Effectiveness of conceptual design process respecting “The Axiomatic Design Theory”

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Abstract

In order to improve competing power against rival companies, manufacturers need to release highly-valued new products for customers over a short amount of time. Because of this situation, in this paper, we want to focus on the efficiency of conceptual design stage after product planning stage. In particular, even if engineers grasp customer needs in real field, it’s not easy to convert good ideas for customer needs into a commercial reality. In most cases they decide on the final design proposal based on trial and error. So, they have to spend a lot of time, obsessed with the fixed idea that their experience and flair is the best. That’s why we thought respecting “The Independence Axiom (Axiom1)” and “The information Axiom (Axiom2)” at “The Axiomatic Design Theory” is directly linked to the efficiency of conceptual design stage. Axiom 1 and 2 are respectively to maintain the independence of the functional requirements (FRs) and minimize the information content of the design. To be more precise, we try to standardize effective conceptual design process, utilizing “Contradiction Matrix (CM)” for Axiom1 and “Information Integration Method (IIM)” for Axiom2. IIM is an evaluation technique that enables quantitative evaluation based on the concept of Shannon’s information theory, bundling different kinds of features not only performance but also sensitivity field together in a group as a universal scale called “Information”. In this paper we take the evolution of paper cup from past to present as a case example. Based on the proposed conceptual design process we try to propose next generation paper cup, respecting both Axiom 1 and 2. In addition, we would like to show that the proposed next generation paper cup will be basically in line with technical evolution laws from TRIZ.

Keywords: TRIZ Conceptual Design Stage, The Axiomatic Design, Contradiction Matrix, Information Integration Method

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1. Preface

For manufacturing companies, the product development activity plays a pivotal role in their corporate management [1]. The efficiency improvement of its upstream stages such as product planning and design development work, in particular, is vitally important for materializing customers’ required functions economically and also for the speedy product development activity.

In this paper, by focusing on design development work, the way of effective conceptual design process will be proposed to rationally convert customers’ required functions into valuable conceptual designs. More specifically, the proposal in this paper will illustrate “a conceptual design process” with less interference among numerous functions required by customers.

2. Outline of design process

In general, the design process consists of three stages, namely, “Analysis,” “Synthesis,” and “Evaluation” as shown in Fig.1 [2]. In the first stage of “Analysis” basically, the composing elements of the subject manner are clarified by dividing it into details. In the design activity, this is the stage of “functional analysis” for grasping customers’ required functions. The next stage of “Synthesis” is for integrating plural elements. In other words, the vectors of thinking are oriented to the product as a whole. In the design work, this is the stage of creativity by considering the means to achieve the required functions and integrating the elements to create conceptual design proposals. The last stage of “Evaluation” is for selecting the optimum proposal out of several choices. In terms of mode of thinking, Convergent Thinking is applied in the Analysis stage, Divergent Thinking in the Synthesis stage, and again back to Convergent Thinking in the Evaluation stage. In this way, creating the optimum product design drawing by effectively switching between convergent and divergent thinking is the ideal way of design activities [3].

![Fig.1. Three stage of design process](image)

3. Conventional process for considering conceptual design proposals

It is necessary for most manufacturing companies to release new products which can highly satisfy customers in a short lead time in order to stay competitive in the market. To this end, design activities must be done rationally, including the process of grasping customer needs and issues of existing products, creating ideas, considering several product design proposals by combining these ideas and selecting the optimum design proposal as a result of evaluation based on the preset evaluation items. However in reality it is not easy to convert ideas matching the needs of customers into specific products. What most of manufacturers are doing is to undergo trial
and error before reaching their final product design proposal. In other words, brainstorming techniques are not effectively utilized in the idea creation stage, it is assumed that designers’ judgments can be biased by their fixed ideas [4]. In such cases, selecting the product design proposals hastily by depending solely on their past knowledge and intuitions can end up in wasting a lot of time afterwards by the resulting rework. What is important therefore is to standardize the thinking process, so the outcome will be affected less by individual differences in the way of working. This can be achieved by preparing an appropriate Management of Technology techniques, described as “MOT techniques”. These techniques are suitable for the respective modes of thinking, namely, Convergent Thinking or Divergent Thinking.

4. The proposed conceptual design process and the Axiomatic Design Theory

4.1. The proposed conceptual design process

To address the issue of conventional conceptual design activity mentioned earlier, MOT techniques suitable for each mode of thinking are prepared for developing the practically effective procedures to examine the conceptual design proposals, which will be illustrated in this paper (cf. Fig.2.). More specific, as a means of rationally grasping customer needs in the “Analysis” stage, functional analysis techniques in the field of VE (Value Engineering) and QFD (Quality Function Deployment) are utilized to clearly understand the customers’ required functions. The next stage of “Synthesis” is for idea creation based on the function-oriented thinking, and for rationally minimizing interferences between the functions by using Contradiction Matrix of TRIZ. By implementing these approaches, synthesis of the conceptual design proposals can be expected to be made without being biased by the past knowledge or intuition. The following “Evaluation” stage conventionally tended to be dependent on the individuals subjective evaluation work. In this paper, however, Information Integration Method, called IIM hereafter, is proposed as it makes it possible to do quantitative evaluation by bundling the evaluation items both in the performance and sensitivity fields together in a group as a universal scale called “Amount of Information.” The procedures are shown in Fig. 2.

Fig.2. Conceptual design proposal examination procedures
By following the procedures shown in Fig.2, rework mentioned earlier (or the work to be done after responding “No” in the procedures) is expected to be reduced and the highly satisfying conceptual design proposals can be decided efficiently. The content of this design highly satisfying customers demanded functions and also satisfies both “Axiom 1: The Independence Axiom” and “Axiom 2: The Information Axiom” in The Axiomatic Design Theory developed by Dr. N.P. Suh [5].

4.2. Outline of the Axiomatic Design Theory

The Axiomatic Design Theory was developed around 1980 by Dr. Nam P. Suh of MIT (Massachusetts Institute of Technology) as The Principle of Design [6] in the design process. This is a design methodology used to change the conventional decision making solely depending on the individual experience and intuition in the design process to a scientific approach aiming at creating optimum designs.

- Axiom 1: The Independence Axiom
- Axiom 2: The Information Axiom

When considering the product development in accordance with Axiom 1, the product with no interference between required functions can be interpreted as the ideal one. From the viewpoint of TRIZ, the product with interfering parts must have certain contradictions internally, and its value can be improved by solving them. Regarding Axiom 2 also, the information content can be reduced as a result of complying with Axiom 1 and resolving the contradictions caused between required functions, therefore the result is expected to lead to the ideal product development.

The procedure of examining the design using Contradiction Matrix and Separation Principles to resolve functional interferences rationally and selecting the conceptual design proposals with minimum content of information by means of Information Integration Method (IIM), the very approach shown in Fig.2, therefore, is believed to be effective from the practical point of view as well.

4.3. Outline of Information Integration Method

IIM helps to evaluate features requested for system optimization. In this method, all features are evaluated using a common measure called Information based on Shannon’s information theory. Information is defined in following mathematic formulas. Information (I) for communicating the status of feature $a$, which is associated with probability $P_a$, is given as follows:

$$ I = \ln \frac{1}{P_a} \quad (1) $$

IIM expands this concept to measure the difficulties (Information, energy, or effort) required to satisfy the requested features in products design. The smaller the probability $P_a$, the more difficult it is to satisfy feature $a$. In IIM, the System Range is defined as the range of a feature in a product (or system); Design Range is defined as the range of a feature requested from markets or customers; and Common Range is where the System Range and Design Range overlap. A higher Design Range probability density is indicative of a higher level of satisfaction with the requested product feature. In IIM, Information (I) to obtain the Common Range in probability $P_c$ is used as a measure for evaluating the design. It is assumed that the probability density of most product features can be approximated for uniform distribution. Information (I) can be defined as follows if the probability density is subject to continuous uniform distribution (Figure 3).
In IIM, Information (I) can be infinite when it is out of Design Range. In particular, if the System Range is shown as a specified number, for example the price of a product, even if other features are satisfied with requested features, the design will not be selected. To address such situations, a function, which is called Common Range Coefficient \( k_c \) is proposed in IIM. As described in Figure 4, the Design Range falls between 0 and a, and the feature parameter that should be satisfied is c. In this case, Common Range Coefficient \( k_c = 1 \), where the system feature parameter is between 0 and a. Common Range Coefficient \( k_c = 0 \) when the System Range parameter is more than c. Common Range Coefficient \( k_c \) is described in equation 3 as follows, in which the System Range parameter is between a and c, assuming there is a small System Range with width \( w \):

\[
I = \ln \left( \frac{1}{P_c} \right) = \ln \frac{\text{System Range}(l_1)}{\text{Common Range}(l_2)} \tag{2}
\]

\[
I = \ln \frac{w}{k_c w} = \ln \frac{1}{k_c} \tag{3}
\]

Total Information, \( I_T \), is the amount of features’ Information. \( I_T \) is described as
\[ I_T = \sum I_i \quad (i=1…n) \] (4)

where the Information of feature \( i \) is \( I_i \) and the number of features is \( n \). In this study, \( I_T \) is used as a common evaluation measure of the improved design.

IIM has been used with the Nakazawa method in combination with the experimental design [7].

5. Outline of the case study

In this paper, as a means of verifying effectiveness of the proposed conceptual design process (cf. Fig.2), a case study was conducted. The subject product was a commonly used paper cup for hot coffee. In the first half of this case example, the resulted information content by experiments and questionnaires was used to illustrate how to reduce it by resolving contradictions between the required functions.

In the latter half, after grasping the existing issues of paper cups used in coffee shops, Contradiction Matrix was used by a group (of four members) to create ideas by solving the issues. Based on the design proposals which were created by specifying these ideas, a trial model was made. The evaluation of the trial model conducted by using IIM proved the effectiveness of the conceptual design process proposed in this paper.

5.1. Past analysis of paper cups

In response to the proposed conceptual design process (See Fig.2), past analysis of paper cups was held by following the procedure from #1 to #5.

#1: Set up evaluation items

Grasping basic functions based on the functional analysis approach, considering the additional functions by understanding changes in the social environment, these functions were set up as evaluation items (to evaluate design proposals). Fig.5. shows the functional diagram with additional functions. Looking at the features of modern society through the viewpoint of social microenvironment analysis, the present society is termed as “speed-oriented society”. The numbers 1) through 6) are the evaluation items in response to each function.

![Fig.5. Functional analysis and evaluation items](image-url)
Functional diagram (See foreside of Fig.5) is one of the techniques utilized in VE activity and shows the cross relationship among each function defined through function analysis. More specifically, Functional diagram organizes and describes the cross relationship between each function from the viewpoint of “purpose and means” hierarchically.

#2: Experiment and survey condition

Evaluation items are divided into engineering items which require experiments for setting up the System Range and sensitivity items which are set up by conducting questionnaire surveys.

i) Engineering item

Heat retention (1) is set up as an engineering item.

The data was obtained by measuring temperature changes of served coffee in the experiment.

The preconditions were as described below.

- Initial temperature: 85°C (as the result of hearing to the coffee shop)
- Measurement time: 20 minutes (time commonly spent for drinking)
- Design Range: 55°C ~ 70°C (ideal temperature to drink)

ii) Sensitivity item

Evaluation items, (2) to (6) shown in Fig.5 were set as sensitivity items. The data was gathered from the result of questionnaire survey based on a scoring method.

Each Design Range was set up based on a questionnaire survey for 20 coffee shop staff members (male: 13, female: 7). After the survey, the average score of each sensitivity item was defined as the minimum value of Design Range and the maximum score as the maximum value of it. Table 1 shows the Design Ranges for each sensitivity item.

Table 1 Maximum score of each sensitivity item and minimum value of Design Range

<table>
<thead>
<tr>
<th></th>
<th>2)Thermal insulation</th>
<th>3) Frictional performance</th>
<th>4) Accumulating</th>
<th>5) Mobility of coffee</th>
<th>6) Ease of drinking while walking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scoring</td>
<td>5-point</td>
<td>3-point</td>
<td>5-point</td>
<td>5-point</td>
<td>3-point</td>
</tr>
<tr>
<td>Design Range</td>
<td>4.14-</td>
<td>4.33-</td>
<td>3.00-</td>
<td>4.14-</td>
<td>2.57-</td>
</tr>
</tbody>
</table>

For setting up the System Range, a questionnaire survey was conducted with 30 people including not only coffee shop staff but also its guests (male: 14, female: 16). The System Range was decided by calculating average (=μ) and standard deviation (=σ), and by utilizing the formula (5) as described below.

\[ \mu \pm \sigma \]  

#3: Subject of this study: Paper cup

Features of the paper cups as the subject of this study are shown in Table 2.

Table 2 The features of each paper cup for hot coffee

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Usual paper cup</td>
</tr>
<tr>
<td>B</td>
<td>Paper cup with assist handle</td>
</tr>
<tr>
<td>C</td>
<td>Paper cup with lid</td>
</tr>
<tr>
<td>D</td>
<td>Paper cup with solo lid (lid with small hole for drinking)</td>
</tr>
<tr>
<td>E</td>
<td>Paper cup with solo lid and insulating sleeve</td>
</tr>
<tr>
<td>F</td>
<td>Paper cup with solo lid and embossed effect</td>
</tr>
</tbody>
</table>
The six types of paper cups, A to F, were selected as the result of surveys of both some paper cup manufacturers and coffee shops and studying the history of evolution regarding paper cups for hot coffee. The paper cups commonly used at coffee shops today in Japan are Type E used at Starbucks or Tully's Coffee, for example, and Type F used at McDonald's or Doutor Coffee, etc.

#4: Compute the features’ information content

Based on the result of the experiment and a series of questionnaire surveys, utilizing formulas (2) and (3), each evaluation item’s information content was calculated for each product. Table 3 presents the results.

<table>
<thead>
<tr>
<th></th>
<th>1) Heat retention</th>
<th>2) Thermal insulation</th>
<th>3) Frictional performance</th>
<th>4) Accumulating</th>
<th>5) Mobility of coffee</th>
<th>6) Ease of drinking while walking</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.61</td>
<td>∞</td>
<td>0.922</td>
<td>0</td>
<td>∞</td>
<td>3.33</td>
<td>∞</td>
</tr>
<tr>
<td>B</td>
<td>1.61</td>
<td>0.003</td>
<td>1.56</td>
<td>0</td>
<td>∞</td>
<td>∞</td>
<td>∞</td>
</tr>
<tr>
<td>C</td>
<td>0.159</td>
<td>∞</td>
<td>0.922</td>
<td>0</td>
<td>0</td>
<td>∞</td>
<td>∞</td>
</tr>
<tr>
<td>D</td>
<td>0.311</td>
<td>∞</td>
<td>0.922</td>
<td>0</td>
<td>0.024</td>
<td>0.381</td>
<td>∞</td>
</tr>
<tr>
<td>E</td>
<td>0.069</td>
<td>0</td>
<td>0.499</td>
<td>0</td>
<td>0.024</td>
<td>0.381</td>
<td>0.97</td>
</tr>
<tr>
<td>F</td>
<td>0.143</td>
<td>3.55</td>
<td>0.081</td>
<td>0</td>
<td>0.024</td>
<td>0.381</td>
<td>4.18</td>
</tr>
</tbody>
</table>

The result of calculation about the amount of a feature’s Information can become infinite. It is because it’s calculated based on logarithm natural. It means that the feature, which is one of evaluation items, has a high degree of urgency to improve functionality. If the content of a feature’s information is “0”, it means that customers are satisfied with functionality with the intended evaluation item with “0”. It’s because the System Range for it is within the Design Range.

#5: The evolution of paper cups from the viewpoint of resolving contradictions

Based on the result of calculation of the features’ information content, for the evolution of products (coffee cups), technical and physical contradictions were applied for creating ideas for their functional improvement. The effectiveness of this approach of resolving contradictions was verified below.

i) Functional improvement made by finding an idea to solve a physical contradiction (Type C to type D)

In the process of evolution from “A” to “C”, in order to improve “1) Heat retention”, a cup lid was introduced. As the result, the amount of 1)’s information was largely decreased. On the contrary, the amount of 6)’s information became infinite because of the lack of “6) Ease of drinking while walking”. With this in mind, “the physical contradiction” was defined as shown in Fig.6.
ii) Functional improvement made by finding an idea to solve a technical contradiction (Type B to Type E and F).

In the process of evolution from “A” to “B”, in order to improve “2) Thermal insulation”, a handle was added on the side of paper cup. As the result, although the amount of 2)’s information was largely decreased, the handle part was unstable and not satisfying “3) Frictional performance”, “5) Mobility of coffee” and “6) Ease of drinking while walking”. Understanding these, “the technical contradiction” was defined as shown in Fig.7.

5.2. New product planning for a next generation paper cup

In order to practice the planning and development of a next generation paper cup, a case study was carried out in accordance with #1 to #4, which were mostly following the conceptual design process (See. Fig.2).
#1: Interview on the present coffee cups

In order to abstract the problems related to Type E and F, which are popular paper cups at present, an interview-based survey was conducted to 20 users (male: 9, female: 11) at the coffee shop. The users of the coffee shop, in this case, were defined as those who came there to drink hot beverage twice a week or more. Table 4 shows their main problems of Type E and F.

“Ease of disassembly” was added as “7) evaluation item”, as the problem causes were thought to be arising from the paper cup itself. In the meantime, by focusing on the flow of the liquid, “6) Ease of drinking while walking” was changed to “6) Easiness to drink”.

#2: Localization of problems

In order to set up two sets of additional Design Ranges for 6) and 7) evaluation items, an questionnaire survey was held to 20 coffee shop staff members (male: 13, female 7).

Prior to the survey, scoring criteria on the 5-point scoring method were redefined and communicated to them for sharing information. After the survey, each average score was defined as the minimum value of each Design Range. In order to set up the System Range, a questionnaire survey was held to 30 people including not only the coffee shop staff but also its guests (male: 14, female16) in the same way as mentioned in the previous clause (5.1). Reflecting the result of the questionnaire survey, the amount of each evaluation item’s information was calculated. This survey focused only on Type E and F for comparison, because our purpose was to design a new product after type E and F.

Table 5 shows the content of each evaluation item’s information for Type E and F.

---

### Table 4 Main problems of type E and F

<table>
<thead>
<tr>
<th>Functional problems</th>
<th>number of times</th>
<th>The concrete contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ease of disassembly</td>
<td>7</td>
<td>It’s very hard to take off lid for pouring sugar and milk, or for disposal</td>
</tr>
<tr>
<td>Stability of sleeve</td>
<td>3</td>
<td>Slippery sleeve</td>
</tr>
<tr>
<td>Ease of scramble up</td>
<td>2</td>
<td>Putting sugar or milk in thick coffee like cafe latte, it’s hard to run together each other</td>
</tr>
<tr>
<td>Easiness to drink</td>
<td>2</td>
<td>It’s very hard for thick liquid like cafe latte to flow through the small hole on lid.</td>
</tr>
<tr>
<td>Design sensibility</td>
<td>1</td>
<td>Sleeve of corrugated paper is frumpy</td>
</tr>
</tbody>
</table>

---

### Table 5 The content of each evaluation item’s information for Type E and F and their totals

<table>
<thead>
<tr>
<th></th>
<th>1) Heat retention</th>
<th>2) Thermal insulation</th>
<th>3) Frictional performance</th>
<th>4) Accumulating</th>
<th>5) Mobility of coffee</th>
<th>6) Easiness to drink</th>
<th>7) Ease of disassembly</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type E</strong></td>
<td>0.069</td>
<td>0</td>
<td>0.499</td>
<td>0</td>
<td>0.024</td>
<td>2.19</td>
<td>3.81</td>
<td>6.592</td>
</tr>
<tr>
<td><strong>Type F</strong></td>
<td>0.143</td>
<td>3.55</td>
<td>0.081</td>
<td>0</td>
<td>0.024</td>
<td>2.19</td>
<td>2.34</td>
<td>8.328</td>
</tr>
</tbody>
</table>
The result shows that Type F has a room for improvement regarding “2) Thermal insulation” and Type E for “3) Frictional performance”. In addition, by improving “6) Easiness to drink” and “7) Ease of disassembly” for Type E and F, it was expected to decrease the total content of information and to able to design a next generation paper cup.

#3: Idea creation by resolving contradictions

By utilizing the contradiction matrix, the three localized problems mentioned in the previous paragraph (#2) were converted to each technical contradiction to be used for creating ideas. The preconditions set for this idea generation were as follows.

Target product: Type E and F. Persons being tested: Four graduate students who studied TRIZ at the class. Idea generation time: One hour. Hot beverage for paper cup: Hot coffee, Café latte and Café Mocha

The created ideas which were adopted are shown below.

i) “Thermal insulation (Type F)” VS “Frictional performance (Type E)”

The solution was created to improve thermal insulation and yet to prevent worsening of stability or frictional performance.

By defining the technical contradiction, the solution of a double-layer cup was created as shown in Fig.8.

![Improving Feature (17line)Temperature VS Worsening Feature(13 row) Stability of object](image)

1. Segmentation
32. Color Changes
35. Parameter changes

- Hang the top portion of inner cup on the top portion of outer cup
- Make the inner and outer cup angle different.
- Use different colors for inner and outer cup for differentiation
- Add embossed effect on the outer surface for better frictional performance

Fig.8. Solution proposal about “Temperature” VS “Stability of object”

ii) Idea generation for “#7 Ease of disassembly (lid)”

The idea of a value-added lid was created for taking off easily, pouring sugar or milk easily, too, as shown in Fig.9.
iii) Idea generation for “#6 Easiness to drink (faucet)”

For smooth flow of even thick drinks like cafe latte or Cafe Mocha, an idea of making a groove was created, shown in Fig.10.

5.3. Effectiveness of the next generation paper cup

Using three solution proposals shown in Fig.8 to Fig.10 as references, a trial model was made as shown in Fig.11. Then, an experiment was held to evaluate its heat retention ability. For evaluating other functions, a questionnaire survey was conducted to 30 people including both the coffee shop staff and its guests. Table 6 shows the content of each evaluation item’s information of the proposed paper cup compared with Type E and F.
Table 6 The content of each evaluation item’s information for the proposed paper cup

<table>
<thead>
<tr>
<th></th>
<th>1) Heat retention</th>
<th>2) Thermal insulation</th>
<th>3) Frictional performance</th>
<th>4) Accumulating</th>
<th>5) Mobility of coffee</th>
<th>6) Easiness to drink</th>
<th>7) Ease of disassembly</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type E</td>
<td>0.069</td>
<td>0</td>
<td>0.499</td>
<td>0</td>
<td>0.024</td>
<td>2.19</td>
<td>3.81</td>
<td>6.592</td>
</tr>
<tr>
<td>Type F</td>
<td>0.143</td>
<td>3.55</td>
<td>0.081</td>
<td>0</td>
<td>0.024</td>
<td>2.19</td>
<td>2.34</td>
<td>8.328</td>
</tr>
<tr>
<td>New paper Cup</td>
<td>0</td>
<td>0</td>
<td>0.081</td>
<td>0</td>
<td>0.024</td>
<td>1.54</td>
<td>1.89</td>
<td>3.535</td>
</tr>
</tbody>
</table>

These results clearly show that the content of each evaluation item’s information was decreased by resolving contradictions and reduced the total information content as the result. This means that the proposed product (trial model) is a verified product as a next generation paper cup for users.

6. Conclusion

In this paper, aiming at improving efficiency of product development activities, a proposal was made by combining “an effective contradiction solving technique by reducing interferences between functions” and “Information Integration Method which enables an integrated quantitative evaluation of various evaluation items” as procedures for making conceptual design proposals. With respect to realizing Dr. Suh’s Axiom 1 and 2, these procedures were proved to be a highly ideal design approach through a case example. It must be noted that the resulted trial model satisfies both Axiom 1 and 2. Also from the standpoint of TRIZ, the trial model satisfies “Law of Increasing Ideality” [8] as it has better valuable functions with less harmful effect and also “Law of Completeness of Parts of a System” [8] as it gained higher functional independence. These results, however, are based on only one case example as of now. The proposed procedures (of design approach) need to be applied to more cases for achieving a higher level of perfection.
References


