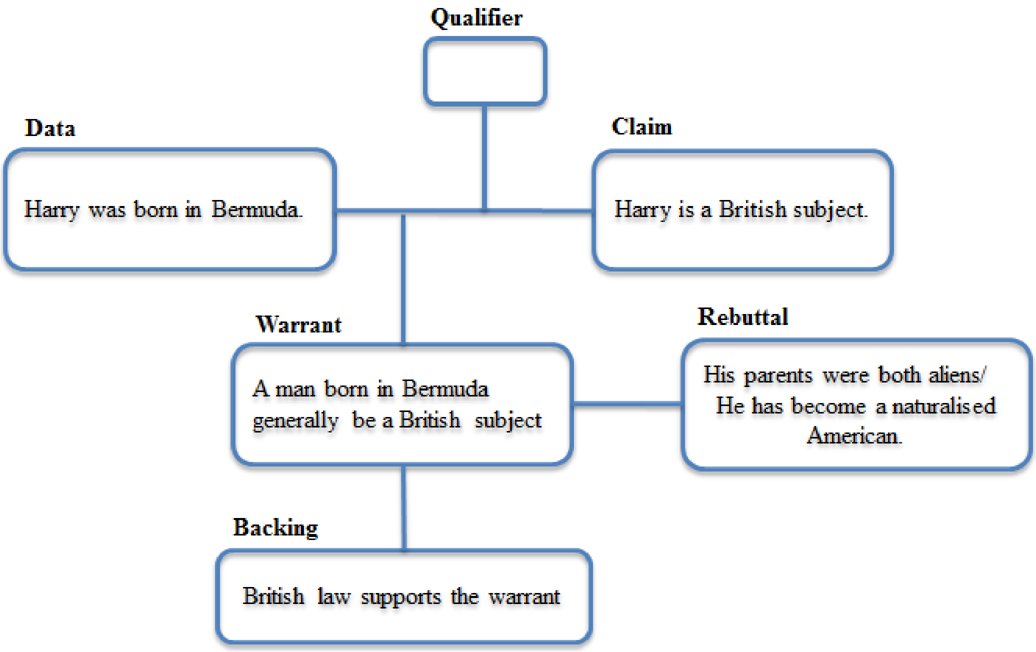

Figure 8: Toulmin's argumentation framework (source [7])

design review because the validity of the design rationale is the most important criterion of a design review.

The logic assigned to Toulmin's framework is verified formally using the tableau method [7], which is a proof procedure for atomic propositions of first-order logic. Using the tableau method, the design logic is validated by detecting contradictions among atomic propositions in Data, Warrant, and negation of Claim in the Toulmin's argumentation framework.

4.4 Validating Design Logic with Inquiries

It is difficult to elicit the Warrant and Rebuttal from the stakeholders directly without facilitation because stakeholders are not aware of the Warrant and Rebuttal in Toulmin's argumentation framework. To accelerate the elaboration and validation of requirements described in Section 3.2, a group of inquiries for stakeholder interviews are suggested.

Inquiry 1: *Designers ask stakeholders a Warrant in order to determine whether the deduction of "Data ⇒ Claim" is true.*

Inquiry 2: *Designers ask stakeholders a Rebuttal, which denies the Warrant.*

Inquiry 3: *Designers ask stakeholders which data sets are required to confirm the reliability of both the Warrant and the Rebuttal.*

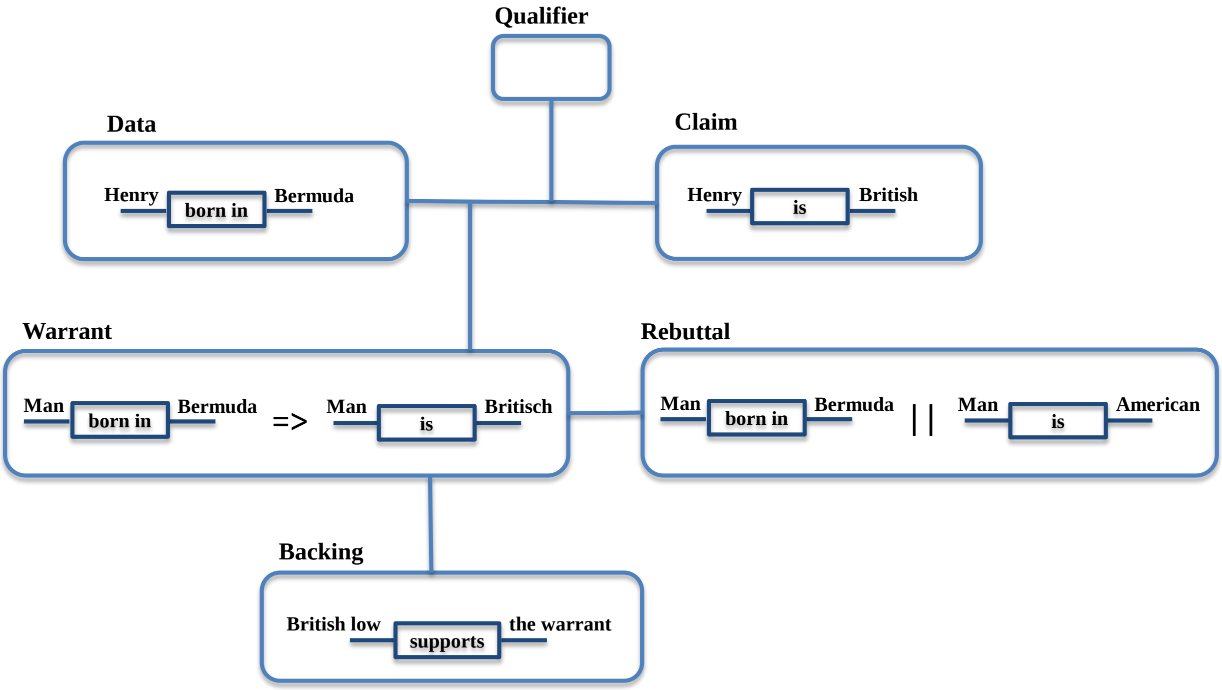

Figure 9: Toulmin's argumentation framework described in atomic propositions

The Warrant and Rebuttal elicited through the interview are not always reliable. These are often just thoughts or suggestions as to a possible course. The validity of the logic behind the argumentation should be estimated with data sets. Designers should facilitate the interview using the three inquiries provided and ensure that the logic behind the design argumentation is robust.

5 Case Study

We have applied the proposed method to a diagnosis system in order to evaluate its feasibility.

5.1 A Pump Diagnosis System in Semiconductor Industry

The equipment of semiconductor manufacture should work all day and night for good productivity. Yet some manufacturing devices require preventive maintenance. Vacuum pumps are one such device. These pumps cool manufacturing equipment to cryogenic temperatures by alternately processing, compressing, and expanding the refrigerants. The seals of vacuum pump, which guard against the leak of refrigerants, and the bearings of rotation mechanism are both gradually worn down by the pump's continuous operation. Without preventive maintenance, such pumps would eventually quit working due to internal abrasions.

One company with considerable experiences in pump maintenance and with rich statistical data sets has begun developing a pump diagnosis system in response to Requirements for Development (RFD) from a semiconductor factory. In that RFD (see Table 2), expert engineers in the semiconductor factory assumed that the pump's operating sounds can be used for diagnosis because the sound often changed at the pump's terminal stage. Thus, the company utilized sound characteristics in their diagnosis system as an indication of the pump's overall health.

5.2 First Design of the Diagnosis System

A prototype of the diagnosis system is designed and implemented with the RFD in Table 2 in 2007, and this RFD was described by the plant maintenance engineers in the semiconductor factory. An overview of the design process for the prototype is shown in Figure 10. The maintenance company built a prototype system and diagnosis algorithm using their preserved data sets and collected data sets through experiments in their laboratory.

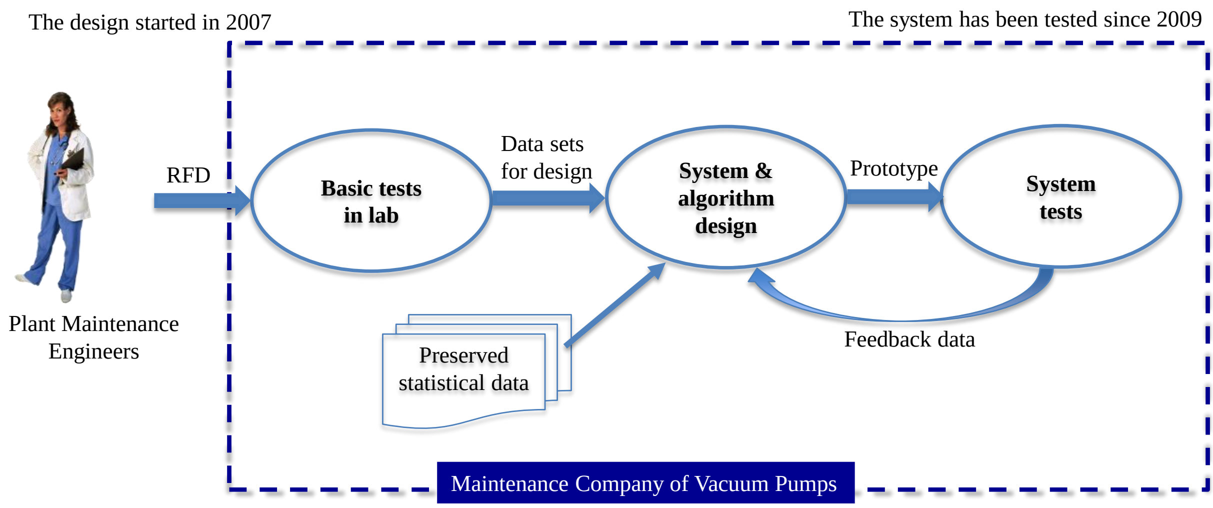

Figure 10: Design process for the first diagnosis system

Table 2: RFD for the diagnosis system

Item	Contents
Goal	Predict fault in pumps in coming six months with 80% accuracy.
Solutions	Operation sound of vacuum pumps indicates abrasion of parts.
Constraints	Temperature is not stable during manufacturing process.
	Vacuum Pumps monitor temperature of the equipment and warn its trouble.

The prototype of the diagnosis system (see Figure 11) had been installed in the semiconductor factory for evaluation. For two years, the maintenance company had attentively tweaked the algorithm based on field data. Yet the prototype failed to satisfy its goals, even though the design process seemed quite proper. The accuracy of diagnosis stayed around 60% through all the field tests and never achieved 80%.

5.3 Failure Analysis for the Initial Design

To clarify the factors that led to failure in the previous design, we conducted interviews with the engineers. The results of those interviews are listed below:

Reliable information from the experts: Maintenance engineers were informed by reliable experts at the semiconductor factory that most vacuum pumps generate abnormal sounds during their terminal stage. The engineers themselves also often heard these abnormal sounds while performing maintenance work both in the lab and at maintenance sites.

Convincing statistical data: For about ten years, maintenance engineers have recorded pumps' error factors in their database (Figure 12). Those data show that 90% of errors are caused by abrasions on refrigerant seals and the ball bearings of the pumps' rotational mechanisms. About 80% of the pumps had lost their grand seals at the terminal stage due to destruction (Figure 12).

Domain knowledge: Maintenance engineers were well aware of the common knowledge that most machines with rotating mechanisms generate abnormal sounds at their terminal stage

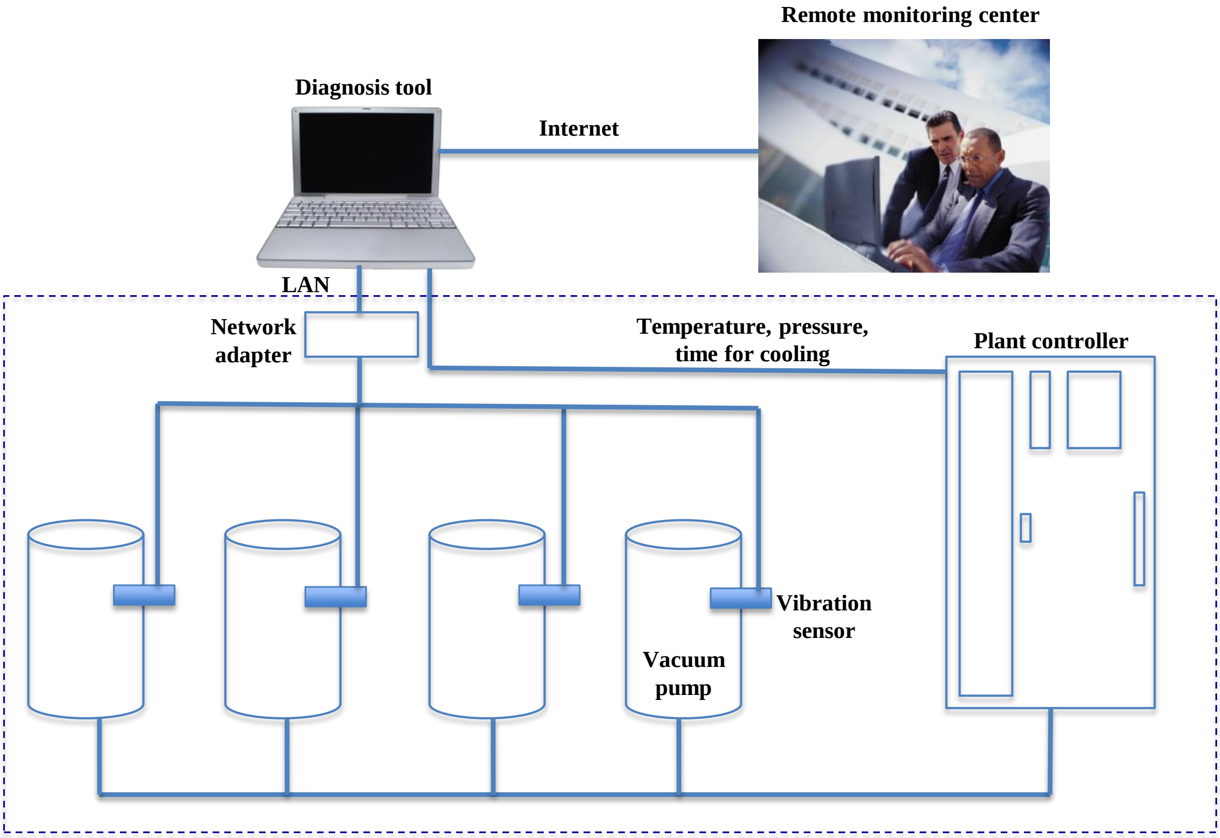

Figure 11: Prototype of the diagnosis system

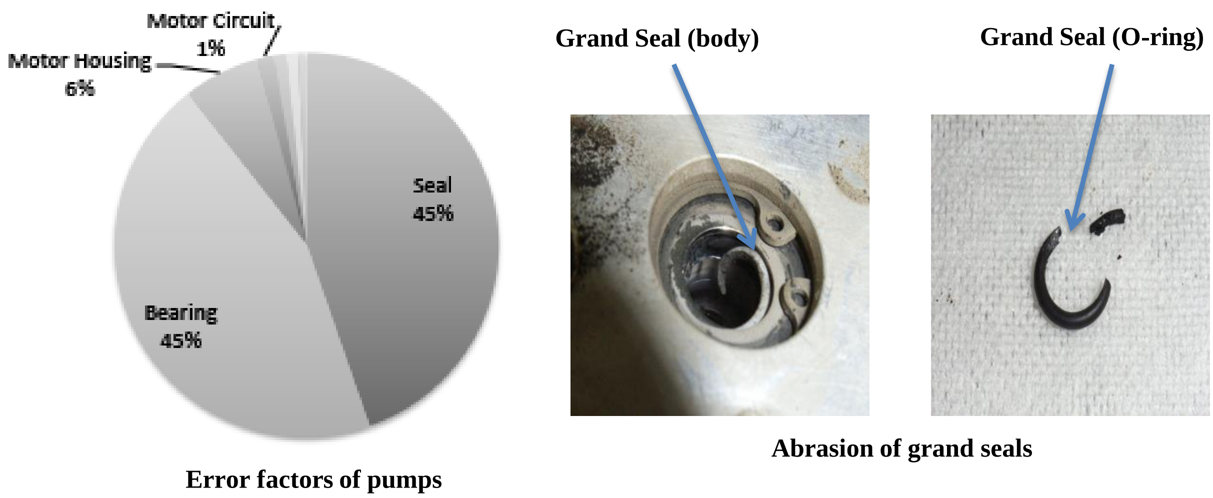

Figure 12: Statistical data for the error factors of pumps

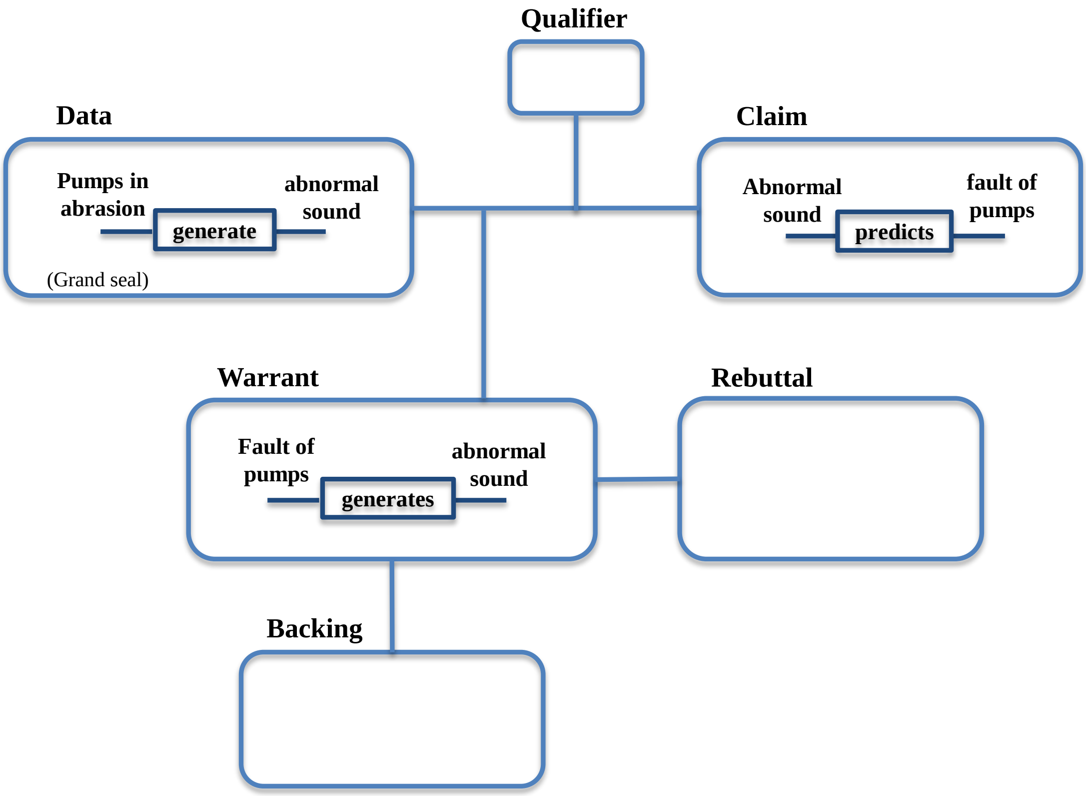

Figure 13: Logic of the initial design

From the results of these interviews, we confirmed that humans' cognitive aspects biased the design logic. The engineers in the maintenance company interpreted the RFD based on their own domain knowledge without any doubts. They believed uncritically that abnormal sounds indicate faults in the pump. The logic of the first design is visualized in Figure 13.

The reasoning process was performed in typical abduction sequences:

$$Claim \wedge Warrant \Rightarrow Data.$$

However, argumentation results are not always valid because the abductive inference is based upon the affirmation of consequences [8].

We can observe a logical inconsistency in Figure 13: many other factors can be assumed to be faults in the pump, and an abnormal sound does not always indicate the deterioration of the pump's cooling performance. However, the engineers never doubted that their hypothesis was invalid because of their cognitive biases. The hypothesis was in fact their conviction based on the testimony of trustworthy experts and statistical data.

5.4 Redesign of the Diagnosis System

Due to the abovementioned problems with the initial design, we redesigned the algorithm to make use of the proposed method, which is described in Section 3.

5.4.1 Extracting hypotheses with abduction

Once a hypothesis has crystalized into conviction, it is difficult to break the hypothesis on one's own. We have introduced the inquiries described in Section 4.4 in order to help engineers break such convictions.

Firstly, the designers of the diagnosis system asked engineers in the semiconductor factory about possible Rebuttals that negate the Warrant given in Figure 13. As a result of this inquiry, the following Rebuttals were elicited:

- *Not every part with an abrasion generates abnormal sounds.*
- *Not every part with an abrasion impacts the deterioration of the cooling performance.*

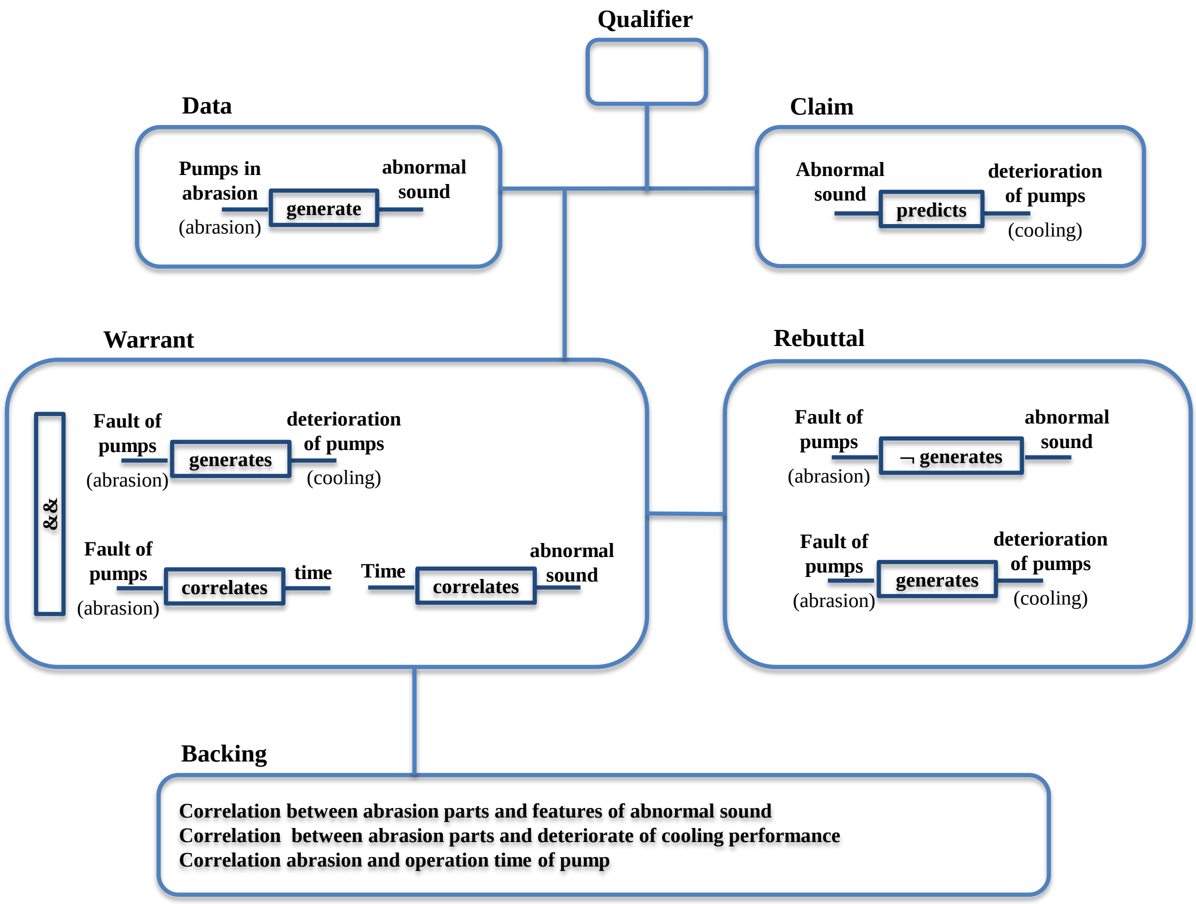

Figure 14: Logic of redesign

In succession, the designers asked the engineers about the data sets required to confirm whether the above Rebuttals are valid. As a result of this inquiry, the following data sets were chosen to confirm the validity of the Rebuttals (Figure 14):

- *Relationship between the parts with abrasions and the features of the abnormal sound.*
- *Relationship between the parts with abrasions and deterioration of the cooling performance.*
- *Relationship between the progress of abrasions and the pump's operation time.*

5.4.2 Verifying Warrants on Data Sets

The data sets required to validate these premises were specified through the analysis to the testing results of pumps.

(1) Relationship between parts with abrasions and the features of the abnormal sound

The engineers extracted parts that may have been worn from continuous operation and discussed the pump's physical structure (Figure 15). As a result, in addition to the grand seal, two other kinds of parts (inlet and cylinder seals) were found to possibly affect the pump's cooling performance.

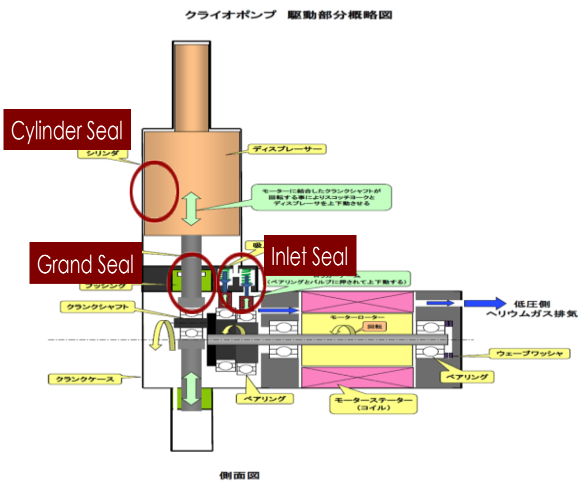

Figure 15: Structure of the vacuum pump

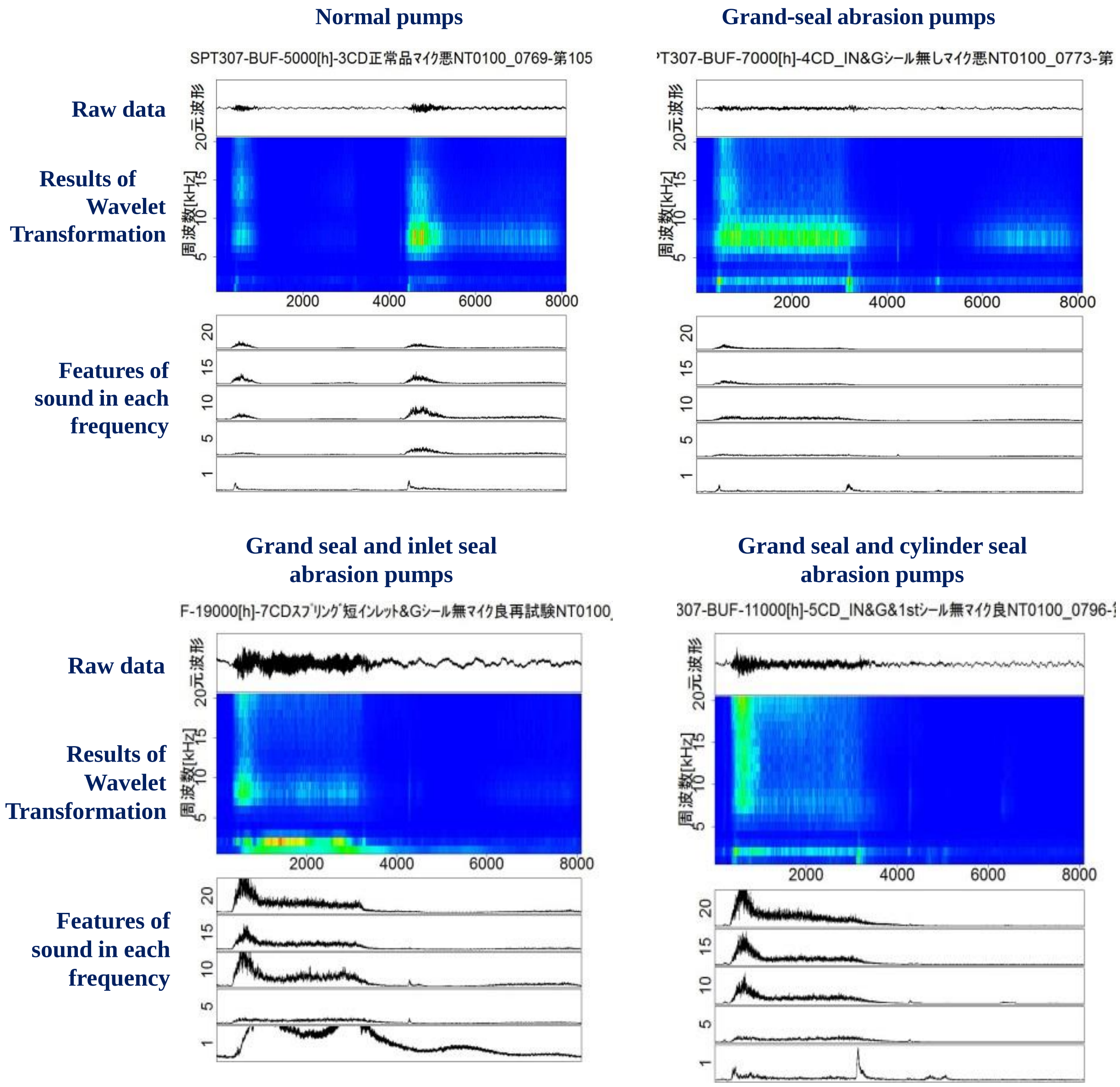

Figure 16: Relationship between abrasions and sound

(the upper part of each graph illustrates a raw waveform of normal operating sounds; the middle and lower parts illustrate the signal intensity of the spectrum from 1 to 20 kHz)

The engineers checked experimental pumps in which each part with abrasions was embedded, and abstracted data sets in order to determine the correlation between parts with abrasions and abnormal sounds and the correlation between parts with abrasions and the pump's cooling performance.

The results indicate that each part with abrasions is associated with unique features of abnormal sounds (Figure 16). However, these features exist outside the audible range. In Figure 16, each sound was analyzed using the wavelet analysis method [13] (frequency: 1–20 kHz, mother wavelet: Haar) to extract features of the sounds. For example, the normal operation sound has two peaks, but the sound of the pump whose grand seal had abrasions lost one of those and exhibited succession noise between the peaks (see the upper part in Figure 16). The atomic proposition in Data (Figure 14) is validated inductively by these data sets.

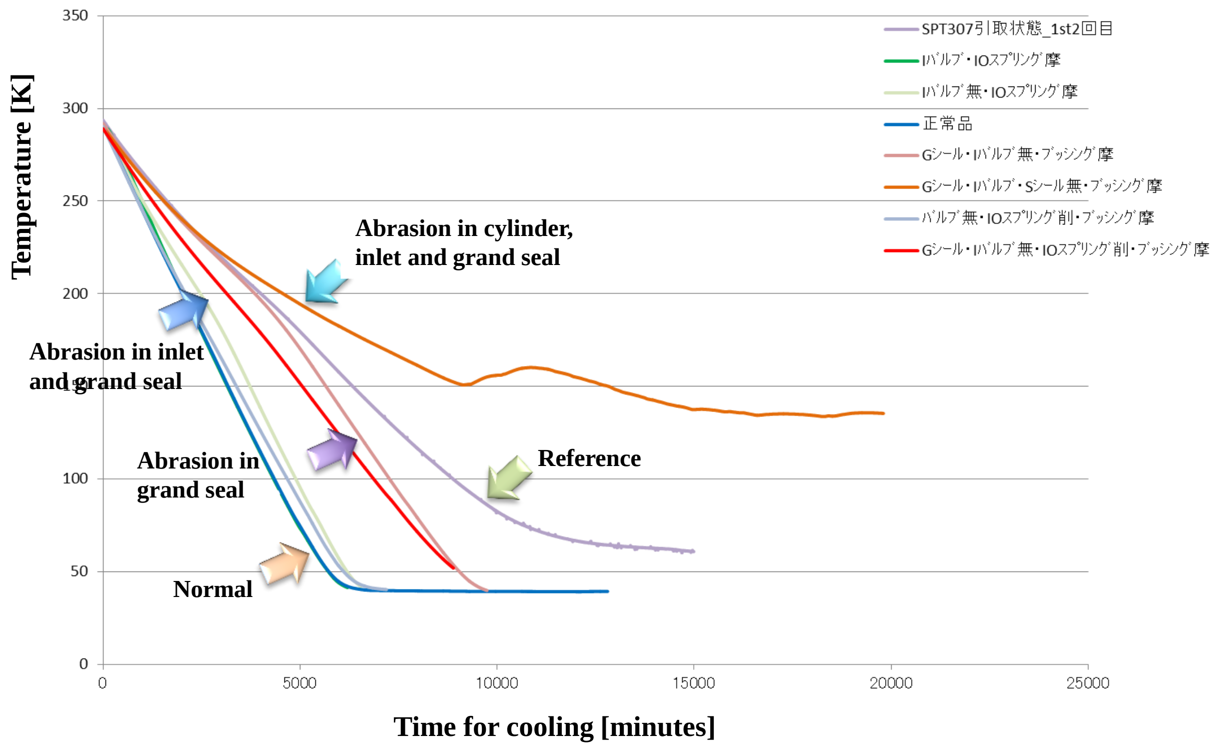

Figure 17: Relationship between abrasions and cooling performance

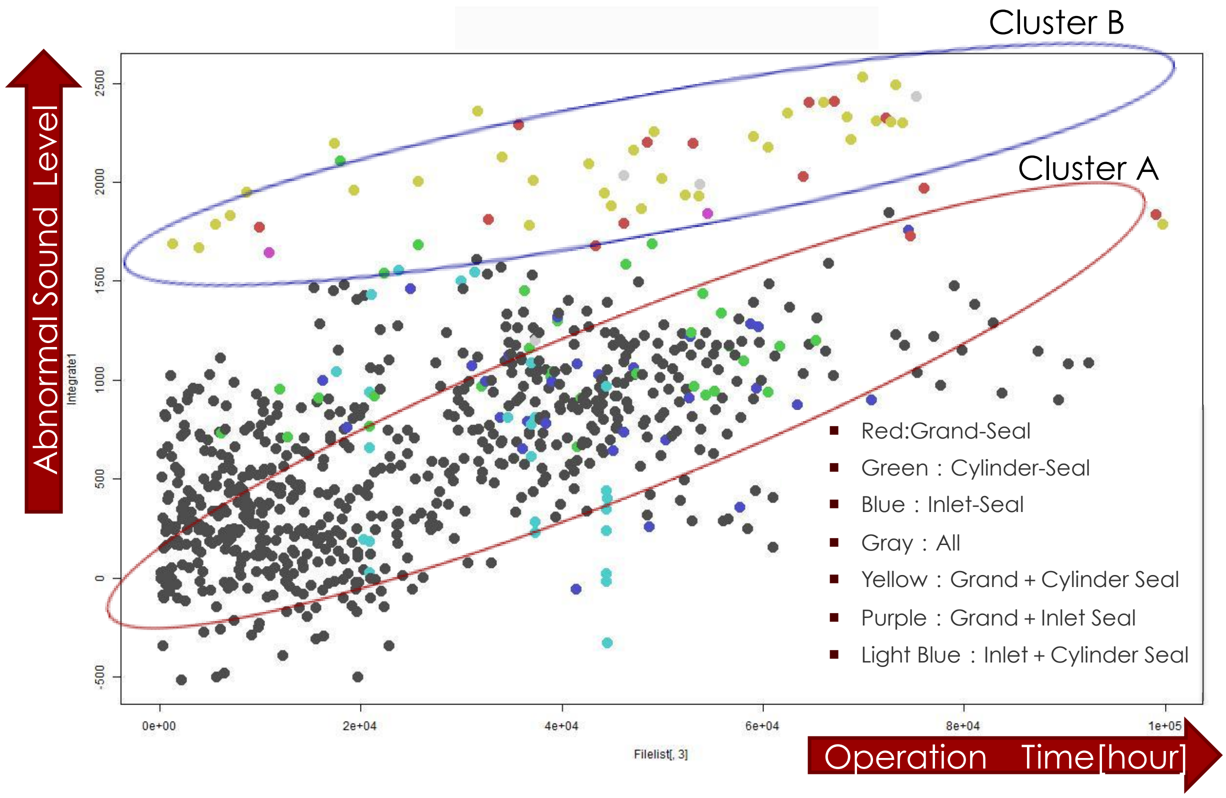

Figure 18: Relationship between abnormal sounds and operation time

The reason that each abrasion part generates unique sounds was inductively reviewed among the maintenance engineers based on the physical structure of the pump. As a result, the engineers discovered that there were two kinds of sounds from their generation mechanism: a refrigerant injection noise coming through the seals and a resonance noise on the principle of the flute [3]. The engineers' expert knowledge deductively confirmed the validity of this elicited reason. Such iterations of inductive and deductive reasoning processes are what make the logic of the design argumentation valid.

(2) Relationship between parts with abrasions and deterioration of the cooling performance

The relationship between parts with abrasions and the pump's cooling performance is shown in Figure 17. In the figure, the horizontal axis indicates the time required for cooling and the vertical axis indicates the equipment's temperature. For example, the pump with a grand seal abrasion requires much more time to cool than the normal, undamaged pump. Cooling performance is degraded gradually until abrasions occur on each part (grand, inlet, and cylinder seals). As a result, the atomic proposition in Warrant (Figure 14) is inductively validated with data sets.

(3) Relationship between abrasions and operation time

The pump's operating sounds may change in proportion to its operating time and thus predict faults in the pump. We have collected sound data from 100 pumps in a semiconductor factory for 1.5 years. By using this long-term field data set, the correlation between abnormal sounds and operation time is showed in Figure 18.

In Figure 18, the level of abnormal sounds increases correspondingly to the operation times (coefficient of determination: 0.57). Abrasions progress in proportion to operation time. We inductively confirmed the warrants (Figure 14) with the data sets.

Through the phase of the elaboration and validation of requirements, the logic behind the design argumentation is tweaked based on the interaction between the logic and data sets. The Data and Warrants shown in Figure 14 are confirmed by the data sets. The claim is deductively led by the Data and Warrants and is thus valid based on logical conclusions that have been backed by the Data.

5.4.3 Redesigned System

Figure 19 summarizes the relationships among abrasions, abnormal sounds, and operation times using a cause-effect graph [12]. The grand, inlet, and cylinder seals are worn down concurrently during operation, and the level of abnormal sound rises proportionally to the operation time. Grand seal abrasions drastically impact sounds in that the exhaust sound vanishes. Grand seals are often destroyed during operations; however, cooling performance remains within its practical use range. On the other hand, the pump loses its cooling performance when all tree parts are worn away. The prototype (Figure 20) of the diagnosis system was redesigned and implemented with the proposed logic model (Figure 14).

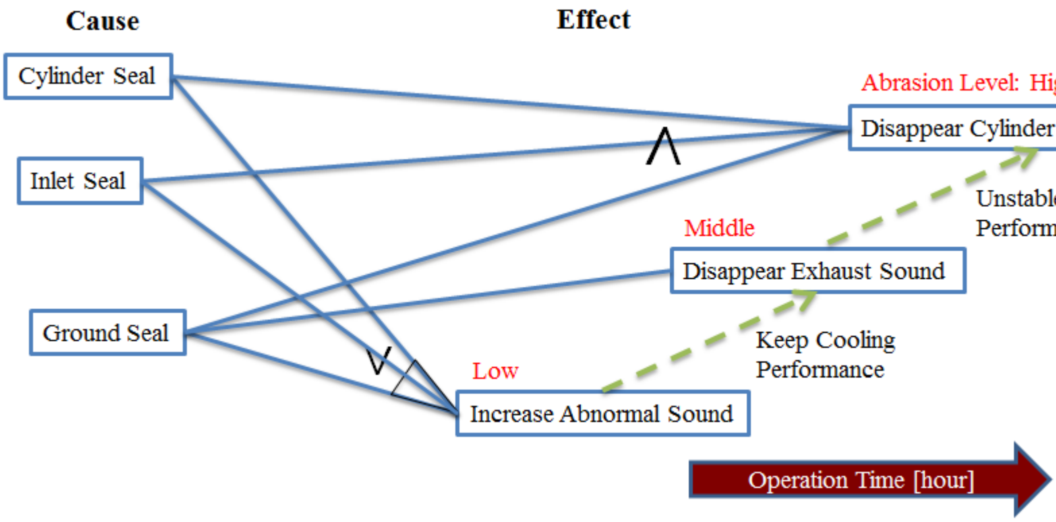

Figure 19: Relationships among abrasions, sounds, and operation times

We have begun field tests using the acoustic diagnosis method [10]. Its diagnosis capability was confirmed (Table 3). The prototype achieves a precision of 0.85 and a recall of 0.88. We confirmed that the prototype is successful in predicting pump failures. These results satisfy our goal.

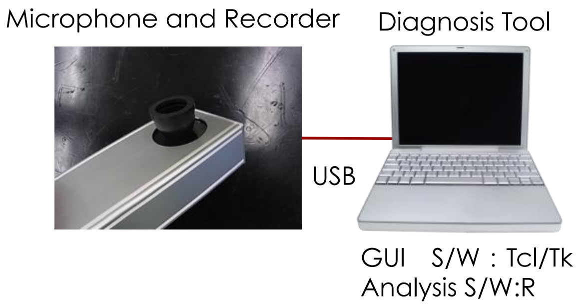

Figure 20: Diagnosis system outlook

Table 3: Diagnosis accuracy

Results	**Leak Level**			
	Normal	**Low**	**Middle**	**High**
Reference	185	124	99	33
Diagnostic Results	171	134	112	34

5 CONCLUSION

The design of cyber-physical systems is a promising domain because data markets are expected to penetrate it. However, such design has the problem of that any hypothesis can be supported by data sets in the market although engineers focus (whether intentionally or not) on only one particular part of the data.

The validity of such a hypothesis could not be estimated by the data itself - rather, it could only be confirmed by the robustness of the logic behind the design argumentation. Although logic validation is significant, cognitive aspects (which humans do spontaneously) disrupt design argumentation reasoning. A design method that overcomes such human cognitive aspects is thus indispensable to CPS designers.

In this paper, we have proposed a design method for CPSs based on the interaction between the logic and data sets. This design method is implemented as a logic visualization tool. We then applied the proposed method to the design process of a pump diagnosis system in Semiconductor Industry. As a result of this trial, we confirm that the proposed method has benefited the establishment of valid design models.

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