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Two Aspects of Function for Technical Systems

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Abstract

Function is very important to understand to understand technical systems. It is defined as ‘specification of an action performed by a material object (Function Carrier) that results in a change or preservation of a value of an attribute of another material object (Object of the Function)’. (International Association of TRIZ (MATRIZ) definition). This ‘Subject-Action-Object’ function model, which is widely used in innovation process, is ‘action’ oriented definition. Sometimes, however, understanding the function from an outcome perspective and solving problems produce better results. In this paper author proposes two aspects of function definition (action oriented function and outcome oriented function) to understand technical systems and find creative solutions.

Keywords: Function carrier, object of the function, action oriented function, result (outcome) oriented function, core problem.

1. Introduction

The meaning of existence of technical systems is the main reason why people make technical systems. That’s why function analysis is so important to understand a technical system. We use the ‘ideality’ to qualitatively evaluate the development level of technical systems and define it as the sum of the useful functions which a system performs divided by cost and harmful functions. A technical system is evaluated as the sum of its functions.

There are several important TRIZ tools associated with the function such as FOS (Function-Oriented Search), function analysis and trimming. Function-Oriented Search is a method or a tool for problem solving based upon identifying existing technologies in other areas of technology from a function perspective. Function analysis is an analytical method to model technical systems and their supersystems in terms of functional carriers, objects of the functions and their actions. Function carrier is a material object that performs (delivers) a function. It can be either a substance and a field, or a combination of both. Function modeling helps us to better understand, visualize, and categorize functional relationships between the elements in the system, and identify problems. Trimming is a method for improvement of a technical system by removing (trimming) certain components and redistributing their useful functions among the remaining system or supersystem components while preserving quality and performance of the system. We can also define the contradiction as the case when a component performs a useful function and a harmful function simultaneously.

MATRIZ defines the function as ‘specification of an action performed by a material object (function carrier) that results in a change or preservation of a value of an attribute of another material object (object of the function)’ (Souchkov, 2018a). Function analysis slices the technical system into small simple unites which are delivered function created by substance-action-object, S-a-O model (Gadd, 2011). It’s very reasonable approach and this action oriented definition of function helps us to analyze a technical system and solve the problems effectively (Song et al. 2017). This is the “Mini-Problem” solving technique, which TRIZ suggests to solve with priority. In TRIZ society, Mini-Problem means a type of inventive problem definition which is obtained by imposing the following constraints on a given inventive situation: everything remains as is (without any changes) or becomes even simpler but the required positive effect is provided or the harmful effect disappears. Definition of Mini-Problem targets at obtaining a solution required with as minimal changes in the existing technical system as possible (Souchkov, 2018b). But sometimes solving a Mini-Problem doesn’t satisfy us and we need a new approach-to solve a Maxi-

Problem, which does not impose constraints on future inventive solutions. To define the Maxi-Problem we need another aspect of function definition, the result/outcome-oriented function.

2. Two Aspects of Function for Technical Systems

MTRIZ definition of function for a technical system is focused on 'action' of components (action-oriented function; AF), but what we really want from the technical system is not an action itself, but the "result/outcome" of action in function (result-oriented function; RF). For example from the action point of view, the function of glasses is to refract light. But what we really want is to see clearly, the result of action between lens and light. Therefore function analysis should be done in two respects; Action and Result/Outcome aspects.

2.1 Action-Oriented Function

The functional definition of the technical system in terms of action is the traditional technique in TRIZ society and very good method to understand the system and highlight problem places for any system or situation. This method will be briefly described as a general approach in TRIZ society.

The steps of action-oriented function analysis are:

(1) Components analysis

- List the components of the system of interest (sub-system components)
- List the super-system components of the system, which have interactions with the system components.

(2) Interaction analysis

- Identify interactions between components (sub-system and super-system components)
- It can be performed by creating a matrix

(3) Function Modeling (Subject-action-Object (S-a-O) Model)

- Subject is the active tool of an action, action provider
- Object is the passive receiver of an action. It is changed in some way by this action from the subject
- Action is provided by some kind of field between Subject and Object components. And the action is portrayed as transitive verbs

The action-oriented function analysis is used not only to understand a technical system, but also to analyze and solve problems. All system problems can be shown by S-a-Os (harms, insufficiencies, contradictions). S-a-O model reveals the problem areas in which two or more components are harmfully, insufficiently interacted to each other. Any problems are identified with the concrete elements and the interactions between them. If we understand the nature of the problem through functional analysis, we can derive a variety of solutions with TRIZ tools.

2.2 Result/Outcome-Oriented Function

What people/customers want to get from a technical system is not the "action" itself, but the result of the action it does. Therefore, it is necessary to define the function and solve the problem from the viewpoint of the result. The "Result/Outcome-oriented Function (RF)" helps to get a new approach to the problem. (Maxi-Problem approach). The action-oriented function and result/outcome-oriented function are closely related to each other and can be expressed as follows:

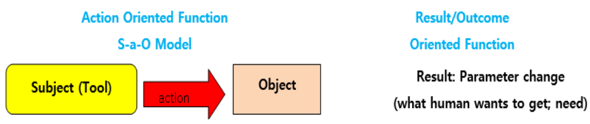

Fig. 1 Two aspects of function for technical systems, AF and RF

RF can be expressed as 'human need' or 'what the human wants to get'. The result/outcome can be obtained by changing the parameters of the object by the action. For example, RF of a military helmet is to protect the head, while its AF is to block the bullet. RF of a fan is to cool the person, but AF is to move the air (make the wind). When solving the problems of a fan, we should focus how to effectively move the air (AF). However, in some cases it may be necessary to come up with a solution that will satisfy the resulting function, "how to cool the person effectively" (see Fig.1). This concept was proposed in 1989 by Royzen as a TOP (Tool-Object-Product) model (www.trizconsulting.com). In this paper, the author combines two different aspects of function to understand the whole concept of function to solve problems effectively.

CASE STUDY

In the 1990s, a combo system was developed that could read both CDs and DVDs and installed in computers. Optical diodes that read CDs and DVDs were different, and two LD light sources were installed, which made the system complex (see Fig.2). CD lasers were typically AlGaAs semiconductor material with a wave length of 780nm and the DVD diode emitted the light of the wave length of 650nm. Combo systems equipped with CD laser diodes and DVD diodes of different wavelengths were complicated to read data and arrive at a single detector to transmit information.

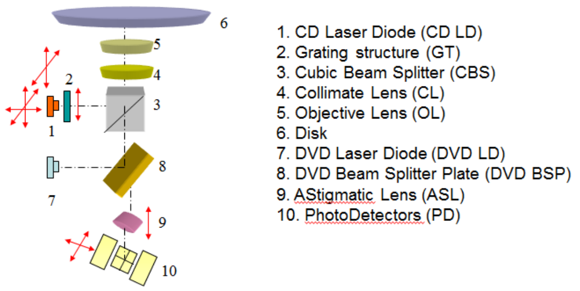

Fig. 2 CD-DVD Combo system.

This technology was developed by a foreign company and patented at home and abroad. A key element of the technology is to use different lenses to guide light of different wavelengths to a detector. A Korean company tried to develop a combo system by avoiding this patent. Researchers had developed various optical systems to collect light of different wavelengths in a detector while avoiding existing patents (Kim, 2009) (see Fig.3). They tried to change the position of laser diodes and the arrangement of optical lenses. (Fig.3 (a), (b) and (d)) Researchers had also developed combo systems of using a beam splitter (Fig.3 (f)) and hologram element (Fig.3 (e)).

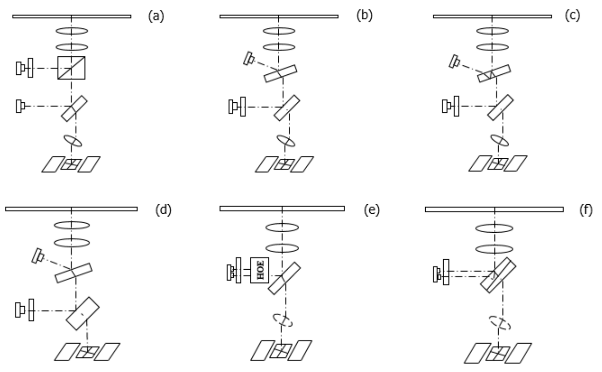

Fig. 3 Various CD-DVD Combo optical systems, developed by a Korea company.

However, the developed optical system was difficult to avoid foreign patents. When the company researchers developed new technology, they focused mainly on the action-oriented function, 'how to guide two lights emitted from different location into a detector' and tried to implement AF diverse and effectively. After many mistakes, engineers had defined the problem in terms of the RF, "what do we want to get from the combo system?" What people want to get from this system is to read information from CDs and DVDs. Therefore, they switched the core-problem from "how to guide (refract) different lights to a single detector" to "how to read CD and DVD data while avoiding patents". The researchers were able to get a solution easily by considering how to realize the RF. Instead of using a complex optical system that refracts two lights emitted from different places into one place, two detectors were installed at the points where the two lights reach. It was a very simple but creative idea! (see Fig.4)

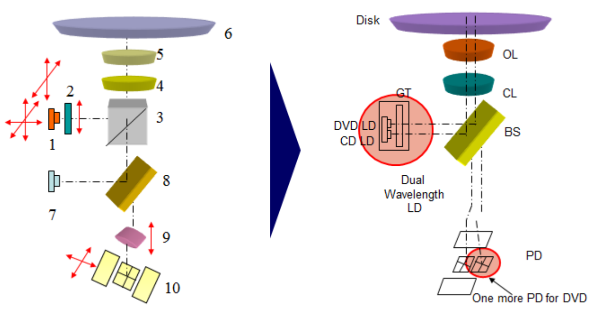

Fig. 4 The idea that had been solved in terms of RF – two detectors were installed.

The combo system with two detectors was able to reduce the cost by 40% compared with the existing system, because the number of optical lenses had been reduced from six to four, the number of joint points had been reduced from 38 to 26, and the number of adjusting joints had been reduced from 13 to 8. In addition, it increased the reliability by 33% and improved the productivity by 38%. The company reported that it earned $ 100 million over three years through this solution.

3. Conclusions

In TRIZ society, a function is analyzed by action. This function analysis helps to solve problems by approaching system problems with "Mini-Problem" perspective. However, defining a problem with a "Maxi-Problem" perspective and solving problems in a technical system, it is necessary to think about the AF and RF at the same time, to define the problem in two aspects and to draw out the solution.

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Online Education Improvement Using Environment-Based Design Approach

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Abstract

Online education is currently widely used to replace traditional face-face teaching and learning activities due to the recent COVID-19 epidemic. However, critical challenges exist in online education practice, such as the difficulty of teachers to learn about students' status. Aiming at identifying the key conflict and conceptual design of a solution to improve online learning and teaching. This paper analyzes and tackles these barriers in online education using the Environment-Based Design (EBD) approach. A process consisting of environment analysis, conflict identification, and solution generation is applied to generate the solution for online educa-tion improvement. This novel solution suggests monitoring students' whole bodies and facial expressions, which can be referred to by teachers for the adjustment of teaching contents. Experimental validation in the education of high school students is given to show the effectiveness of the proposed solution. The satisfaction rate is increased by around 20%.

Keywords: online education, conceptual design, environment-based design

1. Introduction

Due to the recent COVID-19 epidemic, online education has been widely adopted to replace traditional face-face teaching and learning activities (Jena 2020; Dhawan 2020). The emergence of information or communication technologies and the booming development of digital devices have facilitated online teaching and learning (Miftachul et al. 2018; Alfatmi et al. 2018), getting more students involved, including those with special needs (Haynes 2018). Real-time communication software (e.g., Zoom, QQ, Classin, etc.) is used for such online activities. However, since the software is not initially designed for online education, several drawbacks are found during the daily experience. The teacher often worries that the teaching quality cannot be guaranteed, while the students complain about the terrible learning experience.

However, Chang et al. (2018) stated that the website administrators should offer professional development resources to teachers and communicate with students about the learning expectations. Fang et al. (2018) pointed out that the quality of online learning is lower compared to face-to-face learning. They suggested that the improvement of students' external and internal learning conditions can enhance students' engagement and summarized vital influencing factors. Ni et al. (2020) identified the factors on online education, they conducted a survey on what would most improve online teaching experiences for MPA students. How to provide more communication is one of the key factors on effective online education. Gao (2020) analyzed and discussed the development of K12 online education in China. This study focused on the status, profit model and development problems. However, few researchers have proposed a concrete solution based on available software to improve the online learning experience. There is a design method called environment-based design, which includes three activities: environment analysis, conflict identification, and solution generation. EBD can help the designers better understand the requirements of customers, the structure of the organization, the process of the business models, and the inherent critical conflicts. Therefore, EBD can be a practical design methodology, which can be referred to when designing the online education system.

This paper uses the Environment Based Design (EBD) methodology (Zeng 2004, Zeng 2011, Sun et al. 2011) to investigate online education – analyze the environment of online learning, identify the significant conflicts for both teacher and student, and eventually propose the solution to improve the online learning.

2. Environment-based design approach

2.1 Overview

Zeng et al. (Zeng 2004) presented the environment-based design methodology, a step-by-step approach for understanding and performing the conceptual design process. The basic idea of EBD (Zeng 2011, Sun et al. 2011) is that a design problem is implied in a product system and is composed of three parts: the environment in which the designed product is expected to work, the requirements on product structure, and the requirements on the performance of the designed product. The start of a design process is the analysis of the environment. The design and product environment include three major environments: natural, built, and human environments. A product operates in the environment and influences and changes the environment.

The requirements on product structure and performance are related to the product environment. The EBD includes three main activities: environment analysis, conflict identification, and solution generation. These three activities work together progressively and simultaneously to generate and refine the design specifications and design solutions, as shown in Figure 1.

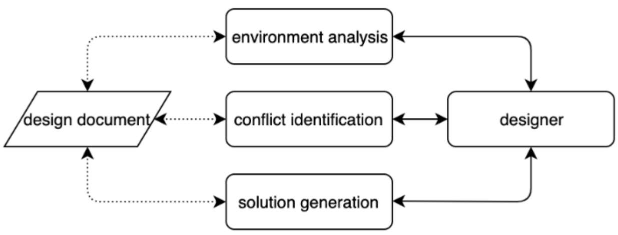


Fig. 1. Process flow of EBD.

2.2 Environment analysis

The objective of environment analysis is to identify the environment in which the desired product is to work. According to the EBD, the environment includes its components and the relationships between those components. One of the key methods for environment analysis is using the Recursive Object Model (ROM) (Zeng 2008). As explained in detail by Zeng (2008), the ROM includes two types of objects, i.e., object and compound object, and three kinds of relations between any two objects, i.e., connection, constraint, and predicate.

According to environment analysis, it is clear that the purpose of online education improvement is "to design a solution that improves current teaching quality and promote student's learning experience". Based on EBD analysis, the corresponding ROM and its description are shown in Figure 2 and Table 1, respectively. Based on the ROM diagram, questions can be asked to clarify every object in the ROM diagram.

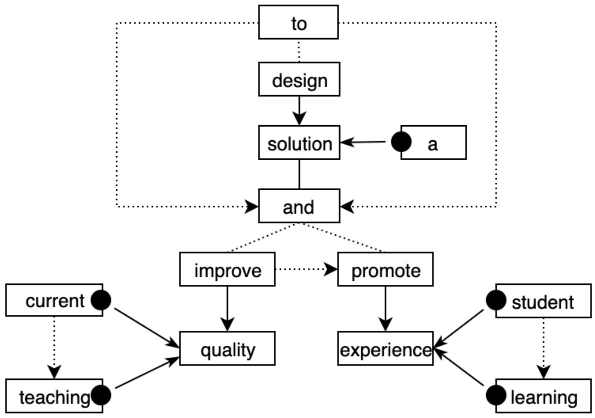


Fig. 2. Recursive object model (ROM).

Table 1 Elements in the ROM diagram

Graphic representation	Description
	object
	Constraint relation
	Connection
	Predicate relation

Apparently, "quality", and "experience" are the most constrained objects, thus constructing the key environment components. A few questions (Wang and Zeng, 2009) are generated to clarify these objects. A survey was conducted to an online English learning company with 10 classes (8 TOFEL, 2SAT), 10 teachers, and 58 students. Questions are listed as follows.

"Quality" questions are asked to the teacher,

(1) What is the definition of good teaching quality?

(2) What is the difference between classroom-based and online in terms of teaching quality?

(3) What is your expectation of online teaching quality?

(4) What are the factors impacting online teaching quality in priority sequence?

"Experience" questions are asked to the student,

(1) What is the definition of a good learning experience?

(2) What is the difference between classroom-based and online in terms of learning experiences?

(3) What is your expectation of the online learning experience?

(4) What are the factors impacting the online learning experience in priority sequence?

After finishing the environment component questions, relation objects "improve' and "promote" questions are generated,

(1) What is your proposal on improving online teaching quality/ learning experience?

(2) What are the functions you mostly wanted basing on current communication tools?

Naturally, both teachers and students will refer to the traditional classroom-based experience to share their ideas. The following are the analytics from the answers of the teachers and students.

Currently, a typical online education environment would be a meeting room opened via communication software, which the teacher hosts. The speaker is mainly a teacher, while all students listen and watch the materials (doc/slides) shared by the teacher. Both students and teachers use one display screen to share (from teachers) or view (from students). A typical environment of online education is illustrated in Figure 3.

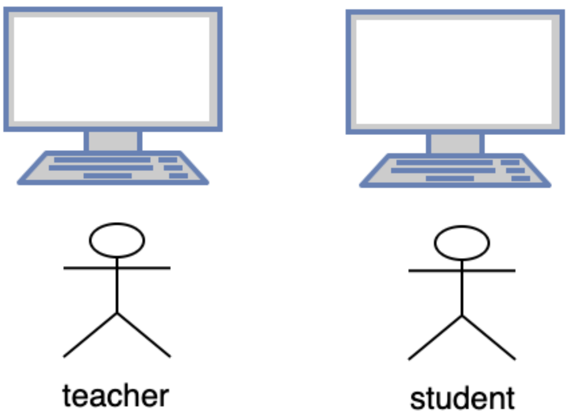


Fig. 3. A typical environment of online education.

The communication software is designed for video talk between two people, and therefore on the display screen, one can see another one's face clearly. Also, each party can get feedback from another quickly and easily. However, considering the online education environment, one teacher could face 20-30 students (or even more). The teacher will generally mute everyone to avoid noise so that students' voices cannot be heard during the course.

Interviewing several teachers and students helped us identified the following major problems within the current online teaching system.

(1) Lack of monitoring.
(2) Harm for eyes.
(3) Not enough interaction.
(4) No immediate feedback.
(5) Teachers being poor at computer skills.

For the five problems, we identify the two major issues that impact the "quality" and "experience" of online education are "monitoring" and "interaction."

- ***Monitoring***

Monitoring is mainly from the teacher's viewpoint. A teacher wants to see every student's behavior, which is extremely important as he/she can adjust the language speed and facial expression to call students attention, or ask someone to answer the question based on the observation of students' body language, facial expression, etc. Also, when doing an online quiz or test, monitoring is essential to guarantee the effectiveness and fairness of measuring a student's capability. Hence, monitoring is one of the critical components of online education. In this study, the generation of a better monitoring function will be paid sufficient attention.

- ***Interaction***

As shown in Figure 5, interaction is from both teacher and student's viewpoints. The teacher likes to get feedback from students, and the students want to call the teacher's attention if they have any questions. This is not an issue in a real classroom, and every student can raise a hand and get a chance to speak out when needed. However, this is difficult in the online environment as the teacher will generally mute every student to avoid noise. The students can only get a chance to speak by using the "raise hand" function provided by the communication software. Following signs illustrated the Zoom and Tencent meeting function, the teacher can easily ignore such a small button when talking/presenting some materials.

(a) "Raise hand" in Zoom/Tencent

(b) "Raise hand" in Tencent Meeting

Fig. 5. "Raise hand" in a different online meeting room

Some students also propose "anonymous" feedback as they may not want the teacher to know who raises such questions. This is a significant advantage over traditional classroom-based teaching as the communication software can easily hide the name of the feedback provider, and it somehow encourages the student to raise questions.

It should be noted that even for the onsite education scenario, when a teacher asks whether his students have any questions, few will raise their hand and ask a question. Due to many students are too shy to ask questions. Therefore, the function of "anonymous" feedback can assist the interaction between teachers and students.

We continue the process of asking the questions, collecting the answers, and then updating the environment components until we figure out all the relevant components to the design problem. Comparing with Figure 2, a detailed and updated ROM is shown in Figure 6. As shown in Figure 6, solutions are also generated to enhance monitoring and integration during online education. Essentially, the formulation of a better communication mechanism is the key both to online and onsite education.

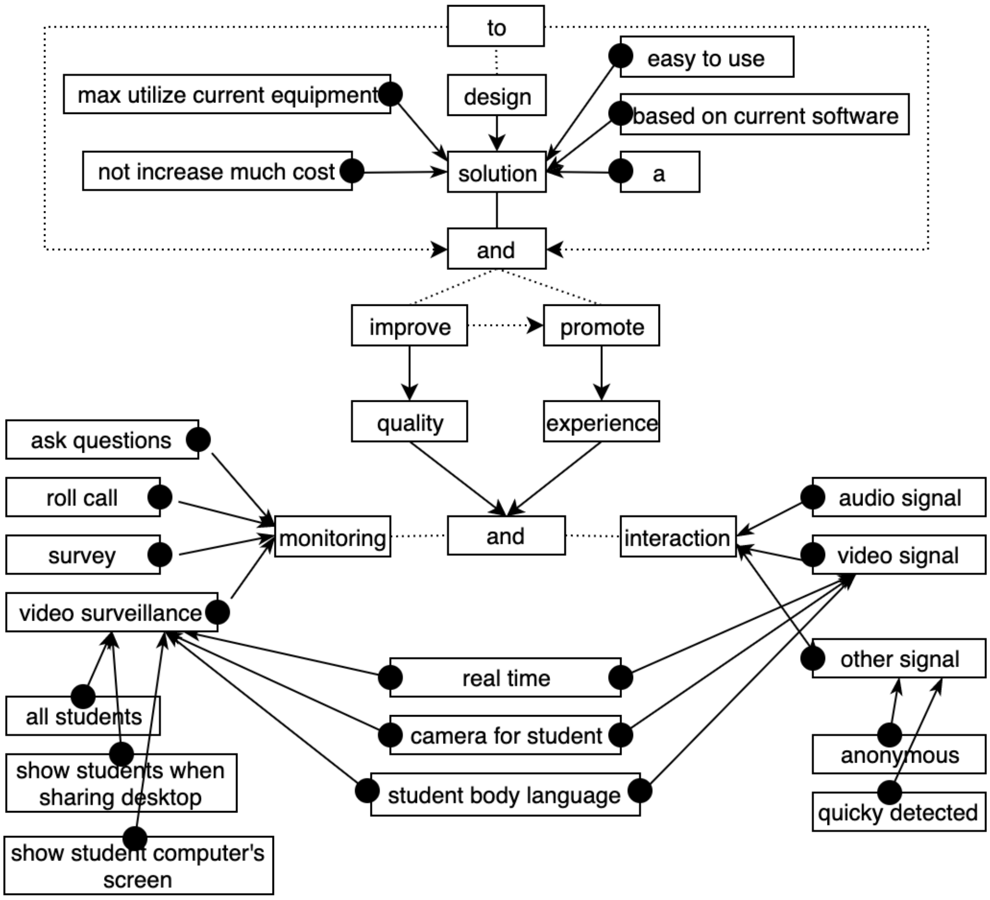


Fig. 6. Updated ROM

3. Conflict identification

According to EBD methodology, conflict refers to the insufficient resources required for an object to produce the required actions in its environment or to accommodate the actions of an object in its environment. There are three kinds of conflicts, i.e., active conflict, passive conflict, and key conflict. The active conflict refers to the shortage of resources to generate a response from the object. A passive conflict will occur when resources are insufficient to accommodate an object or its response. Among all conflicts, the key conflict is the conflict that has the most substantial impact on other conflicts. As shown in Figure 7, A, B1, B2, R1 and R2 represent different objects, C represents possible conflicts, A represents the original objects, B1 and B2, and R1 and R2 are parallel.

Based on the environment analysis and the updated ROM (see Figure 6) as mentioned above, and following the rules introduced by Yan and Zeng (2011), and Tan et al. (2012), we can identify five key conflicts as shown in Table 1.

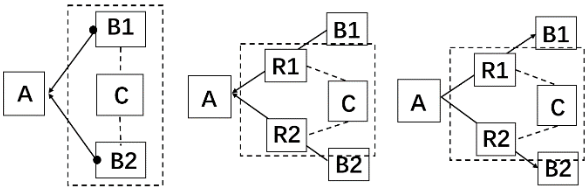


Fig. 7. Three possible conflicts in ROM (adapted from Tan et al. 2012)

Conflict 1: Current communication software cannot show the student's video when the teacher's desktop is sharing.

Conflict 2: Current communication software cannot video a student's body due to the camera's position. The camera typically sits on top of the laptop. When students look at the laptop's screen, the camera can only take the students' faces. As described above, the face is not good enough for the teacher's monitoring.

Conflict 3: The video monitoring wants to take all the students on one screen, which may introduce two issues:

(1) The network bandwidth for the teacher is limited; therefore, it is hard to get real-time video monitoring while keeping all students on the screen. Assume there are 50 students in an online course, and the video stream will typically take no less than 256kbps, which in sum is 50*256k = 12.8Mbps

(2) The display screen of the teacher is not big enough to hold all the students.

Conflict 4: As stated before, current communication software cannot support "anonymous" feedback from the student, like "I cannot understand this section," "the teacher talks too fast," "can the teacher repeat the problem A's solution?" etc. The student may be reluctant to share his/her name among the class. The "anonymous" mechanism help resolve this situation. Also, it requires such timely feedback and is shown on the teacher's screen to respond to improve learning experiences quickly.

Conflict 5: Current communication software cannot monitor the student computer's screen. This is important as the student may watch movies or other entertainment videos during the class. At the same time, the standard monitoring mechanism can only show how concentrated the student is focusing on the screen but cannot tell what content the student is focusing on. Also, when doing a quiz or test, student screen monitoring is essential as the student may refer to other materials to find out the answers. The screen monitoring mechanism can prevent such cheating.

Table 1. Identified conflicts

Number of conflicts	Illustration of conflicts
Conflict 1	show students when sharing desktop → video surveillance ← based on current software
Conflict 2	camera for student; student body language → video surveillance ← based on current software
Conflict 3	real time → video surveillance ← all students
Conflict 4	quickly detected; anonymous → other signal ← based on current software
Conflict 5	show student computer's screen → video surveillance ← based on current software

4. Solution generation

The environment-based design approach provides a rule for solution generation. Based on the EBD approach, the order of conflict to be solved is Natural conflict > Artificial conflict > human factor conflict. For solving the conflicts listed in Table 1, the conceptual design process is carried out in sequence according to the EBD approach.

4.1 Solution to conflicts 1&2

It is challenging to ask current communication software to support the second screen (conflict 1) or change the video camera's physical position (conflict 2). Therefore, this section proposes a method using two accounts to resolve conflicts 1 and 2. Each teacher and student have two accounts – a "monitor" account and an "education" account; a "monitor" account is used to set up the video monitoring system, "education" account is for regular online education.

As shown in Figure 8, the teacher has two screens in front of her, one to construct the virtual classroom using the "monitor" account, which shows the students' body behaviors. Another one is for sharing the desktop or materials/slides using an "education" account.

Similarly, the student will have two accounts to log in to, and the "monitor" account is typically using a cell phone. The cell phone's camera will take videos of students – the face and the body. These figures will automatically fit in the virtual classroom in front of the teacher. "Education" account is used on laptops for online education.

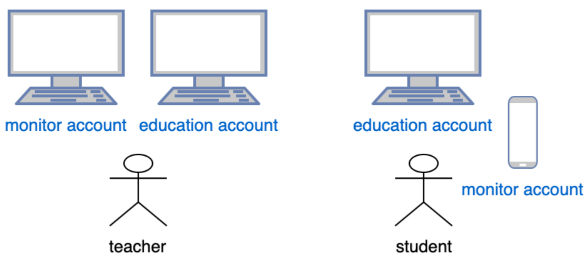


Fig. 8. A new environment for online education

4.2 Solution to conflicts 3

To resolve conflict 3, we propose a method like "filming" in the monitor area1 (see Figure 9), the virtual classroom will only show at most nine students figures at one time, lasting 2-5 seconds, then moving to the following nine students, and the next … The "filming" rotates between all the students. This effectively resolves the bandwidth limitations (only nine videos need to be transmitted at one time, approximately 9*256Kbps=2.3Mbps) and the video size issue (only nine videos need to be shown on one screen).

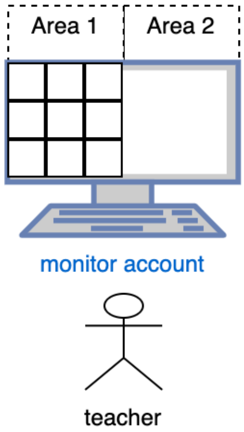


Fig. 9 "Filming" in monitor area 1.

4.3 Solution to conflict 4

On the teacher's monitor screen, we leave one area (area2 in Figure 9) for quickly catching the teacher's timely status. During the class, the message will prompt as,

Alarm: student A raises the question, "can you please repeat the process?"

Alarm: Anonymous, "speak too fast."

Alarm: student B raises his/her hand.

A student's education account will have the button "raise hand" like most communication software does today and have the option of anonymous feedback. An illustrative case was presented in Figure 10.

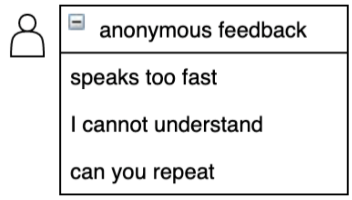


Fig. 10. Anonymous feedback

4.4 Solution to conflict 5

Apparently, current communication software does not show meeting participants' screens due to privacy reasons. While used for online education purposes, we propose the software to enable the option "monitor student's screen." These screen copies are not sent to the teacher, and they are sent to a backend analysis server instead. During the teaching activity, when the teacher shares the materials/docs to the students, the analysis server will automatically compare the screen copies with the contents shared by the teacher and raised alarms to the teacher if finding some student's screen copy is not expected (using the monitoring area 2 in Figure 8). The teacher can then alarm the student on concentrating back on the class contents. Again, during the quiz or test, the analysis server will automatically compare the screen copies with the quiz contents; an alarm will be raised if finding students change the quiz contents to other pages (like searching the answers via Baidu/Google).

4.5 Solution validation and discussion

Since the solution to conflict 3/4/5 requires modification on current communication software, we have initialized the discussion with several video communication software providers, and the solution has not yet been validated. Therefore, we developed a solution to conflicts 1 & 2.

The solution to conflicts 1&2 – i.e., two accounts solution is tried on online education of one TOFEL/SAT training company. We select the online courses with less than 9 students as samples, and the satisfaction rate is shown.

Samples: 10 classes (8 TOFEL, 2 SAT), average 6 students/1 teachers per class. Totally 10 teachers, 58 students.

Communication Software: Zoom

Satisfaction survey on teachers: 3.5 (5 – very satisfied, 1 – not satisfied at all)

Satisfaction survey on students: 3 (5 – very satisfied, 1 – not satisfied at all)

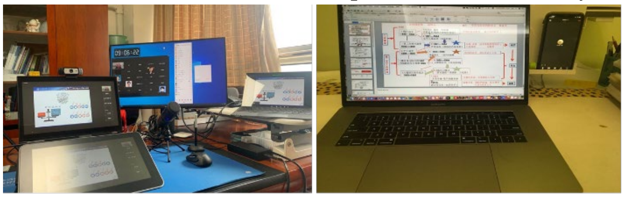
After we applied the two accounts solution, the satisfaction rate is increased by approx. 20% for the teacher, 10% increase for the student. This result is not surprising, as the two accounts solution is more helpful to the teacher than the students.

Satisfaction survey on teacher: 4.1 (5 – very satisfied, 1 – not satisfied at all)

Satisfaction survey on students: 3.4 (5 – very satisfied, 1 – not satisfied at all)

The possible solution to conflicts 1&2 has the potential to improve the satisfaction of online education. Both teachers' and students' environments are improved by using this solution. As shown in Figure 11a, for teacher's environment, two laptops are used as education account and monitor the account, respectively. For the education account, a handwriting board, a camera, and a microphone enhance the communication between teacher and students. For the education account, all the slides can be annotated by a teacher using a handwriting board. A teacher can use the monitor account to log in to the online education platform. On this hand, a teacher can observe the state of the education account (e.g., see the state of the slides and body language of a teacher), and on the other hand, can help a teacher to see the state of all the students via video and get to know what the students' real-time communication is and in time for user feed. As shown in Figure 11b, a student also has an education account to see the slides or other contents of a course. A monitor account is usually a cell phone. The cell phone's camera will take videos of students – the face and the body. These figures will automatically fit in the virtual classroom in front of the teacher.

Although solutions were developed to improve the satisfaction of online education, only conflicts 1&2 are solved. Because the solution to conflicts 1&2 depends less on software. However, some solutions depend on the development of new software functions, e.g., Zoom, Classin, which are out of the scope of the current study.



(a) Improved teacher's environment (b) Improved student's environment

Fig. 11. Solution for online education

5. Conclusion and outlook

This paper analyzes and tackles the barriers in online education using the Environment-Based Design (EBD) approach. Five key conflicts are identified by using the EBD approach, and the solution is generated to solving the five key conflicts. Surveys on both teachers and students revealed that the solution could promote the satisfaction of online education.

Our future work is to continue working with communication Software Companies to combine the two accounts into two roles of one account so that teachers and students do not need to log in using a different account and integrate the solution to conflict 3/4/5. Also, we will expand the trial to more audiences, recursively develop the system, and hopefully improve the experience of online education like traditional classroom-based.

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Application of Soft Computing for Time Series Water-Level Prediction in Jamuna River†

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Abstract

Time series analysis is one of the essential and complicated research methods. It is a well-known fact that improving time series prediction accuracy is a vital yet challenging issue. Recently, soft computing has become popular in time series forecasting in various application areas. Soft computing is a fusion of research of evolutionary and genetic algorithms, neural networks, fuzzy set theory, and fuzzy systems and provides rapid dissemination of results. This study investigates a model for time series water-level prediction using soft computing techniques which is reliable and effective. To illustrate the applicability and capability of soft computing, the Jamuna river, Bangladesh, was used as a case study. We used four areas of the Jamuna river (i.e., Aricha, Bahdurabad, Shariacandi, and Sirajganj) water-level and rainfall events with daily data collected in the past 12 years. In experiments, past 2 to 4 days' time-series wa-ter-level with and without rainfall has been applied to predict 1 to 4 days ahead water-level. The experimental results demonstrated that the adaptive neuro-fuzzy inference system (ANFIS) performs superiorly to traditional methods, such as nonlinear autoregressive neural network with external input (NARX) and focused time-delay neural network (FTDNN).

Keywords: Time series analysis, soft-computing, water-level prediction, ANFIS, NARX, FTDNN

1. Introduction

Time series prediction is a widely research and applied area, including weather forecasting, intelligent transportation, trajectory forecasting, and earthquake prediction. Time series analysis is highly complex due to the variation of knowledge, noise, and every observation is somehow dependent upon past remarks. However, the purpose of the forecast is to minimize the risk in decision-making. Time series water-level prediction is vital and essential research. Last few decades, many models have been used, including the general hydrodynamic numerical modeling system (Box et al., 2015). At present, water-level predictions have come to different intelligent methods to make decisions. Consequently, artificial neural networks (ANNs) and fuzzy techniques are employed as an efficient alternative in hydrodynamic numerical simulation studies.

Soft computing is one of the modern approaches for constructing computational intelligent or expert systems. Its ultimate goal is to emulate the human mind as closely as possible. Soft computing is a blend of methodologies designed to solve real-world problems using logic, which do not resolve or are complicated to solve mathematically. It includes neural networks, genetic algorithms, and fuzzy logic. Recently, these techniques identified as emerging alternatives to the standard well-established 'hard-computing' methods.

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The unique property of soft computing is, deep involvement in learning from experimental data makes it suitable for time series analysis. For these reasons, artificial neural networks, fuzzy systems, and adaptive neuro-fuzzy systems are practiced for time series analysis (Michie et al., 1995; Ross, 2010).

The water-level prediction model plays a significant role in providing relevant information on potential impending floods in populated locations. A prototype design can reduce the damage in areas by decreasing the environmental and economic impact of floods. For this reason, water-level variation analysis, as well as prediction, has been the subject of many research activities. We aim to investigate and implement a reliable and effective model for water-level prediction using a soft computing technique. The result of this study can support foretelling water-level or floods. Past time series water-level and rainfall are used to predict the future water-level, i.e., 1 to 4 days ahead. From the Jamuna river, Bangladesh, four stations (areas) are selected to evaluate the performance of the designed framework. We observe that ANFIS provides superior outcomes for time series water-level prediction compared to traditional NARX and FTDNN models.

This paper is organized as follows. We reported related works on water-level analysis in Section 2. Then, Section 3 explores a soft computing framework for time series water-level prediction. Experiment results presented and discussed in Section 4. Finally, we conclude in Section 5.

2. Related works

Time series analysis be classified into two categories: statistical approach and intelligent approach (Gelfand et al., 2019; Michie et al., 1995). Statistical methods utilize the background information by having an explicit underlying probability basis, but the action is supposed without human intervention. Therefore, these techniques show inefficiency for nonlinear and complex problems. The statistical approach includes autoregressive (AR), moving average (MA), and combined AR and MA (ARMA). Recently, experts applied technical-intelligent techniques, such as artificial neural networks (ANNs) and fuzzy logic systems. The intelligent system performs classification terminologies that mimic human reasoning enough to give insight into the decision process (Michie et al., 1995). There are ongoing efforts to integrate ANNs, fuzzy logic, rough set theory, and genetic algorithms (GAs) in the soft computing paradigm. Among these, neuro-fuzzy computing is the most visible.

Soft computing is utilized in many applications, including stock exchange trend prediction, intelligent transportation, trajectory forecasting, and earthquake prediction. ANN is an efficient tool to build expert systems and successfully applied monitoring problems, decision-support technologies, and statistical prediction (Fung et al., 2002; Huang et al., 2009; Seo et al., 2015). ANNs are used to predict water-level by Biswas and Jayawardena (2014) and Guldal and Tongal (2010). The ANN, ARIMA (autoregressive integrated moving average), and NARX (nonlinear autoregressive network with exogenous inputs) models are comparative and better predict water-level than the hydrodynamic models (Grimes et al., 2003). In recent decades, machine learning has become a popular research topic and successfully implemented in research within statistics, including time-series stock exchange price prediction (Abbasi and Abouec, 2008; Abdulsalam et al., 2011; Boyacioglu and Avci, 2010; Castillo-Boton et al., 2020; Chou et al., 2018; Chang and Liu, 2008; Mahmud and Meesad, 2016). Alternatively, the ANFIS provides a novel computational approach, combining the idea of ANN and fuzzy inference learning (Jang, 1993).

Last few decades, many research have been submitted about water-level prediction, each of them used different parameters for comparison (Panda et al., 2010; Seo et al., 2015). Water-level prediction is the act of trying to determine the future condition of water trends. The statistical technique is popular in water-level monitoring and forecast, flood modeling and mapping, and ice-level monitoring. The statistical methods used to determine the likelihood, frequency, and intensity of water discharge affecting floods (Goovaerts, 2019; Zhang et al., 2019). The models and mapping practiced to discover and visualize the extent of possible flooding, abnormal amounts of rainfall, and sudden large amounts of water discharges can be monitored to provide short-term flood predictions (Pamda et al., 2010).

It can be beneficial when several uncertainties are manifested in a system. Soft computing is employed in many practical engineering situations because of its capability in dealing with obscure and imprecise information (Ahmed et al., 2019; Yue and Kontar, 2020). The powerful aspect of the soft computing model is that most human reasoning and concept formation are transformed into rules. The combination of rough and incomplete information and the imprecise nature of the decision-making process makes the neuro-fuzzy model efficient in modeling complex engineering, control, classification, prediction. This approach consolidates imprecision and subjectivity in model formulation and solution processes (Lu et al., 2017; Ramachandran, 2020). Nevertheless, optimal neuro-fuzzy systems design are complicated tasks, and it builds by determining the most suited number of rules, fitted parameters, and structure of the fuzzy-logic systems (Tekeli et al., 2019).

3. Method

It is challenging to deal with time series temporal data. The aim of this study is time series water-level prediction using soft computing. Past temporal water-level and rainfall data are applied to predict future water-level. The proposed model is shown in Fig. 1.

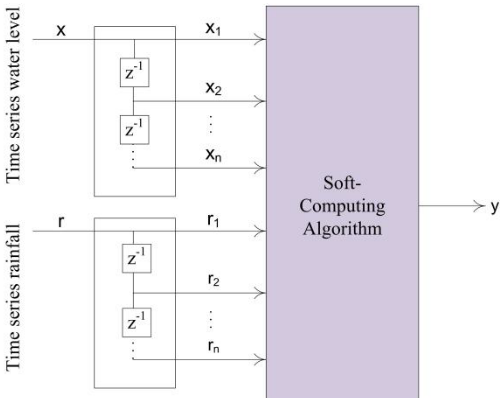

Fig. 1. Architecture of the proposed soft-computing model.

3.1 Workflow

The workflow of the proposed model as follows.

Step 1. Data preprocessing: Time series data sampling as a train and a test set.

Step 2. Parameter selection: To design the framework, we perform the prediction horizons selection and how many ahead have to predict.

Step 3. ANFIS design: In this study, a traditional five-layers ANFIS network is adopted. To design the ANFIS network, we applied two to four inputs, the 'bell-shaped' membership function and fuzzy rules generated from 'genfis1', where 'genfis1' generates a single-output Sugeno-type fuzzy inference system (FIS) for ANFIS using a grid partition on data.

Step 4. Training model: After loading the training data and generating the initial model structure, we start training according to the learning algorithm.

Step 5. Test model: Finally, we test the model against the test sub-dataset and evaluate the result.

3.2 Time series data

Time series is a sequence of records from past to present, denoted by $x(k), k = 1,2,\dots,n$. Extending backwards from time k has time series $x(k), x(k-1), x(k-2),\dots, x(k-n)$. From this, the prediction x is at future time h,

$$x(k+h) = f\big(x(k), x(k-1), x(k-2),\dots, x(k-n)\big) \quad (1)$$

Assume, in case of $h = 1$, the time series $x(k), x(k-1),\dots, x(k-n)$ as the inputs and the predicting value $x(k+1)$ can be obtained as the output. The prediction error $e(k)$ is the difference between actual value $x(k+1)$ and prediction value $y(k)$ can be expressed as

$$e(k) = x(k+1) - y(k) \quad (2)$$

3.3 Adaptive neuro-fuzzy inference system (ANFIS)

ANFIS integrates the advantage of the neural network's learning capabilities and fuzzy system's transparency. The basic ANFIS network is illustrated in Fig. 2.

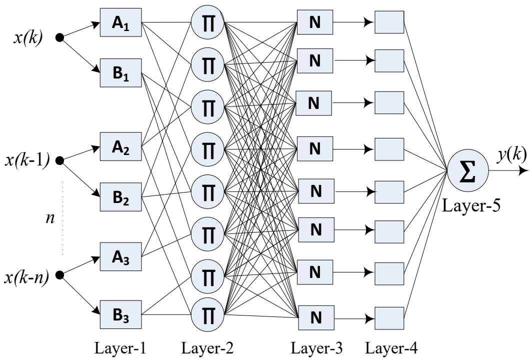

Fig. 2. Jang's ANFIS architecture.

The first layer is the fuzzification layer. Each input node i generates a membership grade of the crisp inputs which belong to each of the convenient fuzzy sets by using the membership functions. There are various membership functions such as 'gaussian', 'sigmoidal', 'triangular', and 'trapezoidal'.

The second layer is the product layer. Every node of this layer (marked as $\prod$) multiplies the incoming signals from the fuzzification layer. The output of each node represents the firing strength of fuzzy rules.

The third layer is the normalization layer. Every ith node (marked as N) computes the ratio of the ith rules firing strength to the sum of all rules strengths.

The fourth layer is the defuzzification layer. Every node i (square node) with a node function computes the contribution of each ith rule toward the total or the model output.

The fifth layer is marked by $\sum$, which calculates the overall output by summing all the incoming signals. Fuzzy results are transformed into a crisp value in this layer by the defuzzification process.

Experimental results and discussions

4.1 Dataset and data preprocessing

In this study, past time-series water-level and rainfall data are adopted to predict water-level. The experiment emphasizes water-level prediction for the Jamuna river, Bangladesh. The dataset has been collected from the Bangladesh Water Development Board (BWDB), which contains water-level and rainfall followed by twelve years of consecutive data from January 2005 to May 2017. We selected four stations of the Jamuna river: Aricha (3,730 days), Bahadurabad (3,270 days), Shariacandi (3,550 days), and Sirajganj (3,430 days), to predict water-level. Among the total dataset, 60% used as a train-set and the remaining 40% used as a test-set.

3.2 Experiment setup

The experiments were set up to predict water-level for 1 to 5 days ahead, using past consecutive 2 to 10 days of time-series data. We observed that significant results are achieved for two to four days of input and one to four days ahead of prediction. The experiment focused on two types of models,

-Type-1 model: predict water-level using past water-level (WL), without applying rainfall.

-Type-2 model: predict water-level using past water-level with rainfall (WLR).

For model comparison, we compared results of dynamic neural networks, such as FTDNN (focused time-delay neural network), NARX (nonlinear autoregressive neural network with external input), and ANFIS (adaptive neuro-fuzzy inference system).

4.3 Result analysis and discussion

In experiment 1, for Aricha station (Table 1), it is found that ANFIS performed significantly better than NARX and FTDNN in all cases, i.e., 1 to 4 days ahead without rainfall. The best accuracy achieved for one-day ahead prediction using the previous three-days input, which is 99.58%, whereas one-day ahead prediction using 2 to 4 days past data accuracy is similar. In applying rainfall, accuracy gained significantly for one-day ahead prediction using 2 to 4 days of previous data, where accuracy is above 99.50%.

In experiment 2 for Sirajganj station, in Table 2, also noticed ANFIS performed significantly better than NARX and FTDNN in all the cases, i.e., 1 to 4 days ahead prediction using with and without rainfall. The highest accuracy is 99.67%, achieved for one-day ahead prediction with the past three days' input. While we applied rainfall, a notable result was gained (99.65%) for one-day ahead prediction using the past two days of water-level with one-day rainfall data input. One-day ahead prediction using 2 to 4 days past input accuracy is quite similar, i.e., higher 99.60%.

Table 1. This Performances for Aricha station. (Acc: Accuracy and bold value indicates best result).

	Models												
		Without rainfall (WL)						With 1 day rainfall (WLR)					
		NARX		FTDNN		ANFIS		NARX		FTDNN		ANFIS	
Prediction	Input series	RMSE	Acc	RMSE	Acc	RMSE	Acc	RMSE	Acc	RMSE	Acc	RMSE	Acc
1 day ahead	2 days WL	0.07	95.86	0.07	95.82	0.07	**99.57**	0.08	95.81	0.07	95.75	0.08	**99.56**
	3 days WL	0.37	94.86	0.08	95.72	0.07	**99.58**	0.07	95.80	0.09	95.71	0.08	**99.56**
	4 days WL	0.13	95.38	0.13	95.45	0.08	**99.56**	0.10	95.58	1.64	88.34	0.11	**99.50**
2 days ahead	2 days WL	0.07	95.84	0.14	91.04	0.14	**99.10**	0.07	95.92	0.14	91.14	0.14	**99.09**
	3 days WL	1.08	92.53	0.94	88.67	0.14	**99.11**	0.08	95.70	0.16	91.27	0.14	**99.09**
	4 days WL	0.08	95.58	0.24	90.48	0.17	**99.07**	0.14	95.28	1.50	85.18	0.21	**98.97**
3 days ahead	2 days WL	0.08	95.53	0.21	86.05	0.21	**98.59**	0.08	95.40	0.20	86.32	0.21	**98.59**
	3 days WL	0.08	95.29	0.20	86.46	0.21	**98.60**	0.12	94.92	0.21	86.24	0.21	**98.59**
	4 days WL	0.11	94.97	0.28	85.28	0.24	**98.54**	0.09	95.28	0.27	85.57	0.32	**98.40**
4 days ahead	2 days WL	0.09	95.01	0.30	80.66	0.28	**98.08**	0.09	95.04	0.27	81.98	0.28	**98.09**
	3 days WL	0.87	94.91	0.28	81.05	0.27	**98.08**	0.99	91.59	0.27	81.40	0.28	**98.07**
	4 days WL	0.11	94.50	0.57	79.24	0.31	**98.00**	0.24	93.54	0.64	78.40	0.43	**97.84**

Table 2. This Performances for Sirajganj station. (Acc: Accuracy and bold value indicates best result)

	Models												
		Without rainfall (WL)						With 1 day rainfall (WLR)					
		NARX		FTDNN		ANFIS		NARX		FTDNN		ANFIS	
Prediction	Input series	RMSE	Acc	RMSE	Acc	RMSE	Acc	RMSE	Acc	RMSE	Acc	RMSE	Acc
1 day ahead	2 days WL	0.13	95.03	0.12	95.25	0.12	**99.65**	0.11	95.26	0.15	94.97	0.13	**99.65**
	3 days WL	0.24	94.35	0.14	95.31	0.12	**99.67**	0.14	95.13	0.13	95.16	0.17	**99.64**
	4 days WL	0.24	94.18	0.35	93.87	0.14	**99.64**	0.30	93.97	0.16	94.88	0.14	**99.63**
2 days ahead	2 days WL	0.18	94.88	0.21	88.90	0.22	**99.20**	0.13	95.26	0.21	89.38	0.25	**99.19**
	3 days WL	0.31	93.69	0.22	89.18	0.21	**99.24**	0.23	94.11	0.19	89.61	0.24	**99.22**
	4 days WL	0.34	93.96	0.21	89.20	0.29	**99.16**	0.12	95.18	0.28	88.50	0.26	**99.15**
3 days ahead	2 days WL	0.13	94.60	0.29	83.34	0.31	**98.71**	0.13	94.57	0.34	82.47	0.39	**98.69**
	3 days WL	1.20	90.62	0.31	82.31	0.29	**98.78**	0.12	94.68	0.29	83.41	0.33	**98.76**
	4 days WL	0.20	93.56	0.30	82.94	0.45	**98.65**	0.13	94.41	0.29	83.53	0.43	**98.60**
4 days ahead	2 days WL	0.13	93.95	0.38	76.68	0.40	**98.27**	0.13	93.73	0.37	77.16	0.52	**98.21**
	3 days WL	0.17	93.45	0.39	76.40	0.37	**98.34**	0.12	94.10	0.36	77.92	0.40	**98.32**
	4 days WL	0.14	93.65	0.65	74.02	0.53	**98.17**	0.15	93.67	0.38	76.54	0.62	**98.06**

Table 3. Performances for Bahadurabad station. (Acc: Accuracy and bold value indicates best result).

	Models												
		Without rainfall (WL)						With 1 day rainfall (WLR)					
		NARX		FTDNN		ANFIS		NARX		FTDNN		ANFIS	
Prediction	Input series	RMSE	Acc	RMSE	Acc	RMSE	Acc	RMSE	Acc	RMSE	Acc	RMSE	Acc
1 day ahead	2 days WL	2.98	75.39	0.29	91.04	0.97	**99.46**	0.53	89.20	0.30	93.16	0.80	**99.48**
	3 days WL	5.74	65.09	0.41	91.94	2.12	**99.06**	0.48	90.59	0.35	91.82	2.35	**98.96**
	4 days WL	0.77	85.42	0.46	89.43	5.83	**98.11**	0.47	88.59	0.09	79.62	3.85	**98.58**
2 days ahead	2 days WL	1.12	60.04	0.45	85.35	1.97	**98.87**	2.00	83.64	0.18	82.29	1.74	**98.90**
	3 days WL	0.72	87.56	0.47	81.66	3.6	**98.32**	0.53	89.76	0.17	83.47	4.21	**98.06**
	4 days WL	0.84	88.16	0.51	82.98	8.94	**96.77**	0.41	90.07	0.17	80.42	7.70	**97.09**
3 days ahead	2 days WL	2.02	76.26	6.71	46.68	2.74	**98.33**	2.13	75.87	0.26	73.92	2.41	**98.33**
	3 days WL	0.47	89.20	0.55	77.17	4.68	**97.74**	1.23	82.56	0.25	75.65	5.66	**97.35**
	4 days WL	5.34	55.95	0.58	77.18	8.41	**96.35**	0.47	90.33	0.25	73.72	10.56	**95.61**
4 days ahead	2 days WL	2.19	73.68	0.73	68.19	3.32	**97.81**	0.34	89.52	0.33	70.15	2.96	**97.80**
	3 days WL	0.30	90.34	0.69	66.26	5.48	**97.27**	0.44	86.95	0.32	63.60	6.67	**96.83**
	4 days WL	0.50	87.64	4.42	47.42	11.49	**94.66**	1.05	80.48	0.32	36.90	16.04	**93.92**

Table 4. Performances for Shariacandi station. (Acc: Accuracy and bold value indicates best result).

	Models												
		Without rainfall (WL)						With 1 day rainfall (WLR)					
		NARX		FTDNN		ANFIS		NARX		FTDNN		ANFIS	
Prediction	Input series	RMSE	Acc	RMSE	Acc	RMSE	Acc	RMSE	Acc	RMSE	Acc	RMSE	Acc
1 day ahead	2 days WL	0.09	95.77	0.09	95.81	0.08	**99.76**	0.10	95.68	0.09	95.66	0.09	**99.75**
	3 days WL	0.87	95.83	0.08	95.94	0.08	**99.76**	0.93	95.52	0.09	95.70	0.09	**99.74**
	4 days WL	0.12	95.57	0.08	96.03	0.08	**99.75**	0.32	94.37	0.09	95.67	0.12	**99.71**
2 days ahead	2 days WL	0.21	95.14	0.18	90.91	0.18	**99.46**	0.14	95.48	0.18	90.85	0.19	**99.45**
	3 days WL	0.08	95.70	0.17	91.03	0.18	**99.46**	0.09	95.69	0.17	90.93	0.18	**99.45**
	4 days WL	0.10	95.59	0.17	91.02	0.18	**99.45**	0.11	95.23	0.19	90.51	0.23	**99.39**
3 days ahead	2 days WL	0.09	95.55	0.38	84.79	0.26	**99.16**	0.10	95.29	0.26	86.15	0.28	**99.16**
	3 days WL	0.10	95.27	0.26	86.13	0.26	**99.17**	0.10	95.10	0.26	85.59	0.27	**99.15**
	4 days WL	0.22	94.50	0.26	85.87	0.28	**99.13**	0.93	95.17	0.27	85.33	0.33	**99.08**
4 days ahead	2 days WL	0.10	94.70	0.36	80.29	0.34	**98.86**	0.10	94.89	0.35	81.34	0.36	**98.86**
	3 days WL	0.10	94.70	0.34	81.06	0.34	**98.87**	0.15	94.27	0.34	80.56	0.35	**98.84**
	4 days WL	0.10	94.54	0.35	80.47	0.36	**98.83**	0.10	94.73	0.34	80.62	0.41	**98.76**

Furthermore, in two other experiments for Bahadurabad and Shariacandi stations, Table 3 and 4, respectively, illustrate that ANFIS performed significantly better comparing NARX and FTDNN in 1 to 4 days ahead prediction. According to the experimental results, we noted including rainfall data as input to the model shows no significant improvement in performance.

In contrast, the RMSE (root mean square error) for the four individual experiments is different because of the variation of data. It also noticed that FTDNN and NARX models have lower accuracy (Acc.). ANFIS provides better prediction, whereas FTDNN and NARX provided poor results for several cases (see Figs. 2-5 for more details). Figures 2, 3, 4, and 5 displayed a time series response length n = 100 generated by the NARX, FTDNN, and ANFIS model for Aricha, Bahadurabad, Shariacandi, and Sirajganj stations, respectively. In the figures, we observed while ANFIS is reasonably good of the actual prediction, the FTDNN and NARX are badly affected and provide a poor estimation for several points. The advantage is, ANFIS and NARX both rely on component adjustment by previous time prediction. Nevertheless, many data points are measured on large-inverse difference prediction in FTDNN and NARX. For a sudden location which is no issue.

Conclusion

This study proposed and evaluated a soft computing model to predict time series water-level. Time series water-level and rainfall are employed to estimate future water-level for one to four days ahead. In this case study, four stations of Jamuna river were experimented with to evaluate the performance of soft computing techniques. Experimental results confirmed that ANFIS provides superior results for time series water-level prediction compared to NARX and FTDNN models. In the experiment, we used twelve (12) years of data. This model can be more reliable and stable if potential to test on more historical data. It is worth to noting that our model is not proficient in predicting the monsoon river floods, storm surge floods, and flash floods because of more features needed, i.e., brute-force and tide force.

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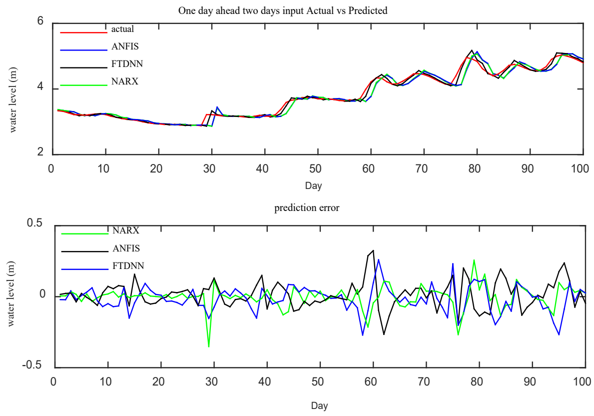

Fig. 3. One day ahead prediction using two days water-level with rainfall of Aricha station.

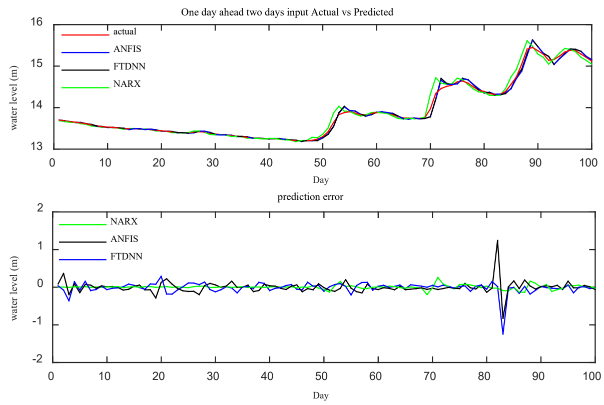

Fig. 4. One day ahead prediction using 2 days water-level with rainfall of Bahadurabad station.

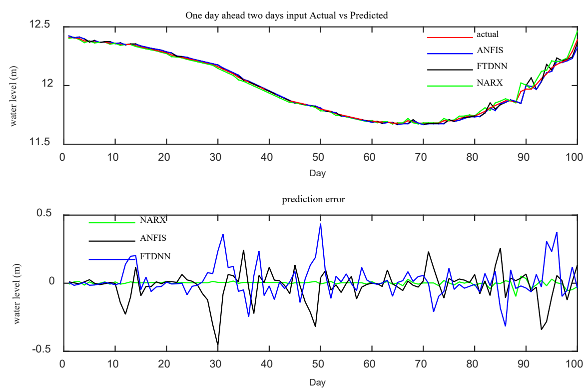

Fig. 5. One day ahead prediction using 2 days water-level with rainfall of Shariacandi station.

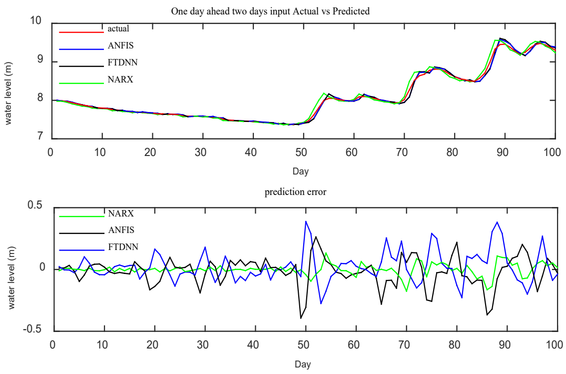

Fig. 6. One day ahead prediction using 2 days water-level with rainfall of Sirajganj station.

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Systematic Customer Value Analysis: A Case Study in the Automotive Industry

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Abstract

Providing high quality with competitive prices is generally essential in the automotive industry because of the customers (directly automotive OEMs and indirectly their end-users) demanding new and costly features without showing additional willingness to pay. For this reason, accurate analysis of customer value can be very helpful for developing new concepts, and hence for correct positioning in this competitive area. Although one of the most important parts of the engine in an automobile is the clutch, there are very limited studies on its value analysis in the literature. Correspondingly, to fill this gap, this paper analyses the customer value of automotive clutch components and their functions by using a two-phase QFD methodology, and a fuzzy-logic based data-fusion methodology. While the former phase determines relative weights of the bene-fit through the House of Quality, the latter phase performs the parts (and cost) deployment to determine the costs of the clutch functions by using a reverse costing analysis incorporating the product teardown cost in-formation. Having obtained benefit, cost, and technical difficulty information, a fuzzy-logic model evaluates the competitive importance of each clutch function. This work identifies the three most important clutch functions and their related subcomponents.

Keywords: Automotive clutch, customer value analysis, fuzzy systems, quality function deployment.

1. Introduction

Cost is one of the most important factors in the developments in today's highly competitive automotive industry. Improving the durability and reliability with low-cost solutions is, therefore, the main concern of the automotive suppliers. It becomes more critical for the parts requiring maintenance or renewal by time depending on the operating conditions. As an important example to these parts, automotive dry clutch, used in the manual and automated manual transmissions do not have the same lifecycle as the vehicle, and therefore improving its functions with this concern is crucial for staying competitive. Fig. 1 illustrates a typical automotive dry clutch system. A clutch system transfers the torque between an internal combustion engine (ICE) and transmission shaft and it may suffer from excessive operating conditions that may result in service visits.

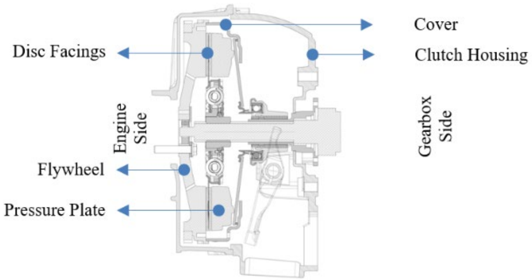


Fig. 1. A typical automotive dry clutch system.

Automotive clutches are not directly in interaction with drivers. However, there are many requirements linked to the clutches regarding driving functions and the comfort of passengers. These customer requirements shape the clutch design and affect its cost as well. Pedal comfort, durability, reliability, no slippage, NVH performance, allowing good gear shifting, enough torque transmission are the main customer requirements that clutch manufacturers consider.

Pushed by the necessity to lower CO_2 emissions, there is a clear trend towards the electrification of road transport. According to Schaeffler (2018), over the next few years, the number of powertrain concept variants for motor vehicles will continue to develop. Moreover, ICEs will still play an important role in 2030: 30% are expected to be maintained as ICE and 40% of the manufactured electric vehicle will be Hybrid Vehicle (HEV), which means with a gearbox. In the same direction, more than 1.000 market experts and automotive executives interviewed by KPMG (2019) project a balanced mix of powertrains in the product portfolio of the future: by 2040 with a similar split, being, in this case, the percentage of ICEs and HEVs equal to 45%. Regarding trucks, for example, today, the reality is that only 0.04% of all trucks on EU roads are electrically chargeable (ACEA, 2019).

Accordingly, it is anticipated that the ICEs, so the dry clutch systems will play an important role for the next decade of the automotive industry. Fig. 2 illustrates the transmission types comprising dry clutch systems and their market evolution estimation within a decade. Manual and automated transmission types comprise single dry clutch systems, while double-clutch transmission (DCT) has dry or wet double clutch systems. Their total market share is 52% in 2020, and the estimation for 2030 is 40%. On the other hand, damper systems have additional potential for being used in also HEVs having a 40% market share in 2030.

When considered the competition in the market, value analysis of dry clutch functions is an essential issue of the research and development activities. However, very few studies in the literature systematically examine the customer value of the automotive clutch. Torres et al. (2010) propose a methodology to provide design information flow between customer needs, functional requirements, key characteristics, and design parameters by integrating QFD, Axiomatic Design (AD) concepts, Failure Mode Effect Analysis (FMEA), and MOKA (Methodology and software tools Oriented to Knowledge-based engineering Applications) with support of a Computer Aided Drawing (CAD) system. Yan and Liu (2012) address the relationship between failures and design theory and experimental methods to reduce failure rate and improve product reliability. They employ the Root Cause Analysis (RCA), QFD, and D-FMEA to improve the design theory and the experimental methods. Xie et al. (2016) employ the RAHP method for rating the importance of customer requirements of the automotive clutch. In this way, they obtain a more accurate priority sequence of the final customer requirements. Likewise, Yan et al. (2018) employ a similar methodology to assess customer requirements for clutch friction material. Table 1 shows a summary of the relevant literature studying clutch applications.

The preliminary studies are restricted to doing a QFD analysis of the customer requirements, without any consideration of the benefit-cost ratio of clutch functions, and cost deployment for Value Engineering (VE). This study aims to extend these efforts by employing cost deployment (i.e., VE) and considering the benefit-cost ratio assessments.

These ratios are essential for accurate analysis of the customer value and correct positioning in this competitive area. This topic needs further investigation and therefore this has been the inspiration and starting point for the research.

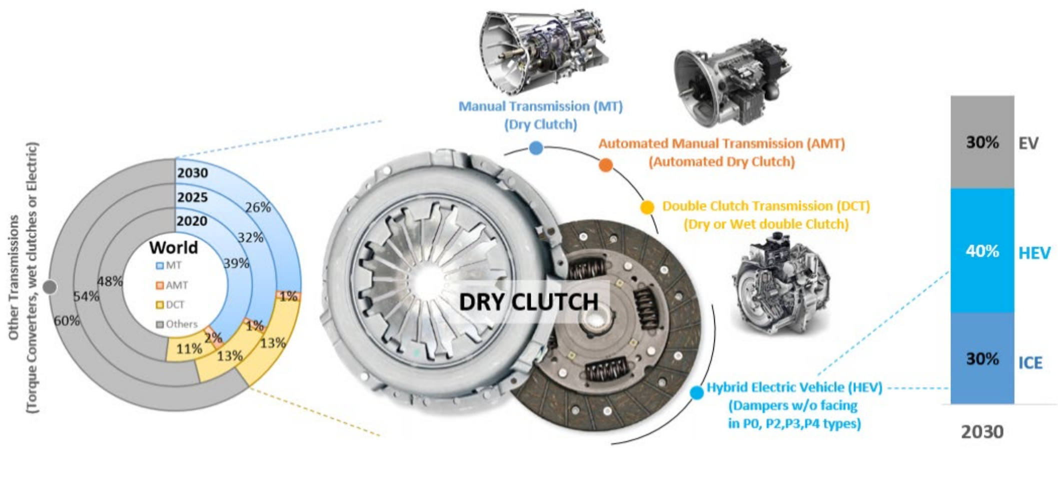


Fig. 2. Transmissions including dry clutch systems.

Table 1. A summary table of the relevant literature.

Literature	Customer requirements													Methods
	Good performance			Reliability			Service			Ergonomic Comfort				
	Slippage	Gear shifting	High speed stability	Burn	Fracture	Durability	Interchangeability	Maintanence	Pedal Comfort	Vibration and noise	Compact structure	Cost	Environmental	
Torres et al. (2010)	●	●	○	●	●	●	○	●	●	●	●	●	○	QFD, AD, FMEA, MOKA
Yan and Liu (2012)	●	●	○	○	●	○	○	○	●	●	○	○	○	RCA, QFD, DFMEA
Xie et al. (2016)	●	●	●	●	●	●	●	●	●	●	●	●	●	Delphi, AHP
Yan et al. (2018)	●	●	●	●	●	●	●	●	●	●	●	●	●	AHP, QFD
This work	●	●	●	●	●	●	●	●	●	●	●	●	●	QFD-VE, Kano, AHP, Fuzzy Logic

With this purpose in mind, this study performs an advanced investigation of clutch functions to obtain the benefit-cost ratios (which are crucial to prioritize the product development attempts). This investigation is based on a systematic customer value analysis procedure employing the two phases of QFD (i.e. House of Quality, and Parts-costs deployment), Kano, AHP, and fuzzy logic (to support VE). It should be noted here that this study is a real case, and conducted by a team of clutch experts. This advanced investigation identifies and maps critical clutch functions and their correlated subcomponents, concisely. This concise map could help the developers to arrange and assess the worthy systematic innovation attempts. This study also addresses a case of Theory of Inventive Problem Solving (TRIZ) as an illustrative example.

The rest of the paper is organized as follows. Section 2 presents the methodology. Section 3 presents the "House of Quality" assessing the customer benefits of clutch functions. Section 4 presents the "parts deployment" assessing cost shares of each clutch function. A customer value analysis using a fuzzy inference system is given in section 5. An innovative clutch concept is provided in section 6. Finally, conclusions and future work are given.

2. Methodology

Yoji Akao introduced the concept of QFD in 1969, and later many researchers enhanced the power of QFD through several methods. The review by Sivasankaran (2020) and Singh et al. (2018) encompasses a range of approaches used in the literature. Typical QFD processes are generally based on data expressed in natural language. A great majority of works in recent literature have therefore addressed the issue, computing these ambiguities regarding the voice of customer, by proposing fuzzy QFD approaches. Reviews on fuzzy QFD can be found in Abdolshah and Moradi (2013), and Singh and Rawani (2020).

A typical QFD process focuses on customer satisfaction. On the other hand, providing the functional needs at a low cost is the main topic of Value Engineering (VE) literature. Providing better customer value with retaining the cost of the product has been overlapping literature of QFD and VE. Correspondingly, some integrated QFD and VE (QFD-VE) approaches have also been proposed in the literature by integrating cost deployment into QFD to achieve the target cost by keeping a balance with customer satisfaction. A recent literature review for the integration of QFD and VE in improving product quality can be found in Ishak et al. (2020).

Rather fewer attempts at analyzing automotive dry clutch functions have been reported in the literature. It is worth pointing out that some authors have used the QFD methodology for analyzing customer requirements, but previous research typically only investigated the "House of Quality", the first phase of QFD. Further investigations are required for such a complex part to assess the sub-functions and their correlated subparts.

With this purpose in mind, this study employs a QFD-VE approach performing a three phases procedure (that is summarized in Fig. 3) to analyze automotive dry clutch functions. While the first phase (i.e. House of

Quality phase) aims to clarify the "benefit" of each functional requirement from the point of the customer view, the second phase (i.e. parts-cost deployment phase) calculates the "cost" share of each functional requirement by considering the function-part relations. In the final phase (i.e. customer-value analysis phase), a type-1 fuzzy inference system helps in fusing these benefits, costs, and technical difficulties data to infer the "importance" of each functional requirement under consideration. This study provides a systematic customer value analysis for automotive dry clutch functions. It should be noted here that this study employs fuzzy logic to support the VE process. Therefore, the methodology of this work is related to the integrated QFD and VE, instead of fuzzy QFD literature. The use of fuzzy logic in QFD-VE is not common when compared to fuzzy QFD literature. Ishak et al. (2020) review the literature of QFD-VE. This review study has listed only one fuzzy approach for QFD-VE enabled target costing (Gandhinathan et al., 2004). Gandhinathan et al. (2004) employ the fuzzy logic to strengthen the QFD-VE model through better handling the uncertainty associated with the cost of various elements. In contrast to this use of fuzzy logic, this study employs a type-1 fuzzy system as a data-fusion methodology, to fuse the difficulty, benefit, and cost data, for inferencing the importance of clutch functions.

Through the procedure followed by this work, we provide a comprehensive customer value analysis for the automotive clutch, one of the most important parts of an automobile. In this way, we have identified the most important clutch functions and their related subcomponents as a concise list for consideration during the new product development process. On the other hand, from the methodological point of view, the procedure proposed in this work is a practical framework incorporating an enhanced QFD methodology through fuzzy systems and the Kano model for an accurate customer value analysis.

3. House of quality for automotive clutch

Customers are generally considered as "those companies want to create value for." Linking the "voice of customers" to the "voice of technicians" is essential to fulfilling customer requirements, and hence to create "customer value." The first phase of QFD (also called HoQ – House of Quality because of its house-shaped diagram) is the unique phase providing a systematic procedure for illustrating this link with a conceptual map. Correspondingly, the procedure of a typical HoQ is conducted to analyze "customer value" for the automotive clutch in this study. Fig. 4 shows a conceptual map of the relationship between "customer requirements" and "clutch functions."

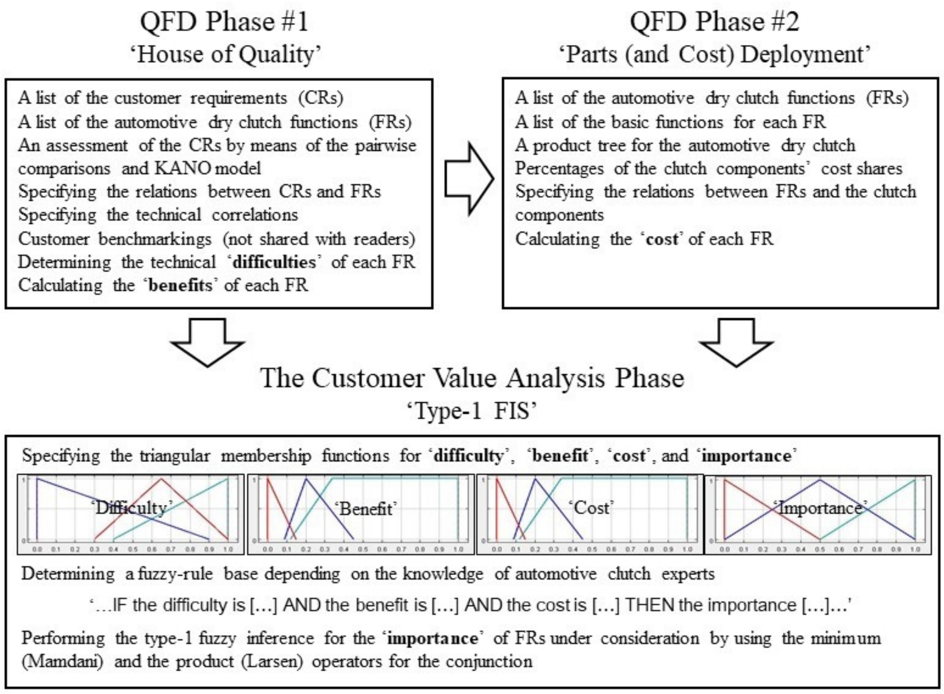
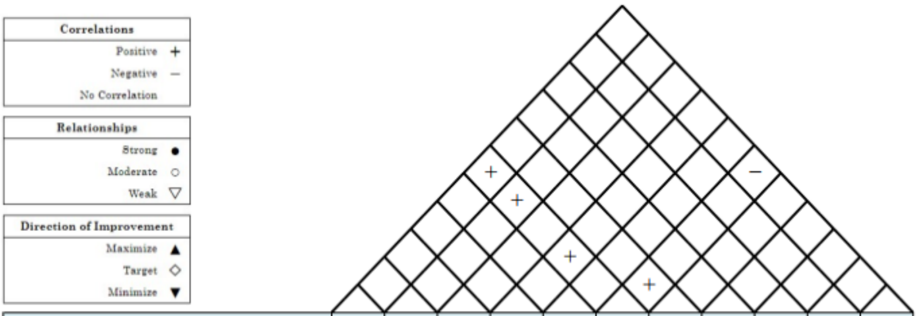


Fig. 3. A summary of the procedure followed by this study.



			Column #	1	2	3	4	5	6	7	8	9	10	11
			Direction of Improvement	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲
Row #	Relative Weight	Maximum Relationship	Customer Requirements (Explicit and Implicit) / Functional Requirements	Transmitting the torque between engine and gearbox	Allowing the disconnection between engine and gearbox during gear shifting	Assuring correct installation and correct assembly at customer's site	Ensuring engine starting/shut down	Allowing the right packaging and transport	Assuring reliability	Filtering vibrations / rotations irregularities of the motor propulsor unit	Absorb misalignments and eccentricity of the input shaft as regards the crank shaft	Avoid noise during slippage phase (gearshifting and start-up)	Not polluting	Being recyclable
1	15,0%	9	(P) Enough power, without slipping	●					●					
2	15,0%	9	(P) Engage and disangage function	○	●				●					
3	7,5%	9	(P) High-speed stability	●	○				●					
4	4,9%	9	(R) Friction plates does not burn	●					●					
5	9,8%	9	(R) Parts not fracture	○					●		●			
6	9,8%	9	(R) Long life for use	▽	○		▽		●		●			
7	4,5%	9	(S) Parts of good interchangeability			●								
8	1,9%	9	(S) Disassembly, adjustment and maintenance			●								
9	8,5%	9	(ER&CO) Pedal comfort		●				○	●				
10	13,4%	9	(ER&CO) Vibration and noise		●		▽		●	●	○	●		
11	1,2%	3	(ER&CO) Simple and compact structure			○		▽						
12	3,5%	9	(ECO) Cheap price						●					
13	4,8%	9	(ENR) Meet environmental protection requirements										●	●
			Technical difficulty (Low 1-10 High)	6	7		5			10	8	9		
			Max Relationship	9	9	9	1	1	9	9	9	9	9	9
			Technical Importance Rating	331,5	384,8	61,3	23,2	1,2	737,1	197,5	217	120,8	43,3	43,3
			Relative Weight	15,3%	17,8%	2,8%	1,1%	0,1%	34,1%	9,1%	10,0%	5,6%	2,0%	2,0%

Fig. 4. House of quality for automotive dry clutch.

The HoQ has been criticized because it does not consider the distinct relationship between "performance" and "satisfaction" and it assumes that there is a linear relationship between them. Integrating the Kano Model (Kano et al., 1984, Löfgren and Witell, 2005) into the HoQ is a common way to enhance the understanding of CRs (Tontini, 2007). Tontini et al. (2014) propose the Improvement-Gaps analysis (IGA) to overcome some limitations of the Kano Model as well. Clarifying design trade-offs corresponding to CRs with a negotiation process, as a part of customer co-creation is another way proposed in Altun et al. (2016).

Taking the shortcoming of traditional HoQ into account before calculating the relative weight of each CR is crucial to assess "customer value", properly. This study integrates the Kano Model to enhance traditional HoQ. Kano Model determines which CRs bring more satisfaction than others do. For each CR, a pair of questions examine whether the customer would feel satisfied or dissatisfied. Table 2 shows the priority categories of each CR obtained from this analysis. The hierarchy of the AHP pairwise comparisons is confirmed by using these priority categories.

The hierarchy class of "good performance" includes the CRs, which have the "performance" tag in the Kano priority list. Similarly, the "reliability" hierarchy class includes the CRs having a "must-be" priority tag except for the CR, "parts of good interchangeability." Some CRs have intentionally assigned to the hierarchy of the "service" by considering the suggestions of the experts. Similarly, the "attractive" CRs are generally the members of the hierarchy class of "ergonomic and comfort." The relative weight of each CR is calculated by "consistent" AHP pairwise comparisons (consistency ratios are less than 0.07). Table 3 shows the importance rates calculated.

After determining CRs and their relative weights, the next step is to create a list of the functional requirements (FRs). The team of clutch experts lists eleven main functions of an automotive dry clutch. The HoQ includes the relationship matrix to deploy CRs to FRs. 1, 3, and 9 scales are used to define the relationship between CRs and FRs (to represent weak, moderate, and strong relationships, respectively). This relationship matrix has been completed through organizing a multi-functional and multi-organizational workshop addressing each relation pair. The list of maximum relationships illustrated in Fig. 4 indicates a true deployment because each CR has a strong relationship, except the eleventh CR that has a moderate maximum relationship.

Some of these FRs under consideration are interrelated to each other. The roof of the HoQ, also called as "Technical Correlation Matrix" identifies which of these FRs must work together. In this phase, the team of clutch experts determines the existing interrelationships among these FRs as indicated in Fig. 4. Mainly, "assuring reliability" has positive relations with other FRs regarding the reliable operating conditions on the vehicle. On the other hand, "being recyclable" necessitates the use of low reliable parts in some specific cases and therefore a negative relation is considered.

This work does not share the customer benchmarking section because of the privacy policy of the company. The team rates the technical difficulty of execution of FRs using a 1 – 10 (low to high) scale showing how hard or easy to improve. Some of these FRs do not have technical difficulty rates in the HoQ because they are redundant when considered customer benchmarking assessments.

Table 2. An assessment of customer requirements with KANO analysis.

Customer Requirements	How would you feel if this was present?	How would you feel if this was absent?	Priority	Hierarchy Class
Enough power, without slipping	Like	Dislike	Performance	Good Performance
Engage and disengage function	Like	Dislike	Performance	
High-speed stability	Like	Dislike	Performance	
Friction plates do not burn	Expect it	Dislike	Must-be	Reliability
Parts not fracture	Expect it	Dislike	Must-be	
Long-life for use	Expect it	Dislike	Must-be	
Parts of good interchangeability	Expect it	Dislike	Must-be	Service
Disassembly, adjustment, and maintenance	Like	Live with	Attractive	
Pedal comfort	Like	Live with	Attractive	Ergonomic & Comfort
Vibration and noise	Like	Live with	Attractive	
Simple and compact structure	Don't care	Don't care	Indifferent	
Cheap price	Like	Live with	Attractive	Economic
Meet environmental protection requirements	Don't care	Don't care	Indifferent	Environmental

Table 3. Calculated relative weights of customer requirements.

Class	Class rates	Customer Requirements	Sub-class rates	Relative weight
Good Performance	0.376	(P) Enough power, without slipping	0.400	0.150
		(P) Engage and disengage function	0.400	0.150
		(P) High-speed stability	0.200	0.075
Reliability	0.245	(R) Friction plates does not burn	0.200	0.049
		(R) Parts not fracture	0.400	0.098
		(R) Long life for use	0.400	0.098
Service	0.064	(S) Parts of good interchangeability	0.700	0.045
		(S) Disassembly, adjustment, and maintenance	0.300	0.019
Ergonomic & Comfort	0.231	(ER&CO) Pedal comfort	0.368	0.085
		(ER&CO) Vibration and noise	0.579	0.134
		(ER&CO) Simple and compact structure	0.052	0.012
Economic	0.035	(ECO) Cheap price	1.000	0.035
Environmental	0.048	(ENR) Meet environmental protection requirements	1.000	0.048

4. Parts (and cost) deployment

With the help of the HoQ phase, the relative importance of each FR is obtained in terms of the customers' points of view. The second phase of the QFD examines the cost of clutch functions. FRs and their basic functions are listed to map relations between clutch components. Automotive dry clutch main components (flywheel, disc, and PPCA) and their subcomponents are listed as well. Relation rates between basic functions and subcomponents are determined with the help of design FMEA reports. Approximate cost shares of subcomponents in total cost are given in terms of percentages. By considering relations between basic functions and subcomponents, cost shares of basic functions and FRs are calculated.

Fig. 5 illustrates how parts and cost deployments are executed. In the line of "avoid slippage", the values of X1, X2, and X3 indicate the allocated relation degrees between the "avoid slippage" function and the corresponding subcomponents. As seen in Table 6 in detail, a standardization is conducted for each subcomponent as their correlated basic function relations are disseminated. Therefore, the total of each column of the relation matrix is one. Cost shares of the corresponding parts are C1, C2, and C3. By taking these relation degrees and their coefficients (i.e. cost shares of the subparts) into account, we calculate the cost of the "avoid slippage" function (it is as Y in the figure). The complete table is given in Table 6 (in Appendix A).

5. A customer value analysis of the clutch functions

A simple ratio between benefit and cost neglecting core competencies may not be helpful to model the value leading its users to a competitive advantage. While the first phase of QFD helps us to calculate the benefit weights of clutch functions, the second phase of QFD calculates the costs of clutch functions. By also considering the technical difficulty data as an indicator of the firm's competency on each function, this study performs a competitive assessment of automotive dry clutch functions.

In this phase, a type-1 fuzzy inference system evaluates the competitive importance of each clutch function by fusing benefit, cost, and technical difficulty data as inputs of the system. This fuzzy system uses triangular membership functions for input fuzzy sets. Degree of "benefit", "cost" and "technical difficulty" fuzzy sets are represented by three membership functions as "low", "medium", and "high" (within the interval of [0,1]). By considering the spectrum of input data, the linear standardization process helps us to specify sensitive membership function parameters being able to differentiate the assessments. Fig. 6 shows the membership functions of the fuzzy inference system.

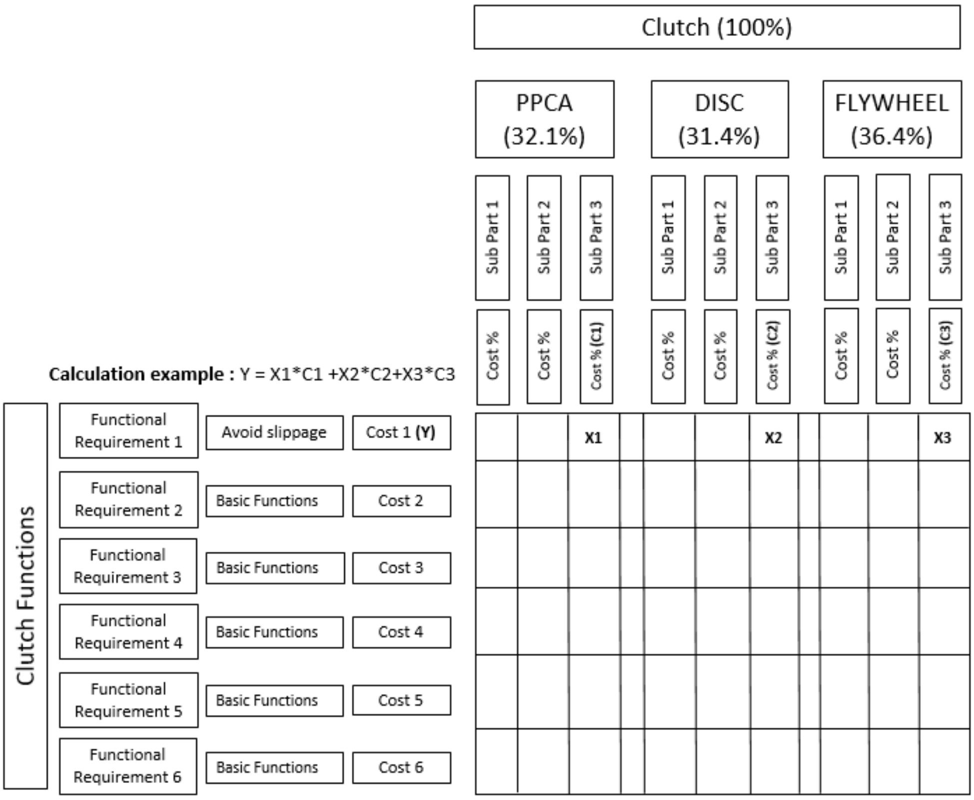


Fig. 5. An illustrative calculation for parts (and cost) deployment.

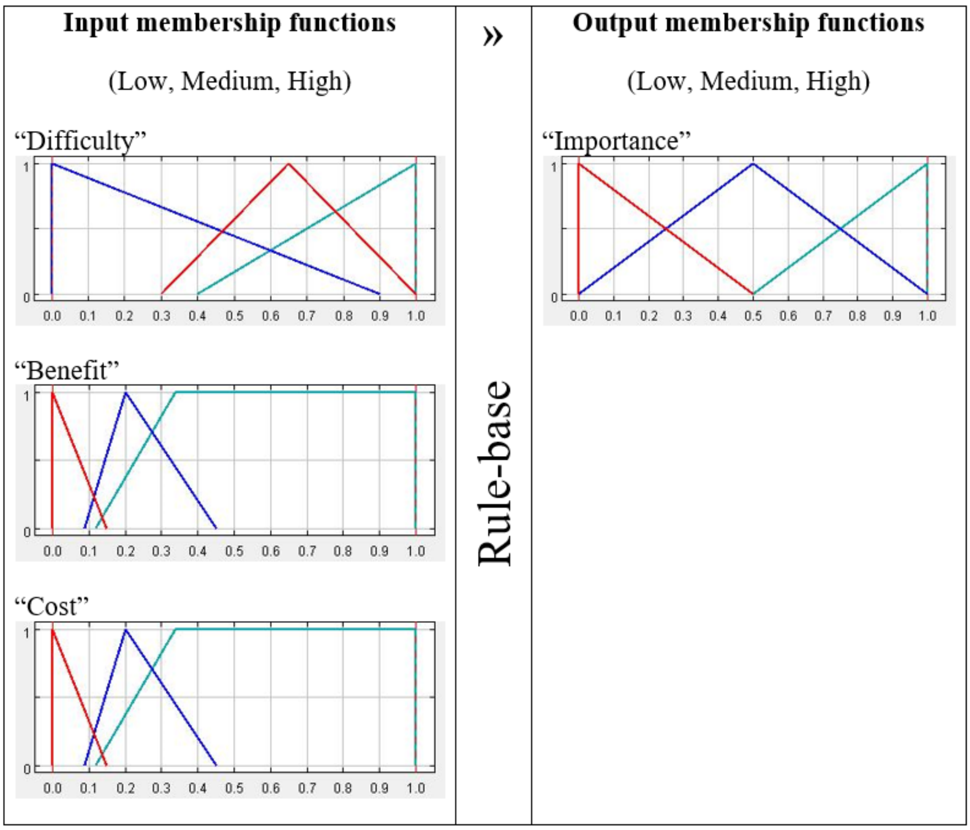


Fig. 6. Membership functions of the fuzzy inference systems.

After determining the parameters of fuzzy sets, a rule-base is needed to obtain competitive importance appraisals of clutch functions. In this phase, the knowledge of the clutch experts has been converted into a fuzzy rule-base. The list of the rules is given in Table 4 (in Appendix C).

When parameters of the clutch functions are entered into the system, the importance of each clutch function is obtained employing this fuzzy inference system. In this study, we present a real case of a clutch manufacturer. The technical benchmarking results show that there are six relevant functional requirements to improve the relative overall customer value. In this phase, the minimum (Mamdani) and the product (Larsen) operators are used for conjunction in the fuzzy inference system.

Table 5 shows the assessment results of the importance. We marked the top three functional requirements using bold font. Both operators used for the conjunction lead to the same rank order of the considered automotive dry clutch functions. According to these assessments, the three most important clutch functions are "Allowing disconnection between engine and gearbox during gear shifting," "Transmitting the torque between engine and gearbox," and "Ensuring engine starting/shut down." These top three clutch functions are placed in the improvement list of the company with the highest priority tags.

As seen in Fig. 4, "assuring reliability" has positive relations with these important clutch functions. Although it is intrinsically important because of these relations, in our case, we neglect it in the further analysis since the results of our customer benchmarking say that improving "assuring reliability" does not make sense on the customer value.

Once the component level of these functions is considered through the parts (cost) deployment matrix, the top three components corresponding to these functions are pressure plate, disc facings, and clutch cover. The following components are ED hook rivet sub-assembly, diaphragm, and flywheel cast iron. The outcome of this study proves beneficial to research in discovering not only the clutch components costs, but also in detailing the importance of clutch functions.

Table 5. Importance rates of clutch functions.

	Inputs of the fuzzy system			**Obtained results**	
Clutch functions under consideration	**Difficulty**	**Benefit**	**Cost**	**Importance (Minimum)**	**Importance (Product)**
FR#1 – Transmitting the torque between engine and gearbox	0.6	0.153	0.154	0.441	0.485
FR#2 – Allowing disconnection between engine and gearbox during gear shifting	0.7	0.178	0.116	0.599	0.526
FR#4 – Ensuring engine starting / shut down	0.5	0.011	0.010	0.369	0.369
FR#7 – Filtering vibrations / rotations irregularities of the motor propulsor unit	0.999	0.091	0.064	0.225	0.237
FR#8 – Absorb misalignments and eccentricity of the input shaft as regards the crankshaft (with a rigid flywheel or DMF) and secondary flywheel (with DMF) twisting	0.8	0.010	0.010	0.265	0.256
FR#9 – Avoid noise during slippage phase (gear shifting and start-up)	0.9	0.056	0.024	0.168	0.187

6. Developing innovative clutch concepts

The results obtained in this work provide a new perspective on project portfolio management. The company uses these results to determine worthwhile innovation paths. Having obtained the importance rates of clutch functions, where to focus to innovate is clearer. The three most important clutch functions have been listed in this systematic customer value analyses process.

The R&D center of the company has conducted some workshops to generate innovative ideas corresponding to these clutch functions. Through some sensitivity analyses based on these results, ideas generated in these workshops have been assessed whether they improve the customer value. Two examples of these ideas have been discussed in Cakmak et al. (2021a) and Cakmak et al. (2021b).

One of the most important three functions is FR#1, transmitting the torque between engine and gearbox. As seen from the parts deployment for automotive dry clutch functions (Table 6), FR#1 is heavily in relation to the pressure plate and cover assembly (PPCA). The basic functions of FR#1 are also listed in Appendix.

A pressure plate is a part, which is cast iron manufactured, and it is the heaviest part of the automotive dry clutch system. Repetitive clutch engagements cause dramatic temperature rise. Temperature change affects negatively the torque transmission (FR#1) since the friction coefficient reduces by temperature rise.

On the other hand, in parallel to recently released greenhouse gas regulations, "lightweighting" is a strong trend that pushes OEMs and suppliers to present lighter solutions without compromising their performance. Improving the weight of moving objects without worsening shape is one of the main contradictions to handle. The 40th TRIZ Inventive Principles for this contradiction is the 40 IP, composite materials, from the TRIZ Contradiction Matrix.

Correspondingly, in a recent study (Cakmak et al., 2021a), reducing the weight of the clutch pressure plate by using aluminum foam has been researched. Fig. 7 illustrates the proposed concept design. This lightweight concept design prevents the dramatic temperature rise during repetitive engagements. This concept design enhances the convective heat transfer, as well. Enhancing the convective heat transfer of clutch pressure plate through ventilation channels has also been researched in another recent study (Cakmak et al, 2021b).

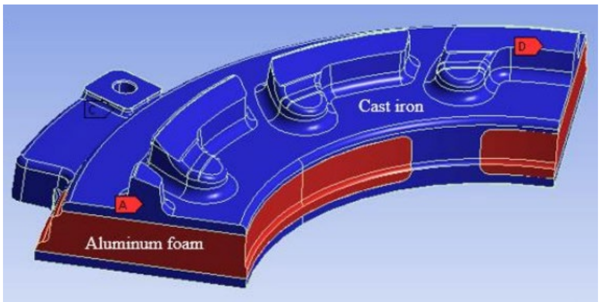


Fig. 7. Lightweight innovative composite dry clutch pressure plate (adapted from Cakmak et al., 2021a).

7. Concluding remarks

Porter's three generic strategies (i.e. cost leadership, differentiation, and focus strategies) describe how to be competitive in the market while fulfilling the customer needs. Although it is common to see different business strategies when considered the automotive original equipment manufacturers (OEMs), it is generally not a similar case for their (co-designer) tire-1 and tire-2 suppliers. According to a report of Deloitte (2017) discussing the future of the automotive value chain, "the automotive industry is in a state of constant pressure: from customers demanding new and costly features – often without showing additional willingness to pay." For this reason, providing high quality with competitive prices can be considered as a necessity to be competitive in the automotive industry. To work with the (price-sensitive) OEMs, the automotive suppliers generally target the cost leadership strategy, producing a standardized product at very low per-unit costs.

Even though the trend towards electrification of road transport over the next few years, Internal Combustion Engines (ICEs) are still to play an important role in 2030: 30% are expected to be maintained as ICE and 40% of the manufactured electric vehicle will be Hybrid Vehicle (HEV), that means with a gearbox. Thus, dry clutch systems are expected to still have an important market share. Although most of their components have changed in their evolved versions, the "automotive dry clutch" can also be considered as one of these conventional parts. In the case the competition is strong and the customer needs have nearly been fulfilled, the manufacturers may improve their product functions to be balanced in their benefit and cost rates to stay competitive. Correspondingly, this study has addressed a real case for the assessment of "automotive dry clutch" functions. By taking these assessments into account, worthy technical contradictions and innovative clutch concept designs can be addressed in future works. The techniques used in this assessment can be generalized to some of the automotive parts (e.g. automotive seats) and therefore future work can address the implementation of such a procedure for other important automotive parts.

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Appendix

A. Parts deployment for the automotive clutch functions

Table 6. Parts (and cost) deployment for automotive dry clutch functions (FR1 – FR3).

					100%																											
					PPCA									DISC																FLYWHEEL		
					32,1%									31,4%																36,4%		
				PARTS	Sub Part 1	Sub Part 2	Sub Part 3	Sub Part 4	Sub Part 5	Sub Part 6	Sub Part 7	Sub Part 8	Sub Part 9	Sub Part 10	Sub Part 11	Sub Part 12	Sub Part 13	Sub Part 14	Sub Part 15	Sub Part 16	Sub Part 17	Sub Part 18	Sub Part 19	Sub Part 20	Sub Part 21	Sub Part 22	Sub Part 23	Sub Part 24	Sub Part 25	Sub Part 26	Sub Part 27	Sub Part 28
			COST SHARES		14,1%	52,3%	11,4%	12,8%	2,7%	2,7%	1,0%	1,0%	2,0%	27,5%	1,1%	4,2%	1,1%	11,1%	1,7%	5,0%	1,4%	10,5%	1,7%	1,2%	4,6%	1,3%	22,7%	2,7%	2,2%	21,7%	70,1%	8,2%
BENEFIT	FR	BF			4,5%	16,8%	3,7%	4,1%	0,9%	0,9%	0,3%	0,3%	0,6%	8,7%	0,3%	1,3%	0,3%	3,5%	0,5%	1,6%	0,4%	3,3%	0,5%	0,4%	1,5%	0,4%	7,1%	0,8%	0,7%	7,9%	25,5%	3,0%
15,30%	FR 1	BF 1	0,154	0,036	0,050	0,093	0,082	0,130	0,073		0,100	0,100		0,098	0,167																	
		BF 2		0,030	0,038	0,093	0,082		0,122					0,098																		
		BF 3		0,030	0,050	0,093				0,081	0,167	0,167	0,333	0,078	0,222	0,049																
		BF 4		0,003	0,063																											
		BF 5		0,024	0,050	0,056				0,081	0,167	0,167	0,333	0,078	0,278						0,129											
		BF 6		0,012																0,250			0,13		0,103	0,190	0,065					
		BF 7		0,020												0,066	0,147	0,119				0,077	0,13		0,128		0,109	0,108	0,086			
		BF 8		0,000																												
17,80%	FR 2	BF 9	0,116	0,036	0,050	0,056	0,066	0,217	0,122	0,081	0,100	0,100		0,078		0,082						0,077							0,069			
		BF 10		0,026	0,038	0,074	0,049		0,073	0,065				0,098		0,066																
		BF 11		0,011	0,050		0,082	0,130	0,073																							
		BF 12		0,013	0,050		0,066	0,174	0,098	0,048																						
		BF 13		0,007										0,059		0,066									0,077				0,052			
		BF 14		0,003			0,082																									
		BF 15		0,000																												
		BF 16		0,000																												
		BF 17		0,000																												
		BF 18		0,018																											0,071	
2,80%	FR 3	BF 19	0,129	0,032	0,063	0,056	0,049			0,081				0,059		0,049	0,118	0,095				0,046	0,094				0,065	0,081	0,069			
		BF 20		0,050	0,050	0,056	0,082	0,130	0,073	0,048	0,100	0,100	0,333	0,059		0,049					0,097	0,077					0,065		0,052	0,077		0,208
		BF 21		0,000																												
		BF 22		0,000																												
		BF 23		0,000																												
		BF 24		0,000																												
		BF 25		0,023			0,066		0,098		0,100	0,100		0,059			0,147	0,119							0,077	0,143	0,087	0,081	0,069			
		BF 26		0,018	0,050	0,074				0,081												0,077							0,069			
		BF 27		0,006																										0,077		

Table 6. Parts (and cost) deployment for automotive dry clutch functions (FR4 – FR11).

					100%																											
					PPCA									DISC																FLYWHEEL		
					32,1%									31,4%																36,4%		
				PARTS	Sub Part 1	Sub Part 2	Sub Part 3	Sub Part 4	Sub Part 5	Sub Part 6	Sub Part 7	Sub Part 8	Sub Part 9	Sub Part 10	Sub Part 11	Sub Part 12	Sub Part 13	Sub Part 14	Sub Part 15	Sub Part 16	Sub Part 17	Sub Part 18	Sub Part 19	Sub Part 20	Sub Part 21	Sub Part 22	Sub Part 23	Sub Part 24	Sub Part 25	Sub Part 26	Sub Part 27	Sub Part 28
			COST SHARES		14,1%	52,3%	11,4%	12,8%	2,7%	2,7%	1,0%	1,0%	2,0%	27,5%	1,1%	4,2%	1,1%	11,1%	1,7%	5,0%	1,4%	10,5%	1,7%	1,2%	4,6%	1,3%	22,7%	2,7%	2,2%	21,7%	70,1%	8,2%
BENEFIT	FR	BF			4,5%	16,8%	3,7%	4,1%	0,9%	0,9%	0,3%	0,3%	0,6%	8,7%	0,3%	1,3%	0,3%	3,5%	0,5%	1,6%	0,4%	3,3%	0,5%	0,4%	1,5%	0,4%	7,1%	0,8%	0,7%	7,9%	25,5%	3,0%
1,10%	FR 4	BF 28	0,010	0,010																										0,128		
		BF 29		0,000																												
		BF 30		0,000																												
		BF 31		0,000																												
0,10%	FR 5	BF 32	0,115	0,054	0,063		0,049		0,073						0,167	0,049		0,095				0,046	0,094				0,087		0,052	0,077	0,095	0,167
		BF 33		0,061	0,050	0,074				0,081				0,059		0,066						0,062								0,103	0,095	0,167
34,10%	FR 6	BF 34	0,285	0,027	0,063		0,082			0,081						0,082	0,147	0,119			0,129	0,077	0,13		0,128		0,109	0,081	0,086			
		BF 35		0,010																										0,128		
		BF 36		0,030																											0,119	
		BF 37		0,041																										0,128	0,119	
		BF 38		0,051	0,063	0,056				0,065	0,100	0,100				0,082	0,088	0,071				0,077						0,108			0,119	
		BF 39		0,030																											0,119	
		BF 40		0,069	0,063	0,093	0,082	0,217	0,122	0,081				0,098		0,082	0,118	0,119	0,286	0,250	0,129	0,077	0,156	0,263	0,128	0,190	0,109	0,135	0,086			
		BF 41		0,027	0,050	0,074				0,081	0,167	0,167				0,082	0,147	0,119				0,077			0,128				0,086			
9,10%	FR 7	BF 42	0,064	0,010																										0,128		
		BF 43		0,037																											0,119	0,208
		BF 44		0,016	0,050	0,056	0,082		0,073	0,048																						
		BF 45		0,001												0,082																
10,00%	FR 8	BF 46	0,010	0,010																	0,161	0,077		0,211			0,065	0,108	0,069			
5,60%	FR 9		0,024	0,024														0,071	0,286	0,313	0,161	0,062	0,094	0,211	0,077	0,190	0,109	0,135	0,052			
2,00%	FR 10		0,046	0,046										0,078					0,214		0,097	0,046	0,094	0,158	0,077	0,143	0,065	0,081	0,052	0,077	0,071	0,125
2,00%	FR 11		0,047	0,047											0,167	0,049	0,088	0,071	0,214	0,188	0,097	0,046	0,094	0,158	0,077	0,143	0,065	0,081	0,052	0,077	0,071	0,125

B. List of subparts and basic functions

List of subparts:
Sub Part 1 Cover
Sub Part 2 Pressure Plate
Sub Part 3 Diaphragm
Sub Part 4 ED hook-rivet S.A
Sub Part 5 Delta Rivet
Sub Part 6 Straps
Sub Part 7 Cover-straps rivet
Sub Part 8 Pressure plate - straps rivet
Sub Part 9 Balancing Rivet
Sub Part 10 Facing
Sub Part 11 Facing rivet
Sub Part 12 Metallic Disc
Sub Part 13 Fastening Rivet
Sub Part 14 Retainer Plate (GB&FW)
Sub Part 15 Pre-damper hysteresis device
Sub Part 16 Main damper hysteresis device
Sub Part 17 Pre-damper friction washer
Sub Part 18 Hub
Sub Part 19 Damper washer with tabs
Sub Part 20 Pre-damper elastic washer
Sub Part 21 Drive Plate
Sub Part 22 Damper elastic washer
Sub Part 23 Damper & Predamper Springs
Sub Part 24 Bushing & H2 H3 Sub groups
Sub Part 25 Stop pin
Sub Part 26 Ring Gear
Sub Part 27 Flywheel Cast Iron
Sub Part 28 Dowel pin

List of basic functions:
BF 1 Avoid slippage
BF 2 Avoid high wearing
BF 3 Avoid burst
BF 4 Ensure the right fastening to the flywheel
BF 5 Withstand torque and over torque in drive and coast
BF 6 Avoid pumping
BF 7 Withstanding torque/over torque during engaging and release
BF 8 Ensure the right fastening to the crankshaft
BF 9 Avoid "not pulling off" / Grant pedal reserve
BF 10 Avoid judder
BF 11 Avoid "stay-out"
BF 12 Allow the disengagement with no excessive loads
BF 13 Allow gear shift without wearing the synchronizers too early
BF 14 Grant suitable hump
BF 15 Transmit load from clutch pedal to the external gearshift lever

BF 16 Avoid noise during pedal actuation
BF 17 Guaranteeing correct clutch fastening face position
BF 18 Withstanding bearing load
BF 19 To be assembled correctly on the flywheel
BF 20 To be assembled correctly on the gearbox
BF 21 To be assembled correctly on firewall/pedal box
BF 22 To be settled correctly into the engine compartment
BF 23 Permit empty and filling on line
BF 24 Avoid pollution from external agents
BF 25 Being identifiable
BF 26 Withstanding shocks
BF 27 Being able to be fitted correctly on crankshaft
BF 28 Transmit the torque of the starter
BF 29 Grant the starting / shut down of the engine
BF 30 Ensure right rising / drop off from idle speed
BF 31 Supplying information to the engine control sensors
BF 32 Withstanding corrosion
BF 33 Withstanding shocks
BF 34 Withstanding fatigue
BF 35 Withstanding wear
BF 36 Avoiding high deformation and withstanding thermal shock
BF 37 Avoiding centrifugation
BF 38 Withstanding stress caused by axial pulsation of the crankshaft
BF 39 Withstanding stress caused by bending of the crankshaft
BF 40 Long-lasting functions
BF 41 Withstand the torsional solicitations (rigid flywheel or DMF) and resonance shocks (DMF)
BF 42 Reducing irregularities of the engine in rotation (inertia)
BF 43 Avoiding rotation noise (unbalance)
BF 44 Avoiding clutch pedal vibrations
BF 45 Filtering axial vibrations
BF 46 Allow movements related to input shaft-damper

C. Fuzzy rule-base

Table 4. Fuzzy rule-base depending on the knowledge of automotive clutch experts.

If Difficulty is [...]	and Benefit is [...]	and Cost is [...]	then Importance is [...]
Low	Low	Medium	Low
High	High	High	Medium
Medium	Medium	High	Medium
Medium	High	High	Medium
Low	Low	High	Low
Medium	High	Medium	Medium
Medium	Medium	Low	Medium
High	Low	Medium	Low
Medium	Low	High	Low
Medium	Low	Low	Low
Low	High	High	Medium
Low	High	Low	High
Low	Medium	Low	High
High	Medium	Medium	Medium
Low	Medium	Medium	Medium
Low	High	Medium	Medium
High	Low	Low	Low
Medium	Medium	Medium	Medium
High	Low	High	Low
Medium	High	Low	High
Medium	Low	Medium	Low
High	High	Low	Medium
High	Medium	High	Low
Low	Medium	High	Low
Low	Low	Low	Medium
High	High	Medium	Medium
High	Medium	Low	Medium

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Detecting Anomalies in the Dynamics of a Market Index with Topological Data Analysis

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Abstract

We investigate the collective behavior of a stock market by studying the dynamics of its representative index's return, using the persistence diagram of the index return's time-delay embedding, an approach of the Topological Data Analysis (TDA) in time series analysis. While the time-delay embedding captures the state space of the index return's dynamics, the persistence diagram encodes the space's topological information under different spatial resolu-tions. Therefore, based on the changes in the point distribution of the persistence diagram over time, we propose a framework to detect its extraordinary movements. Our method provides a measure for the stability level of the mar-ket's collective behavior. After applying this method for the daily return of the S&P 500 index from 1970 to 2020, we demonstrate that the measure efficiently tracks the changes in topological information of the index re-turn. Furthermore, we can capture major American recessions when the measure exceeds a threshold. A continuous and rapid increase of the measure approaching the threshold is considered a warning of a crisis. Hence, our method provides a technical indicator for systematic risk management.

Keywords: anomalies detection, market index, persistence diagram, time-delay embedding.

1. Introduction

Dramatical changes of a financial market are often of great concern to many investors, managers, or policymakers because they have to make decisions such as taking profits, cutting losses, or making policies to avoid market crashes. However, as a complex system, the chaotic and collective behaviors of the market are really difficult to predict. Although there are a lot of mathematical tools to study such behaviors, in stock markets, market indexes are often used to gauge the markets' movements. In fact, since a market index is calculated from the prices of all or underlying shares, it is explicit and available to represent the market's state.

Since the market's movement is complicated and has noise, it is not easy to extract the necessary information within the time series data of its indexes. One way to deal with this problem is using TDA, an approach using new topological and geometric tools to infer information about the structure of point clouds in metric spaces (Edelsbrunner and Harer, 2010). This approach is suitable to deal with noises since it helps study the behavior of a system for a wide range of parameters (Carlsson, 2009). Also, the topological features are expected to reflect the qualitative changes in a time series' dynamics. Hence, TDA is recently used in many works to study the behaviors of time series such as detecting the periodicity of biological time series (Perea et al., 2015), understanding the global behavior of biological aggregations (Topaz et al., 2015), detecting early warning signals of imminent market crashes (Gidea and Katz, 2018), analyzing a bridge deterioration through its vibration data (Umeda et al., 2019), studying the classification problem of volatile time series (Umeda, 2017) …

In this study, we use the TDA approach to construct a method that can detect significant changes in a market index and give signals about financial crises. Similar to the work introduced by Gidea and Katz (2018), we investigate the behavior of the daily log price difference of a market index, called the daily index return. However, for the purpose of getting the state space of the time series' behaviors, we use the time-delay embedding of the financial time series where parameters of time-delay and embedding dimension are chosen from the empirical data. In the context of time series analysis, the time-delay embedding method, which is first introduced by Packard et al. (1980) and Ruelle (1979), is a simple method to convert one-dimensional data into point clouds of another higher-dimensional space, called the state space. It is useful to analyze chaotic time series because, according to the Takens' embedding theorem (Takens, 1981), a chaotic series can be perfectly modeled by a smooth function when it is correctly embedded. Besides, with a suitable time-delay, the consequent series can be an efficient summary of the whole data (Sauer et al., 1991). As a result, an appropriate time-delay embedding of a time series helps reconstruct the original chaotic data such that we are able to capture the data's dynamics in different states. Especially, when combining this method with TDA, meaningful topological features, such as connected components, circles, holes, associated with the reconstructed data can be extracted by TDA's tools. Consequently, the dynamical characteristics of the time series are discovered, for example, its periodicity, its pattern, or the qualitative changes in its states. Some theoretical studies about this method can be listed such as (Fraser and Swinney, 1986), (Sauer et al., 1991), (Kennel et al., 1992), (Abarbanel et al., 1993), as well as practical studies such as (Umeda, 2017), (Brown and Knudson, 2009), (Seversky et al., 2016), (Ma, 2020). Moreover, instead of considering data in only a certain time window by using L^p-norms of the persistence landscape as Gidea and Katz (2018) and Ma (2020), in this work, we compare the topological characteristics of the data with its historical characteristics encoded in the persistence diagram of its time-delay embedding. Hence, our method is expected to find out the time series' anomalies more obviously. For this purpose, we only focus on persistence diagrams and use unsupervised machine learning models such as k-means clustering in comparing them. More details about our method are described in Section 2. In Section 3, we provide our empirical results when applying the method for investigating the dynamics of the daily return of the S&P 500 index in two cases: when the current dynamics of the time series is quite similar to its historical dynamics and when they are much different from each other. Next, in Section 4, we discuss the efficiency of our method in detecting strange fluctuations of the index return series by considering the relation between our calculation with recessions in the United State market. Finally, we give conclusions for our method of using TDA in examining the behavior of a market index and detecting its anomalies in Section 5.

2. Research Method

When we observe a time series data in a period, how can we recognize that its present behaviors are so different from its historical behaviors? The problem can be dissolved by comparing the topological features of the present data with the features of the historical data. The features were used to detect the qualitative changes in many studies such as (Donato, 2016; Umeda, 2019; Ma, 2020). In order to get the features, we firstly embed the observed time series into a higher dimensional space to construct a state space of the data's dynamics. The time-delay embedding method then combines with the persistence diagram, a powerful tool of TDA that helps encode the topological features of the underlying data's behavior. In addition, we use the k-means clustering algorithm to make the topological information's comparison of a given data and its historical data easier. More details are given in the following paragraphs.

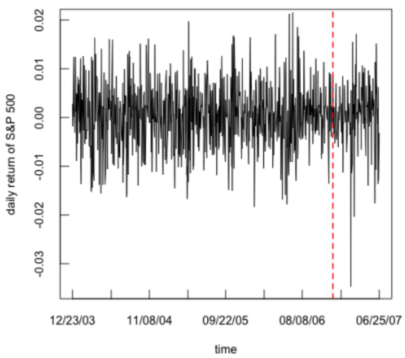
2.1 Time-delay embedding

As discussed in (Sauer et al., 1991), an adequate embedding of a time series can define a state space or phase space of the system from which the data is acquired because it can capture the system dynamics in different states, preserve determinism and create a diffeomorphism for the attractors. So, in our work, before taking a topological analysis of our time series data, we embed the data into a suitable state space.

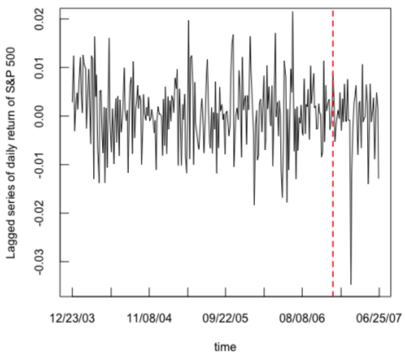
Let remind that a time-delay embedding of a time series (r_t) of length N is a set of vectors $X = (x_1, x_2, \dots, x_{N-(d-1)\tau})$ where each vector is obtained by gathering d adjacent values of the series that is delayed by τ, i.e. $x_t = (r_t, r_{t+\tau}, r_{t+2\tau}, \dots, r_{t+(d-1)\tau})$. The vectors are called reconstructed vectors, τ is called the time-delay and d is called the embedding dimension. Determining values of τ and d such that the corresponding reconstructed space can store the data's dynamical information is an attractive problem. In this work, we choose the lag τ by using the average mutual information (AMI) provided in (Gallager, 1968):

$$\mathrm{AMI}(\tau) = \sum_{t=1}^{t=N-\tau} \hat{p}(r_t, r_{t+\tau}) \log_2 \frac{\hat{p}(r_t, r_{t+\tau})}{\hat{p}(r_t)\hat{p}(r_{t+\tau})} \quad (1)$$

where $\hat{p}(r_t, r_{t+\tau})$ is the estimated joint probability distribution of the bivariate time series $(r_t, r_{t+\tau})$. This measurement tells us how much information about $r_{t+\tau}$ we can receive when r_t is known. As suggested in (Fraser and Swinney, 1986), the time-delay should be chosen where the first minimum of AMI occurs because we should not keep both r_t and $r_{t+\tau}$ when AMI(τ) is large. Besides, a large τ makes much data lost nontrivially. Fig. 1 illustrates a sample data and its lagged version where the lag τ as suggested. In the figure, the dashed line is used to divide the training data and the test data. Moreover, to make the reader comfortable when following our method steps by steps, we use the same data in Fig. 1 – 4.



(a)



(b)

Fig. 1. Daily return of the S&P 500 index and its lagged version with $\tau = 3$ given by the first minimum of AMI.

Otherwise, for finding a suitable embedding dimension, one of the popular methods is the false nearest neighbors method proposed in (Kennel et al., 1992). The main idea of this method is that d is chosen as the smallest number such that, for any point, its nearest neighbor in dimension d is still close enough in dimension d + 1. So, the trouble of this method is verifying the threshold for the distance of a pair of points such that the two points are considered to be close to each other. To overcome this trouble, a new approach to the false nearest neighbors method was introduced in (Cao, 1997). The author defines:

$$a(t, d) = \frac{\|x_{t,d+1} - x_{t^*,d+1}\|}{\|x_t - x_{t^*}\|}, \qquad t = \overline{1, N - d\tau} \quad (2)$$

where x_{t^*} is the nearest neighbor of x_t in dimension d; $x_{t,d+1}$ and $x_{t^*,d+1}$ are the reconstructed vectors of x_t and x_{t^*} in dimension d + 1, respectively, i.e., $x_{t,d+1} = (r_t, r_{t+\tau}, \dots, r_{t+d\tau})$ and $x_{t^*,d+1} = (r_{t^*}, r_{t^*+\tau}, \dots, r_{t^*+d\tau})$; $\|.\|$ represents for the distance between the inside points. In this work, we use the Euclidian distance. Let E(d) be the mean value of a(t, d) over time, and E1(d) be the ratio of E(d + 1) to E(d). If E1(d) stops changing when d is greater than a number d0, it means that the time series comes from an attractor and d0 + 1 should be selected as the embedding dimension. In our implementation below with the financial time series, we choose d0 as the point where the ratio of E1(d) to E1(d + 1) is larger than 95% for any d > d0. Fig. 2 illustrates the result of this method when it is applied for the test data used in Fig. 1.

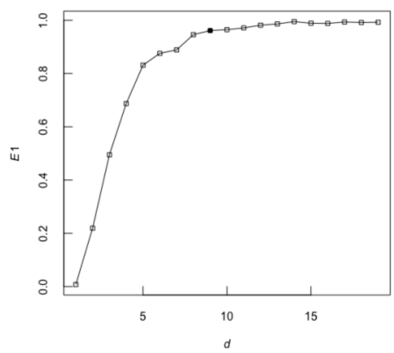


Fig. 2. An example of selecting the embedding dimension (filled point) by the idea of the false nearest neighbors.

We hope that the state space obtained from the time-delay embedding of our time series in previous periods can help recognize strange behaviors of the current data's dynamics. Therefore, we call this space the training space. With the same parameters of time-delay, we also embed the data in the current period into the same dimensional space, which is called the test space. The training space should be large enough and, by partitioning it into consecutive segments of length m, we have a set of sample state spaces having the same size to check whether the test space has different topology. Due to this reason, we suggest choosing m as the size of the test space, i.e., its number of vectors. This enables the observation of periodic property or timing pattern of our data in a period with a certain length.

2.2 Persistence diagram

In order to reveal abnormal behaviors of the observed time series in the present compared with itself in the past, we propose to compare the topological structure of the training space and the test space by using TDA. TDA is an approach that provides topological and geometrical tools to infer information about the structure of a point cloud of a metric space at different spatial resolutions. In particular, for a point cloud whose distribution is unknown, to highlight the point cloud's topology or geometry, TDA's approach is building a "continuous" shape on the points. The shape is often a simplicial complex. Then, the homology groups of the simplicial complex are studied to infer the point cloud's topology. Furthermore, to avoid perturbation or noise in the input data, the point cloud's structure is investigated through a filtration, i.e., a sequence of simplicial complexes ordered by inclusion. The homology groups of each simplicial complex of the filtration represent the point cloud's topology at a certain spatial resolution. So, the persistent homology of the filtration gives meaningful information about the point cloud's topology at different scales. One of TDA's main tools to study the persistent homology is the persistence diagram which encodes the topological information's change of the point cloud's structure through the filtration (Edelsbrunner and Harer, 2010). The diagram is a graph in the plane $\mathbb{R}^2$ such that it includes the diagonal $\{(x, y) \in \mathbb{R}^2 \mid x = y\}$ and points, whose x and y coordinates are the birth and death scales of topological features respectively through a filtration of the space.

In our study, the time-delay embedding of the index return series provides the state space of the data's dynamics. Since the state space is a point cloud of the Euclidean space $\mathbb{R}^d$, where d is the embedding dimension, we can use the TDA's tools to study the persistent homology of the state space, then draw a meaningful conclusion for the index return's movement. For example, the groups of dense 0-dimensional features on the persistence diagram help classify the index return's behaviors, while 1-dimensional features having high persistence values relate to the periodic trend of the system's dynamics. Especially, we expect that by comparing the persistent homology of the index return in a certain period with the one in previous periods, we can recognize strange behaviors in the index return's dynamics.

More specifically, the topological changes over all scales of the reconstructed data in each segment of the training space are tracked by its persistence diagram. In this study, for each segment of the training space, we have a set of m reconstructed vectors, which are embedded points $\{x_{(1)}, x_{(2)}, \ldots, x_{(m)}\}$ of the Euclidean space $\mathbb{R}^d$. We use the Vietoris-Rips complex filtration $(\mathrm{Rips}_\alpha(\mathbb{X}))_{\alpha\in\mathbb{R}}$, where the complex $\mathrm{Rips}_\alpha(\mathbb{X})$ is the set of simplices spanned by $\mathbb{X}$ such that $\|x_{(i)} - x_{(j)}\| \leq \alpha$ for all i, j (Edelsbrunner and Harer, 2010). Since the persistence of a feature is the difference between the scale where the feature appears and disappears, the persistence diagram briefly describes the evolution of the data's structure over scales.

Furthermore, we only pay attention to the 0-dimensional and 1-dimensional topological features. The reason is that 0-dimensional features, which are corresponding to connected components of the point cloud under the filtration $(\mathrm{Rips}_\alpha(\mathbb{X}))_{\alpha\in\mathbb{R}}$, give information about concentration and clustering patterns of the time series' dynamics, while 1-dimensional features, which are corresponding to holes, give information about the dynamics' periodicity. In addition, in persistence diagrams of our financial time series data in many different time windows, we observe that the features having higher dimensions rarely appear or only appear at large scales with short persistence such that they can be considered noises. For example, in Fig. 3, we can observe the numbers and positions of the features whose dimensions are from 0 to 3 in persistence diagrams of state spaces constructed from the training data and test data used in Fig. 1. In Fig. 3, for the features whose dimensions are higher than 1, their number is too small in any persistence diagram. Also, the points corresponding to the features are very closed to the diagonal, so the features' death scales are approximately their birth scales. This means that the features' existences are not steady when the spatial resolution changes. As a result, we are only interested in the distribution of the points corresponding to 0-dimensional and 1-dimensional features.

Next, we merge persistence diagrams of all segments of the training space into one diagram, called the total diagram (ex. see Fig. 4b). This diagram helps get a general view of the "shape" of historical data in periods that are close and have the same length with the test data.

2.3 K-means algorithm

Giving the total diagram constructed from the segments of the training space, we would like to use it as a standard pattern to test the anomalies of the persistence diagram of the test space. Although there are some distance measures to compute the similarity between two persistence diagrams such as the bottle-neck distance and the Wasserstein distance that can be seen in (Edelsbrunner and Harer, 2010) for more details, these measures are not suitable for our comparison because they require examining all of the matchings between the two diagrams while the number of points outside the diagonal in the total diagram is extremely larger than the ones of the persistence diagram of the test space. So, we propose to compare the two diagrams by region. At first, we divide the points outside the diagonal of the total diagram into clusters. After that, we partition the plane $\mathbb{R}^2$ into many regions corresponding to the clusters and compute the regions' degree of commonalities, which will be the key to detect the strange topology of the test space.

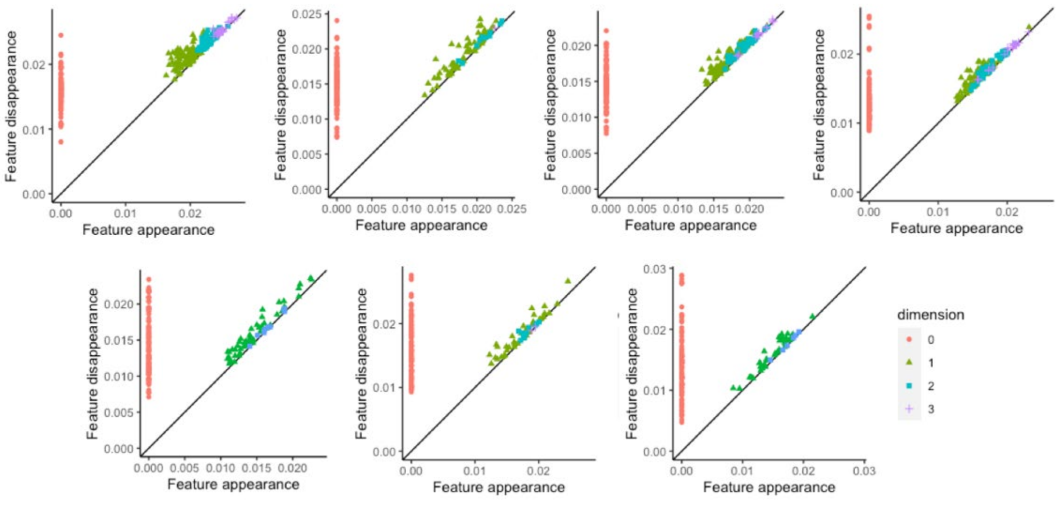


Fig. 3. Persistence diagrams of $(\boldsymbol{Rips}_{\alpha}(\mathbb{X}))_{\alpha\in\mathbb{R}}$ where $\mathbb{X}$ is respectively the state spaces constructed from the S&P 500 index's daily return in some periods; feature appearance and feature disappearance are the values of α that the corresponding feature first appears and disappears in $(\boldsymbol{Rips}_{\alpha}(\mathbb{X}))_{\alpha\in\mathbb{R}}$, respectively.

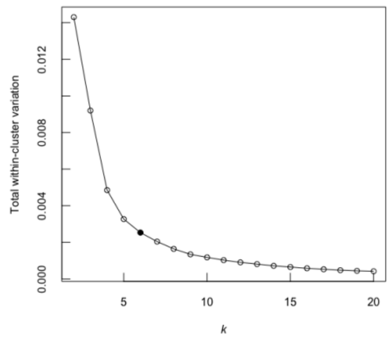
Here, we use a simple but popular k-means clustering algorithm, proposed in (Hartigan and Wong, 1979), to divide our points in the total diagram into clusters. The idea of this algorithm is that, for a given number k, we classify data points into k clusters so that the total within-cluster variation, which equals the sum of square Euclidean distances between each data point assigned to the same cluster and the cluster center, is minimum. The first centers are chosen randomly from the data and are recalculated when one more point is assigned to a cluster. Since all things we have to do is computing the distance between the points and cluster centers, this algorithm is easy to understand and fast. Moreover, it is good enough to classify the points in our financial persistence diagrams because of the points' uncomplicated arrangements. In fact, in the diagrams, the points represented for 0-dimensional features only lie on a line parallel to the vertical axis while the points represented for 1-dimensional features mostly concentrate on a band along the diagonal $\{(x, y) \in \mathbb{R}^2 \mid x = y\}$ (ex. see Fig. 3). Therefore, when we consider each point as a vector of three dimensions including the birth scale, death scale, and homological dimension of the corresponding feature, the clustering using the k-means algorithm run very fast and all points assigned to the same cluster have the same homological dimension.

However, because the algorithm's result is sensitive to its initial value, we should perform many iterations until the result converges. The main disadvantage of our clustering is that the number k of clusters must be verified before clustering the points. In order to solve this problem, we use the elbow method to find the ideal value for k. For more specific, we first apply k-means clustering with different values of k and draw the total within-cluster variation as a function of k. Next, we normalize the input and output values of this function to get the elbow point as the point with respect to the maximum curvature of the curve. Fig. 4 shows the result of selecting k by the elbow method when it is applied for the total diagram constructed from the training data used in Fig. 1.

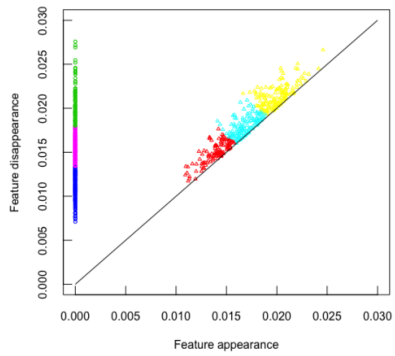
For any cluster i ($i = \overline{1, k}$), we calculate its degree of commonality as the following:

$$P_i = \left\langle \frac{n_{i,j}}{n_j} \right\rangle \tag{3}$$

where $n_{i,j}$ is the number of points assigned to cluster i in persistence diagram j, n_j is the number of points in persistence diagram j and $\langle \cdot \rangle$ is the average over all persistence diagrams of the training space's segments. By Eq. (3), Pi is just an estimator of the probability that a point in the persistence diagram of a state space of our historical data can belong to cluster i.



(a) The number of clusters (filled point) selected by the elbow method.



(b) The total diagram after dividing to clusters.

Fig. 4. An example of applying the k-means algorithm for a total diagram.

2.2 Detecting anomalies of the topological structure of a state space

Let's consider the test data. After constructing its state space with the same time-delay and embedding dimension parameters, we want to know whether there are anomalies in the topological information of its state space when comparing to the topological structure of the training data. For this purpose, the persistence diagram of 0 and 1-dimensional features of the test space are computed to compare with the features encoded in the total diagram.

Next, each point in the persistence diagram of the test space is assigned to cluster i of the total diagram if the cluster is the nearest ones having the same homological dimension with the point. Nevertheless, we need a condition to verify significant changes in this persistence diagram compared with the total diagram. We propose that a point in the persistence diagram of the test space will be assigned to a new cluster, cluster k + 1, if and only if its persistence is larger than a threshold. Especially, we choose the threshold as the mean of the persistence of points belongs to cluster i of the total diagram added 3 times of its standard deviation. Remind that the total diagram is the coherence of many persistence diagrams constructed from disjointed segments of the training space, so we think that the three-sigma rule is valid enough to define the region of the $\mathbb{R}^2$ plane contained cluster i. Consequently, when the persistence of a point in the persistence diagram of the test space exceeds the threshold, the point shows a dramatical difference of topology from its nearest neighborhood. So, we have an acceptable reliability in verifying topological abnormalities of the test data. Besides, let's remember that the new cluster $k+1$ has no points in the total diagram, so its degree of commonality equals zero.

Finally, we simply use the following measure to compute the deviation between the two diagrams through the difference in distributions of their clusters:

$$\delta = \sqrt{\sum_{i=1}^{k+1}(P_i - Q_i)^2} \qquad (4)$$

where Qi is the fraction of points assigned to cluster i in the test space's persistence diagram. Clearly, the larger δ is, the more the deviation of the test data's dynamics and the training data's dynamics is. Thus, a large enough value of δ confirms that the index return's dynamics are much strange relative to its previous dynamics.

Some studies also use TDA's tools to investigate stress periods of a stock market, such as the works of Gidea and Katz (2018) and Ma (2020). The authors use the persistence landscape, another tool of TDA which is equivalent to the persistence diagram in encoding the topological information of a point cloud when the spatial resolution changes. However, their studies don't use the time-delay embedding method to convert a given time series to a point cloud because of the concern of the prior lack of an attractor and the intrinsic stochasticity of the time series of index returns. Instead, they use $\tau = 1$ and use more market indexes to create a point cloud reflecting the market's state, where the number of the indexes is considered the points' dimension. In our opinion, because index returns are usually stationary or closer to being stationary (see Fig. 1), there may be some deterministic properties of index returns' dynamics. This is confirmed by the relative stability of the persistence diagrams of 0-dimensional and 1-dimensional features in Fig. 3. Also, in our empirical study presented in the next section, we show that if the index return's behavior is significant strange in a certain period, the deviation δ between the point distribution of the persistence diagram got in the period and the point distributions of persistence diagrams got from previous periods will be considerably large. On the other hand, we think that by using more major indexes of a stock market to be data of different dimensions of a point to apply TDA, coordinates of a point are not independent of each other. Indeed, even if the indexes are composed of different components, their components must be driven by the same market factor. Meanwhile, by using the time-delay embedding method, we convert the 1-dimensional time series of an index return to a point cloud of a higher-dimensional space to capture different states of the index return's dynamics, where one coordinate of a point is nearly impossible to get from the point's other coordinates. This is certainly more meaningful in our detecting problem. Furthermore, since δ can measure the stability level of an index return's dynamics compared to its historical dynamics, we also show a threshold of δ concerning the dynamics' remarkable changes in the next section.

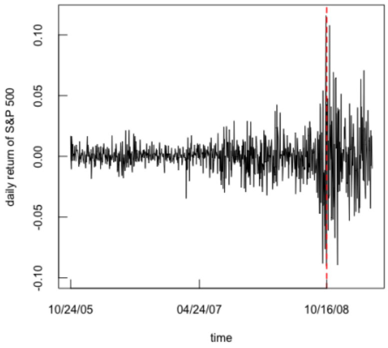
In summary, our anomalies detection method has two main parameters, the size of the test data and the size of the training data. According to the researching purpose, we suggest that the size of the test data must be large enough to capture the market's behaviors in a few months to discover a recession if it exists. In general, a recession is often verified by a negative economic growth for at least two successive quarters. Therefore, in our implementation with the daily return series of the S&P 500 index presented below, we consider the test data including 132 trading days, i.e., about 6 months. On the other hand, although the training data must be large enough as in many machine learning models but, when studying financial time series, the time window of the data should not be too large to avoid outdated information, which can affect the current market's analysis. Hence, in Section 3, we consider the training data including 750 trading days only, i.e., about 3 years. As a result, we think that our method can help quantify the differences of a market index's behaviors in a certain period from its behaviors in preceding periods through the value of δ. So, a large value of δ is expected to give a signal of serious fluctuations, which might change the market's current level of stability.

3. Empirical Results with the S&P 500 Index

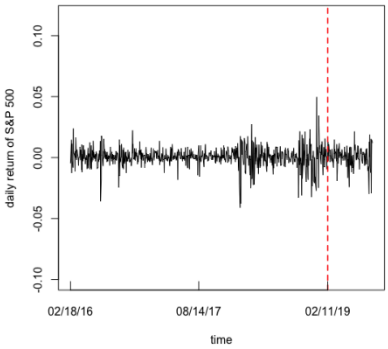
In this section, we study the daily return (rt) of the S&P 500 index where the time series is the log difference of the daily closing value of the index. At first, we study the information got from the topological features of the time series through the persistence diagrams of the corresponding reconstructed vectors in different time windows. Then, we analyze the changes of δ when the test data's dynamics is significantly different from the training data's dynamics and when it doesn't. The two cases are illustrated more clearly through the two example databases described below:

- Database 1: The training data is the return series in trading days from 10/24/2005 to 10/15/2008; the test data is the return series in trading days from 10/16/2008 to 04/27/2009.
- Database 2: The training data is the return series in trading days from 02/18/2016 to 02/10/2019; the test data is the return series in trading days from 02/11/2019 to 08/19/2019.

The values of r_t in the two databases are shown in Fig. 5 where the dashed line divides the training data (on the left) and the test data (on the right). Using the two databases, we compare the behaviors of (r_t) in 132 trading days with its historical behaviors in the 750 closest trading days before. The test data's size approximates the number of trading days in 6 months while the training data's size approximates the number of trading days in 3 years as mentioned at the end of Section 2.4. By tools given in Section 2.1, we found that $\tau = 1$, $d = 9$ and $m = 124$ for the training data in Database 1 while $\tau = 2$, $d = 7$ and $m = 120$ for the training data in Database 2.



(a) Database 1

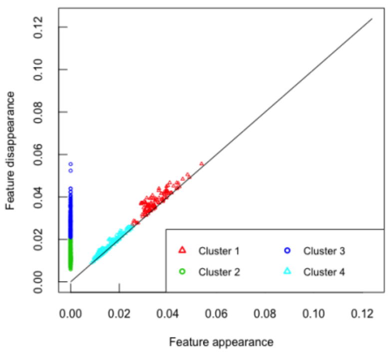


(b) Database 2

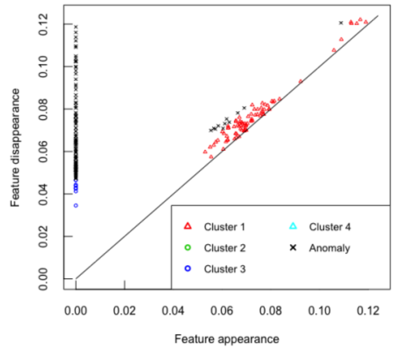
Fig. 5. The daily return of the S&P 500 index.

Fig. 6 and Fig. 7 show the total diagram combined from persistence diagrams of all segments of the training space and the persistence diagram of the test space for Database 1 and Database 2, respectively. From the figures as well as statistics in Table 1 and Table 2, some characteristics of our financial data can be found. Firstly, the 1-dimensional features, which are reflected by points plotted as triangles, are always near the diagonal. Hence, the features have low persistence, which implies the instability of periodicity or repetitive patterns in the dynamics of our data. Secondly, most of the 0-dimensional features, which are reflected by points plotted as circles, tend to have higher persistence than 1-dimensional features. The two phenomena are also observed when we study the daily return in other time windows having the same length. Otherwise, for the persistence diagram constructed by the test data in Database 1 (Fig. 6b), the high death scales of its 0-dimensional features imply the existence of some extreme patterns in the data's dynamics. This means that there are some periods in which r_t's behavior is dramatically different from its normal behavior. Clearly, this result is compatible with the large fluctuation of r_t in test data as observed in Fig. 5a. By contrast, for Database 2, in the persistence diagram of the test space, we don't see any point whose position is dramatically different from points of the total diagram. Consequently, these observations confirm that we can recognize strange behaviors in the dynamics of our financial data through the changes in points' distribution in the persistence diagram.

As mentioned in Section 2.3 and 2.4, the strange behaviors of r_t are detected quantitatively by the measure of dissimilarity between the total diagram found from the training space and the test space's persistence diagram. After applying the k-means algorithm, we get $k = 4$ and $k = 6$ for the total diagram found from Database 1 and Database 2, respectively. The clustering results are illustrated in Fig. 6a and Fig. 7a. Table 1 and Table 2 give some fundamental statistics of the clusters' persistence and their degree of commonality defined by Eq. (3) for Database 1 and Database 2. The results of assigning each point of the persistence diagram of the test space to a cluster given by the total diagram in the two databases are given in Fig. 6b and Fig. 7b.



(a) The total diagram

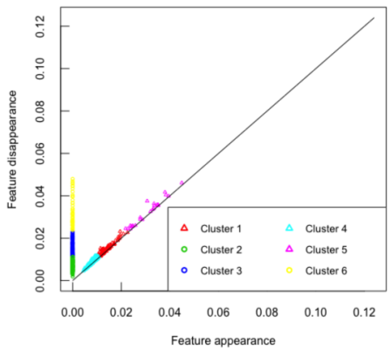


(b) The persistence diagram of the test data's state space

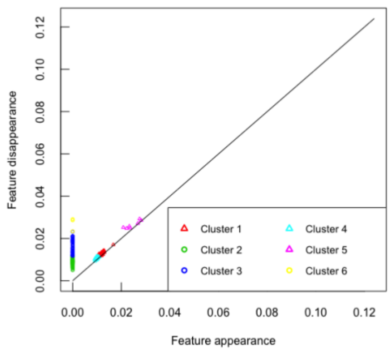
Fig. 6. Comparing the total diagram and the persistence diagram of the test space for Database 1. Circles represent for 0-dimensional features and triangles represent for 1-dimensional features. The black sign × denotes features that cannot be assigned to any clusters of the total diagram.

Table 1. Statistics of features' persistence by clusters in the total diagram for Database 1.

Cluster	Homological dimension	Average persistence (%)	Standard deviation of persistence (%)	Degree of commonality (%)
1	1	0.29	0.22	09.76
2	0	1.25	0.34	43.83
3	0	2.89	0.61	19.62
4	1	0.11	0.09	26.80



(a) The total diagram



(b) The persistence diagram of the test data's state space

Fig. 7. Comparing the total diagram and the persistence diagram of the test space for Database 2. Circles represent for 0-dimensional features and triangles represent for 1-dimensional features.

Table 2. Statistics of features' persistence by clusters in the total diagram for Database 2.

Cluster	Homological dimension	Average persistence (%)	Standard deviation of persistence (%)	Degree of commonality (%)
1	1	0.09	0.08	09.81
2	0	0.74	0.21	47.75
3	0	1.57	0.32	15.84
4	1	0.08	0.06	17.70
5	1	0.15	0.15	02.40
6	0	3.13	0.66	06.50

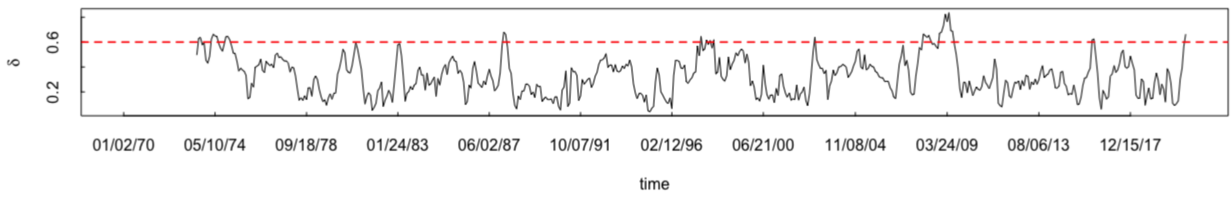
By Eq. (4), we compute that the deviation δ between the point distribution of the total diagram and the point distribution of the test space's persistence diagram is about 83.7% for Database 1 and 11.9% for Database 2. Clearly, the large value of δ for Database 1 is compatible with the extraordinary dynamics of the test data in this database, while the small value of δ for Database 2 is consistent with the indifference between the dynamics of the index return in the test period and the dynamics in the training period.

As a result, the persistence diagram of the time-delay embedding associated with the index return series can reflect the characteristics of the index return's dynamics through its topological information. Therefore, our framework can help detect strange attractors of the time series by recognizing dramatic changes in the point distribution of the diagram.

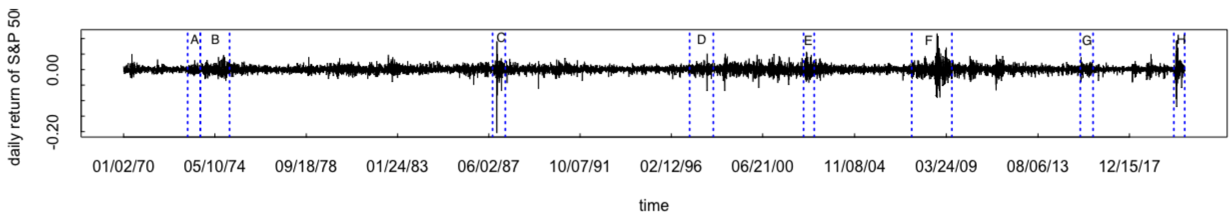
4. Discussions

An important question is how large the value of δ such that it can be considered as a signal of the market phases' switch. For finding the answer, we perform our anomalies detection framework for r_t in each time window, including 132 trading days with 22 rolling trading days, of the long period from 12/18/1972 to 08/04/2020 to get a general view about the value of δ in the U.S. market. Consequently, we get 541 time windows. The dynamics of r_t in each time window is compared to its historical dynamics in 750 preceding trading days. It means that we approximately compare the behaviors of r_t in 6 months to its behaviors in 3 preceding years with 1-month sliding. The value of δ is given in Fig. 8a as a function of time. The maximum of δ approximates 83.7%, which is corresponding to the time window from 10/16/2008 to 04/27/2009, the test period in Database 1. This period has attracted a lot of attention in literature since it is the time when the Great Recession of 2008 happened terribly after the shock of the bankruptcy of Lehman Brothers on 09/15/2008. The average and the standard deviation of δ in our test are about 32.7% and 15.4%, respectively.

Because δ is larger when the point distributions of the test data's persistence diagram and the total diagram of the training data are more different, we consider the values of δ which are on the left tail of its histogram in Fig. 9. Especially, in case that the deviation δ is larger than 60%, we found that the corresponding periods relate to recessions or market crashes. Moreover, this threshold is demonstrated empirically to be large enough to recognize significant changes of the market's state. In fact, there are 32 time windows satisfy this condition of δ in our test. Because the length of each time window is 132 while the length of the sliding period is only 22, some of those 32 time windows intersect with each other. Every pair of time windows which intersect with each other and time windows which lie between them are merged together. Consequently, we get 8 periods, named from A to H (Fig. 8b). The detailed information of these periods is provided in Table 3.



(a) Value of δ plotted at the corresponding test period's last day



(b) Daily return of the S&P 500 index

Fig. 8. Relation of δ and the behavior of the S&P 500 index's daily return.

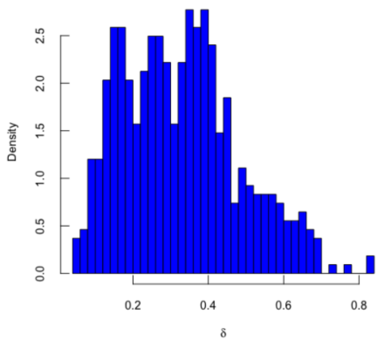


Fig. 9. Histogram of δ from 12/18/1972 to 08/04/2020.

Table 3. Statistics of features' persistence by clusters in the total diagram for Database 2.

Period	Time	Maximum of δ (%)	Average of δ (%)
A	01/22/1973 – 08/30/1973	63.7	63.3
B	10/03/1973 – 01/22/1975	66.3	61.2
C	08/06/1987 – 03/15/1988	68.2	67.1
D	12/27/1996 – 02/13/1998	64.5	58.8
E	06/03/2002 – 12/06/2002	64.0	64.0
F	07/30/2007 – 06/29/2009	83.7	67.0
G	08/12/2015 – 03/22/2016	62.5	62.1
H	01/28/2020 – 08/04/2020	66.4	66.4

We found that the strange dynamics of the S&P 500 index's daily return discovered in periods A and B are corresponding to the 1973 – 1974 stock market crash spreading from January 1973 to December 1974 (Davis, 2003). Besides, periods B also relates to the 1970s stagflation, where the OPEC oil embargo signed on 10/19/1973 is widely blamed for causing the stagflation (Merrill, 2007). Similarly, our framework indicates that there are anomalies in the dynamics of the index in period C because this period relates to the stock market crash of 1987, which was a rapid and severe downturn in the U.S. stock prices that occurred over several days in late October 1987. It is well-known with the name "Black Monday". In addition, this period is a sensitive time with the 1989 savings and loan crisis where more than 1000 of the country's savings and loans had failed. In fact, the crisis is an outcome of uncontrollable bad loans and losses for a long time, especially after the Federal Savings and Loan Insurance Corporation, an institution that administered deposit insurance for savings and loan institutions in the United States, had become insolvent by 1987 (Hanc, 1997; Pyle, 1995). How about period D? Although it doesn't really link to a recession since it just contains to a fast crash in October 1997, which is affected by an economic crisis in Asia started in July. However, the crash is considered as the beginning of the end of the 1990s economic boom in the U.S. (Schwert, 1998) because, after the crash, economic growth became slower in 1997 – 1998. Meanwhile, period E is corresponding to the stock market downturn of 2002, also known as the internet bubble bursting with a dramatic decline in July and September 2002 (Mishkin and White, 2005). In fact, the crash is just the worst result of the dot-com crash 2000 – 2002. Especially, the longest period, period F, is clearly related to the 2008 financial crisis, the worst crisis in the U.S. from the Great Depression of 1929. The crisis officially lasted from December 2007 to Jun 2009, and the bankruptcy of the investment bank Lehman Brothers in September 2008 is often thought to play a major role in the unfolding of the crisis (Williams, 2010). Period G also relates to a substantial change of the market's collective behavior, a stock market selloff that occured between August 2015 to Jun 2016 (Wikipedia definition of 2015 – 2016 stock market selloff). Finally, the last period is corresponding to the COVID-19 recession, which started in February 2020 (Wikipedia definition of Covid-19 recession).

As a result, our method allows us to track anomalies of a stock market's behavior through observing its representative index's dynamics, especially when the market enters a dramatic downside movement. The method provides a new approach in financial analysis when using the changes of the topological structure of the index return's dynamics to capture the market's stability level. In fact, people frequently conjecture a stock market's stability based on analyzing macro factors that can directly affect all of the market's components and drive their movements in the same direction. These factors can be the political situation, the government's financial policies and procedures, the infrastructure, the import and export values, the monetary... Although macro factors can provide a valuable prediction of the market development, this method requires deep knowledge about the economy and take much time to analyze many statistics of different aspects. Furthermore, because the macro statistics are published periodically, it's not easy for investors to get this data to evaluate the market's current situation if there is suddenly any significant change, such as the occurrence of an epidemic or a disaster. Meanwhile, with our method, we can detect significant changes in the market's collective behaviors at any time because the index's value is updated in real-time when the stock exchange opens. In particular, because the value of δ helps measure the level of the market collective behavior's change, we propose that the value of δ can give a warning of systemic changes when it increases rapidly toward the threshold of 60%. When it exceeds the threshold, this indicates that the market is in, or is about to, a recession or simply has extraordinary movements that are difficult to be predicted by experience and historical data. With this extreme case, the value of δ helps gauge the severity of the recession; for instance, the largest value of δ in our test corresponds to the 2008 financial crisis, the worst crisis in the last 50 years.

5. Conclusions

Basing on the persistence diagram of the time-delay embedding associated with a market index's daily return, we can understand more about characteristics of the market's dynamics such as its concentration and periodicity through topological information encoded in the diagram. Furthermore, we also detect anomalies in the market's collective behavior through substantial changes in the point distribution of the diagram. For example, when applying our method for the daily return of the S&P 500 index in 6 months, we found that the index return lacks stable periodicity and repetitive patterns because of the small persistence of the 1-dimensional features. Besides, the extremely high death scales of the 0-dimensional features in some periods are the result of some abnormal patterns of the data's dynamics. In addition, after considering the change over time of the persistence diagram of 0-dimensional features and 1-dimensional features, we found that the deviation δ between the points' distribution of the persistence diagram computed from the return series in a certain time window and the ones computed from the preceding data can efficiently capture the changes of the return's dynamics. Especially when δ exceeds the threshold of 60%, the market has exceptional behaviors that are difficult to be predicted by experience and historical data. Evenly, it may be falling in a dramatic recession. Therefore, the value of δ can be used to evaluate the market's stability level, and a continuous and rapid increase of δ approaching the threshold gives a warning of a recession or crisis. In order to apply our framework of detecting abnormalities to other markets, similar researches should be taken to find their own thresholds. As a result, our study not only demonstrates an application of TDA to time series analysis in the financial context but also provides an easy-to-implement method to evaluate the stability of a financial market at any time without studying many economic factors. Thus, parameter δ can be an efficient indicator of systematic risk management, especially for individual investors who are not easy to get a full analysis of the economy's operation.

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An Implication of Design Thinking in Culture-based Product Design Process: A Case of Vietnamese Tradition

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Abstract

This study, based on Design Thinking initiative, proposes a newly developed culture-based product design process with six phases (i.e., Understand, Observe, Point of View, Ideate, Prototype, and Test) embraced with three levels of culture (i.e., Outer Level, Middle Level, and Inner Level) to promote cultural features in culture-based product design. The process first started with literature research on culture and cultural market survey to understand and observe the target cultural objects resulting in point of view; followed by Affinity Diagram method, Lotus blossom method, and C-Sketch mashed up with three levels of culture to develop as many creative solution concepts as possible; and then scenario building and storytelling with both AEIOU and 5W1H techniques were introduced to help provide distinct perspective and profound knowledge about the solution concepts with target customers. Finally, the chosen solution concept was prototyped and tested. A case with main topic on Vietnamese Lunar New Year Cuisine was demonstrated to present how this newly developed process works.

Keywords: Design Thinking, Culture-based Creativity, Culture-based Product Design, Vietnamese Cultures

1. Introduction

Vietnam is a generally multi-cultural country in which there is a blend of Chinese culture with significant South East Asian influences of Khmer and Japan, and strong Western influences of French and American. Vietnamese cultures have been variously treasured and developed throughout the entire history and geographic expansion of Vietnam, which is one of the factors promoting Vietnam's tourism in addition to natural beauty, geographic and ethnic diversity, fascinating history, political security and low cost (Rubin, 2005).

In the "Culture Program's Priorities in Viet Nam (2012-2016)" proposed by United Nations Educational, Scientific and Cultural Organization (UNESCO), culture is also considered as a powerful source of inspiration and unification as well as the national pride to reveal Vietnam and its best to the world. Culture can be the bridge to connect the local identity to the global market. One of three thematic areas UNESCO's Culture Program in Viet Nam also focused on is Cultural Creativity, which enabled transforming cultures into assets, offering new employment opportunities and maximizing Vietnamese's creative expression and enjoyment of diverse cultural goods and services (UNESCO, 2011). In a study on "The Impact of Culture on Creativity" by European Affairs (KEA, 2009), culture-based creativity is also considered as an important feature of a post-industrial economy from developing new products and services, driving technological innovation to inspire people to learn and building communities.

In other perspective, design is another crucial factor, which is believed as the "point where art and technique meet to create another culture," (Flusser, Maillard & Maillard, 2002). Design is now everywhere in human's life from public to private spaces. Whatever could be a product could be touched by design. Therefore, designers with culture-based creativity can break the usual way of thinking to acknowledge the evolution of a new vision, an idea or a product (KEA, 2009). However, recently in the contemporary design world, design is no longer limited focusing only on products but more becoming a methodology, which is known as

Design Thinking. Design Thinking is a human-centered approach results in innovative impacts on the society development from a large scale of the design industry to a smaller scale of academic environments. Design students have applied design thinking to build up their creative confidence (Kelley & Kelley, 2013; Brown & Katz, 2019). Moreover, Design Thinking also can create a multidisciplinary space in which collaboration will blend the designers' creativity with people's needs and a technological possibility to enable a business strategy to capitalize upon market opportunities (Brown, 2008; Brown & Katz, 2019).

From that point of view, the study focuses on Design Thinking as a crucial platform to build up a culture-based product design process, which can be applied to transform cultural features into modern product design. Moreover, product design with incorporating the cultural features can probably help attract young generations to appreciate the traditionally cultural customs and heritages.

2. Literature Review

2.1 Culture-based creativity

KEA (2009) developed the concept of culture-based creativity, which originated from art and cultural productions or activities "which nurture innovation", not only just "artistic achievements" but also "creative content" for broadband networks, computers and consumer electronic equipment. Moreover, they believed that culture-based creativity could "highlight the elements of culture which trigger creativity". A distinction between culture-based creativity and innovation is also proposed, "to highlight the specific contribution of culture". In order to "characterize" the connection between culture and creativity, the concept of "culture-based creativity" was developed (1) to emphasize the important of creative talents; (2) to recover the meaning of creativity; and (3) to distinguish creativity from innovation (KEA, 2009).

When discussing culture from the perspective of time and space, He (1992) divided "cultural space" into three structural levels: the external, tangible and visible "outer level", the "middle level" of human behavior rites, and regulations in the form of words and language; and the "inner level" of the manifestation of human ideologies. Then more than ten years later in 2003, in a dialogue on culture-based knowledge towards new design thinking and practice, a Hong Kong-based designer Benny Ding Leong mentioned that "spatial perspective of culture" (Figure 1) as one of his research tools. He said it was a manageable framework "to visualize and capture the fluid concept of culture", and helped him to identify the research focus. Using that framework could bring him the concentration on to the "inner" level of traditional Chinese culture research (Leong & Clark, 2003).

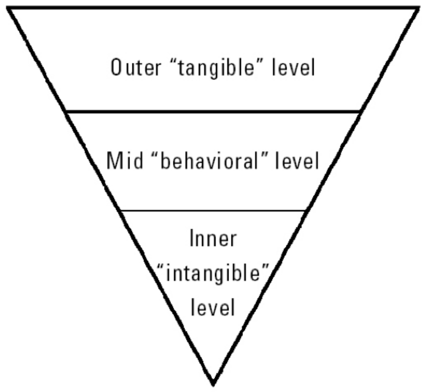


Fig. 1. The "spatial perspective" of culture (He, 1992).

Culture-based creativity is a crucial attribute of a post-industrial economy. It can help the development of products and services meet citizens' expectations or create these expectations. It is considered as "fundamental means for industry and policy decision makers" to embrace and implement more the concept of "user-centered strategies" rather than producing things but providing services (KEA, 2009). It also plays a leading role in provoking social innovation by helping "to promote well-being, to create lifestyle, to enrich the act of consumption, to stimulate confidence in communities and social cohesion". Moreover, it makes a big contribution "to product innovation, to branding, to the management of human resources and to communication."

2.2 Cultural design models

There are various reasons that determined the product consuming, including "practical functions of the product, cultural meanings, aesthetics values, and emotional aspects." Emotional aspects of a product hold an important role in triggering consumers to buy a specific product as it might "evoke effective resonances". One of those might come from the cultural meanings. Every country has its own distinctive and prosperous cultural background, which is always considered as a precious resource of inspiration (Wang et al., 2013). In the 1970s, there was a speedy development in embracing culturally oriented goods and design "as a mean to attract consumers". Therefore "culturally sophisticated products were preferred rather than technological attributes in the 1980s" (Sparke, 2013). Nowadays, culture-based product design is generally mentioned as a creative strategy when some companies and design studios used symbolic value especially national cultural elements in product design to attain a better competitive advantage in the market (Clifton, 2011).

There are many studies revealed that there is an increase in product consuming for symbolic meaning, feelings of pleasure, enjoyed imagery, and aesthetic demand more and more than just for practical or functional needs (Holbrook & Hirschman, 1982; Ravasi et al., 2012; Verganti, 2009). For culture-based branding, Holt (2004) suggested cultural principles for companies, which are aimed "to build up an iconic brand to differentiate themselves to other competitors and also express their identity," (Wang et al., 2013). In the global market, culture-based products guide to make the distinctions instead of uniformity of aesthetic and content (Scott, 2004). Moreover, the intangible value of a product such as emotional arousing, humor, cultural meanings can persuade for the faith of customers to a company (Celaschi et al., 2011; Asokan & Payne, 2008). In summary, transforming cultural features into product design is a potential and future movement in product development, which is also under the impact of culture-based creativity.

2.3 Design Thinking process

Design Thinking process is best described metaphorically as a system of three spaces: Inspiration, Ideation, and Implementation; which separate different sorts of related activities that together might form a continuous sequence of innovation (Brown, 2008). The Inspiration space is for the circumstances, which might be a problem, an opportunity, or both. It is where the search for solutions gets motivated. The Ideation space is to generate, to develop, and to test ideas that might lead to potential solutions. Finally, the Implementation is "for the charting of a path to market" (Brown, 2008).

With a focus on innovation, creativity, critical thinking, problem solving, communication and collaboration, Design Thinking was taken as learning approach to Schools Research Project to prepare for future students with 21st Century Skills (Carroll et al., 2010). The Design Thinking process includes six key components: Understand, Observe, Point of View, Ideate, Prototype, and Test (Figure 2). The six key components are those developed by the Hasso Plattner Institute for Design in Stanford University, but other design process might have a slight difference.

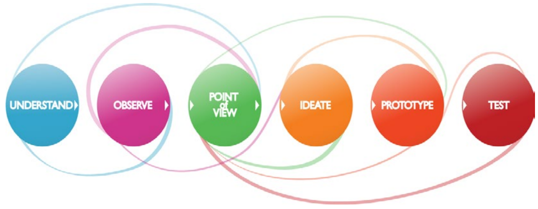


Fig. 2. The six key components of the Design Thinking process (Carroll et al., 2010).

3. Culture-based product design with Design Thinking

This stage of the research generated three spaces in Design Thinking process (Brown & Wyatt, 2010) (Inspiration, Ideation, and Implementation) with six Design Thinking phases proposed by Carroll et al. (2010) (Understand, Observe, Point of View, Ideate, Prototype, and Test) and Three Levels of Culture Theory (He, 1992; Leong & Clark, 2003) to develop a systematic framework for transforming cultural features of Vietnamese traditional Lunar New Year cuisine to ceramic tableware. There were different creativity activities and tools introduced as hands-on practices in different phases to help participants conduct an implication of design-thinking process and achieve specific tasks in each phase.

In Phase 1 – Understand: participants conducted pre-research on culture with literature review, data collection and group discussion in order to understand the fundamental relevant knowledge on cultural objects. In Phase 2 – Observe: participants were required to do a market survey following the three levels of culture (Outer, Middle and Inner Levels) to comprehend deeper customers' behaviors, needs and insights as well as contemporary technologies and cultural products on the commercial market. In Phase 3 – Point of View: participants with data analyzing figured out the customers' needs as well as narrowing down the design problem, in this case for ceramic tableware. In Phase 4 – Ideate: participants were instructed to use a various collection of hands-on practices with creativity tools such as: Affinity Diagram Method, Lotus Blossom Brainstorming Method, Collaborative Sketching (C-Sketch), AEIOU & 5W1H, Scenario & Storytelling, to diverge, converge and develop conceptual idea solutions. Finally with Phase 5 – Prototype and Phase 6 – Test: participants were required to come out either virtual or physical prototypes (rapid prototypes and then 1:1 scale prototypes) for testing with Value Opportunity Analysis (VOA) (Cagan & Vogel, 2012) to help participants ensure if their design solutions could meet customers' needs. Figure 3 demonstrates the framework of this stage, which is based on three main spaces of Design Thinking with six phases and three levels of culture.

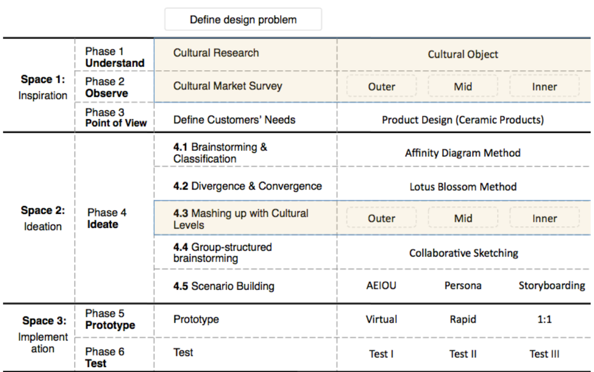


Fig. 3. The systematic framework of the Stage 3: Applying Design Thinking Process with Culture-based Inspiration in Transforming Cultural Features of Vietnamese Traditional Lunar New Year Cuisine to Ceramic Tableware.

3.1 Phase 1 – Understand

After the design problem had been designated, participants who attended this design thinking process were required to: (1) carry out a cultural research for foundational comprehension based on three questions: What is the cultural object? How does it influence the customs and daily products? Is there any cultural product design in our daily life? Therefore the participants could get an overall understanding about the cultural object with its background as well as the influenced customs; (2) present the pre-research before teammates which are from cross-disciplines and conduct a group discussion for a more extensive interpretation of the problem.

3.2 Phase 2 – Observe

With the foundational comprehension from Phase 1 and followed by three levels of culture (Outer, Middle and Inner Levels), participants carried out a market survey with an online field trip to several commercial websites on ceramic tableware in Vietnam in order to verify if there is any possibility of ceramic tableware with cultural features from Vietnamese traditional Lunar New Year cuisines available on the Vietnamese market. Moreover, they interviewed some prospective customers to understand their behavioral and reflective insights. This was also one of the significant features of Design Thinking: human-centered approach (Brown, 2008; 2019).

3.3 Phase 3 – Point of View

Participants analyzed the output data from two previous phases to make a narrower focus on the design problem and define the customers' needs.

3.4 Phase 4 – Ideate

Step 1: Brainstorming & Classification: Affinity Diagram Method. After conducting the market survey, participants were asked to write down all keywords relating to cultural topic of Vietnamese traditional Lunar New Year cuisines on post-it papers. After that, they categorized them in groups of issues. This activity helped participants focus on the potential group of issues, which could meet the customers' needs and be applied in the real market.

Step 2: Divergence & Convergence: Lotus Blossom Brainstorming Method. Participants set cultural topic in the center of Lotus Blossom Map, and then fill the first layer of boxes with main keywords from the previous step of Affinity Diagram Method. Those main keywords in the first layer of boxes would be set as main topics in the center of the second layer for divergence. Following those new central keywords, participants figured out more keywords to expand the map until it was completed. Finally, the convergence of the Lotus Blossom Map would be started from the outmost layer towards the center. With the central keywords of each layer, two other keywords would be chosen for the idea combinations. There would be 8 idea combinations from the final map. They would be written in the format: "Design topic = Keyword 1 + Keyword 2 + Keyword 3 +…+ Keyword n."

Step 3: Mashing up with Cultural Levels: 3 Levels (Outer, Middle, and Inner). For the purpose of concentration on cultural topic, each of the idea combination from the previous step of Lotus Blossom Brainstorming Method was mashed up with one cultural level form three levels of culture. For example, a new idea combination would be re-written in the format: "Design topic A = Keyword A1 + Keyword A2 +…+ Keyword An + Outer Level." The others might be "Design topic B = Keyword B1 + Keyword B2 +…+ Keyword Bn + Middle Level"; "Design topic C = Keyword C1 + Keyword C2 +…+ Keyword Cn + Inner Level."

Step 4: Group-Structured Brainstorming: Collaborative Sketching. From the new idea combinations got in the previous phase of Mashing up with Cultural Levels (Outer, Middle, and Inner) participants would write down that new idea combination on the top of the sketch paper and performed a round of collaborative sketching. They would not have any communication during conducting the Collaborative Sketching. At the end of this activity, they would stick all the sketches on the wall to present about their conceptual sketches and ideas. At this moment, they would discuss more about all the conceptual sketches they got from a round of Collaborative Sketching, and then they would vote for three most potential concepts for next steps of Ideation.

Step 5: Scenario Building: AEIOU & 5W1H, Persona & Storyboarding. From the conceptual idea chosen in the precious step of Collaborative Sketching, participants would use some methods or techniques to build up the scenarios in which the products would meet customers' needs. AEIOU (standing for Activities, Environments, Interactions, Objects, and Users), 5W1H (standing for Who, What, When, Where, Why, and How), Persona (with more detailed characteristics such as: name, gender, occupation, education, hobby, and personality, etc) and Storyboarding (with six panel framework and a brief description based on "who, where, what, when, why, how") are some methods suggested for visually establishing more detailed development for potentially conceptual design solution.

3.5 Phase 5 – Prototype

Participants would make: (1) virtual prototypes by detailed sketching or 3D modeling rendered images; (2) rapid prototypes with paper or simple and cheap material to quickly model up a physically prototyped product; (3) a group discussion with virtual prototype and rapid prototype to evaluate and refine for a better solution, after that a 1:1 scaled prototype by 3D printing with refined details and shape for a better image of conceptual solutions for next step of Implementation.

3.6 Phase 6 – Test

Following three times of prototyping, participants would make three times of testing: (1) The first time was to check if the conceptual sketches from previous phases could be developed after the group discussion about the possibilities and limitations. (2) Getting feedback form group discussion through rapid prototypes might lead to more ideas for improving or developing the product solutions in the real commercial market. (3) At the final testing, the 3D printed conceptual product at the scale 1:1 with refined details and shape would be used to take a qualitative survey with Value Opportunity Analysis (VOA). An in-depth interview would be conducted with a potential customer for more feedback to enhance the conceptual product in Implementation. This phase is to ensure the possibility of the conceptual product as a culture-based product design.

Figure 4 shows a Value Opportunity Chart, which would be used to evaluate how product might meet target customers' needs or insights for usefulness, usability, and desirability. The chart lists 7 classes of Value Opportunity with its attributes in a column. The values are measured in a qualitative range and are described as low, medium, and high for each attribute. If a product did not meet any level of that attribute, no line is drawn (Cagan & Vogel, 2012).

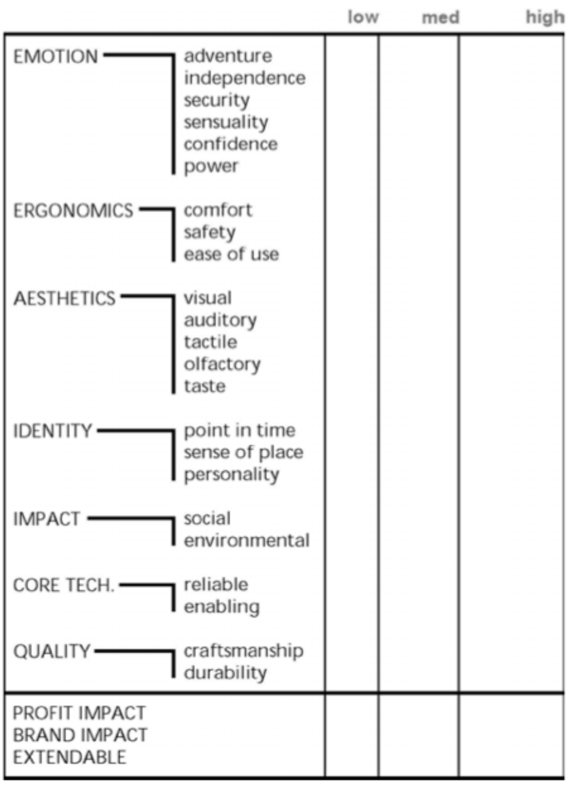


Fig. 4. Value Opportunity Chart (Cagan & Vogel, 2012).

4. Results and discussions

Five Vietnamese graduate students from different departments in Ming Chi University of Technology (New Taipei City, Taiwan) conducted this Stage 3 in one-day mini-workshop on May 5th, 2018. Some parts of the process were conducted after the workshop.

There is a multi-disciplinary collaboration in the group of five participants who joined to demonstrate this implication of design thinking in culture-base product design process. The demographics of this group functionally imitated a "typical company" in its small scale with roles and responsibilities:

* Design Team: including two graduate students from Industrial Design; both of them used to work in Vietnamese companies producing ceramic products. These team members are mainly in charge of designing the products, from the conceptual to developed sketches and models till the sample products.

* Technical Team: including two graduate students. One is from Industrial Engineering and Management; his major is about Ergonomics. The other is from Safety, Health and Environment Engineering. These team members are mainly in charge of technical manufacturing of the products.

* Business Team: including one graduate student from Business Administration. This team member is mainly in charge of business model and profitable abilities of the products.

Moreover, for the culture-based advantages, there is also a multi-regional collaboration in this group. They are from the North of Vietnam (Ha Nam Province), the Middle of Vietnam (the old capital Hue City, the newly developed Da Nang City), the South of Vietnam (Ho Chi Minh City), and one is Guangdong Vietnamese from China Town (Ho Chi Minh City). This interestingly influenced the diversity of the cuisine cultures and customs in the group.

4.1 Phase 1 – Understand

The group of five participants conducted a research for fundamental knowledge about Vietnamese cuisine in Tet – the Lunar New Year in Vietnam. Firstly, the team leader presented her pre-research before other team members, based on three questions: What is Vietnamese traditional Lunar New Year cuisine? How does it influence their customs in using ceramic tableware? Is there any daily life ceramic tableware designed with cultural features of those cuisines? After that, the team discussed more on the research to help other teammates understand deeper the reality of Vietnamese cuisine and customs for Tet among different areas in Vietnam, such as: main traditional cuisines, cuisines required for ancestor worship, activities during the time of "eating Tet", eating-style diversity in various regions in Vietnam (the North, the Middle, the South of

Vietnam, and in a typical Chinese Vietnamese family), etc.

4.2 Phase 2 – Observe

Based on the Understand phase, the group conducted a market survey to learn if there is any application of Vietnamese cuisine to ceramic tableware on the commercial market, especially in export market. With human-centered spirit, they also interviewed potential customers to understand their behaviors in using ceramic tableware, especially Vietnamese ceramic tableware. This observation encourages the group to develop a sense of empathy (Carroll et al., 2010).

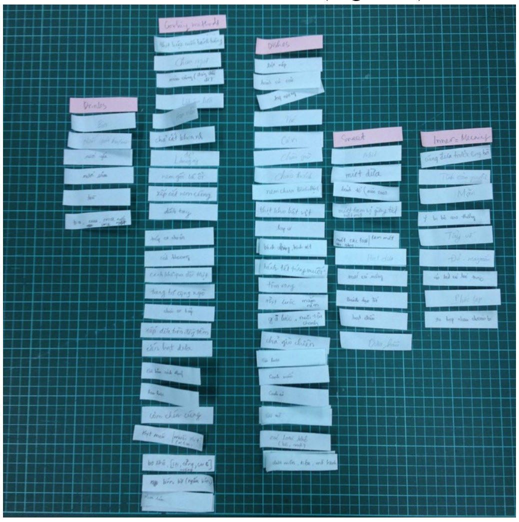
4.3 Phase 3 – Point of View

After the group learned form Phase 1. Understand and Phase 2. Observe, they developed a Point of View that focused on potential customers' needs and insights (Carroll et al., 2010). In this case with culture-based product design, the design problem was narrowed down through their research: (1) there was a lack of design in Vietnamese ceramic tableware market especially for export purposes, (2) Vietnamese young people prefer second-hand Japanese industrial ceramic tableware for the cheap prices and variety in design, (3) the Vietnamese cultural features were often exploited with very old-fashioned concepts and images.

4.4 Phase 4 – Ideate

Step 1: Brainstorming & Classification: Affinity Diagram Method. With new knowledge after the market survey and defined design problem from previous steps, the five participants in the group wrote down all relevant keywords on post-it papers and categorized into groups. They came out totally 71 keywords and grouped into 5 themes: Traditional dishes, Cooking methods, Drinks, Sweets, Cultural Meanings (Figure 5).

Step 2: Divergence & Convergence: Lotus Blossom Brainstorming Method. The participants set Vietnamese traditional Lunar New Year cuisine (coded "VN Tet cuisine" in short) – the cultural topic – in the central box of Lotus Blossom Map, then fill 5 main keywords from the previous categorized groups. They need 3 more to complete the very first level of the 9-window-map. These 8 keywords would be the central keywords of the second level 9-window-map to be continued for divergence. After fulfilling the whole map of 3 levels of 9-window-map, they came out 8 idea combinations (Figure 6).



Traditional dishes	Cooking methods	Drinks	Sweets	Cultural meanings
bột nếp	thịt luộc cuốn bánh tráng	bia	mứt	cúng đưa rước ông bà
bánh củ cải	chua ngọt	nước ngọt	mứt dừa	tình cảm gia đình
lạp xưởng	màu vàng	nước yến	bánh tổ	mặn
tré	lột ăn liền	nước sâm	mứt tam vị	bộ bộ cao thăng
cà ri	hầm mềm	trà	làm mứt	tẩy uế
chân giò	chả cắt khoanh		hạt dưa	đỏ là may mắn
cháo thánh	để lâu ngày		mứt củ năng	ẩn bất cứ lúc nào
nem chua Bình Định	nem gói lá ổi		bánh kẹo Tết	phức tạp
thịt kho hột vịt	xếp cắt nem cúng		hạt điều	tụ họp nhau chuẩn bị
lạp vi	dính tay		dưa hấu	
bánh chưng	hấp chiên			
bánh tét trứng muối	cắt khoanh			
tôm rang	canh khổ qua dồi thịt			
thịt luộc mắm nêm	trang trí cọng ngò			
gà luộc muối tiêu chanh	xếp dĩa tròn đồng tâm			
chả giò chiên	cắn hạt dưa			
canh miến	gà cách thủy			
canh củ	rau luộc			
các loại khô	cơm chén cúng			
dưa món kiệu	thịt muối			
mỡ hành	bò khô sợi tảng cục			
	bím bò			
	nem rán			

Fig. 5. Affinity diagram.

Step 2: Divergence & Convergence: Lotus Blossom Brainstorming Method. The participants set Vietnamese traditional Lunar New Year cuisine (coded "VN Tet cuisine" in short) – the cultural topic – in the central box of Lotus Blossom Map, then fill 5 main keywords from the previous categorized groups. They need 3 more to complete the very first level of the 9-window-map. These 8 keywords would be the central keywords of the second level 9-window-map to be continued for divergence. After fulfilling the whole map of 3 levels of 9-window-map, they came out 8 idea combinations (Figure 6).

Step 3: Mashing up with Cultural Levels: 3 Levels (Outer, Middle, and Inner). From 8 idea combinations got from the previous phase (Lotus Blossom Brainstorming Method), each participant chose one idea combination and one cultural level to mash up. Therefore, there would be 5 newly culture-based idea combinations (Table 1).

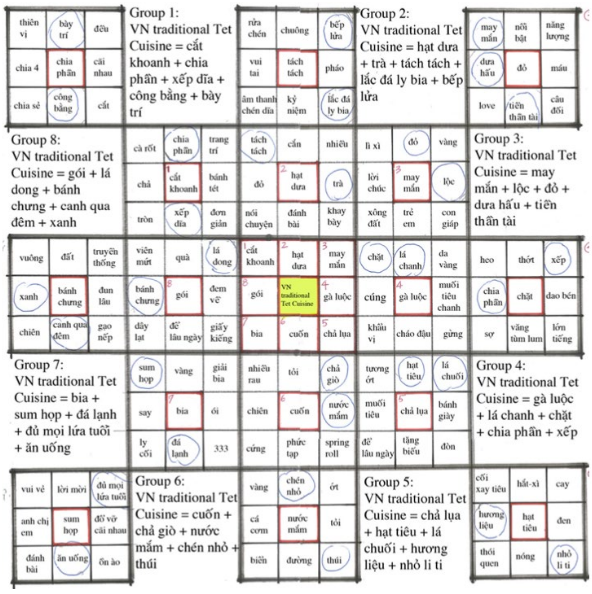
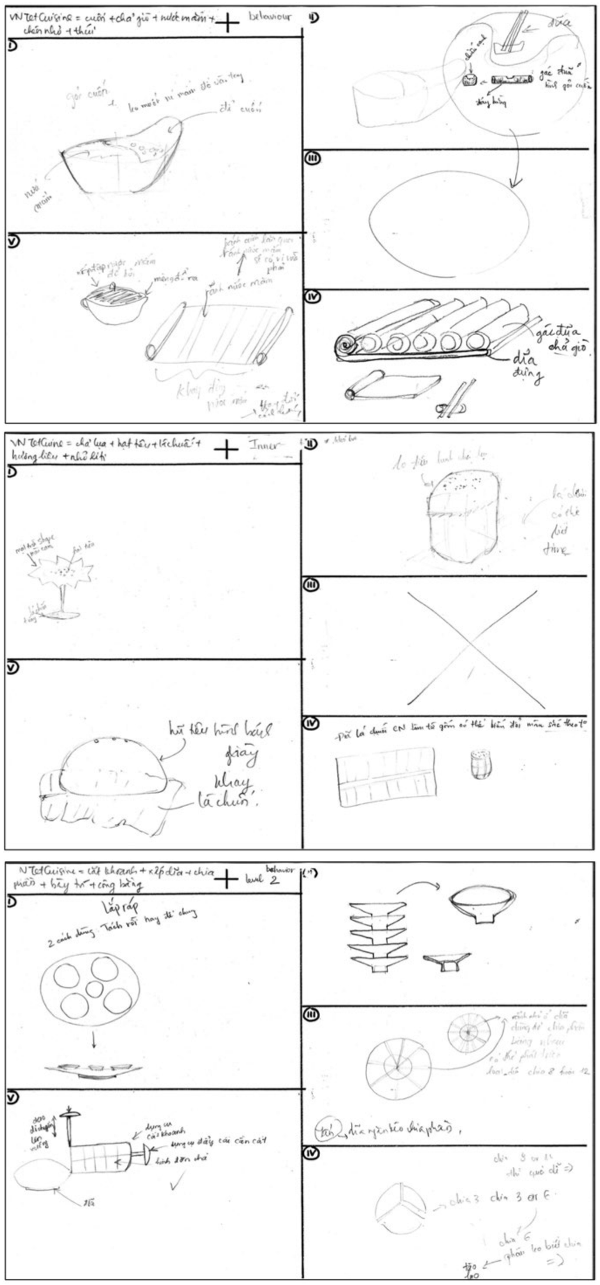


Fig. 6. Fulfilling the whole Lotus Blossom Map with the cultural topic: Vietnamese traditional Lunar New year cuisines.

Table 1. Mashing up 5 idea combinations with Cultural Levels.

	Idea combinations	Cultural Levels
1	VN Tet cuisine = roll + spring rolls + fish sauce + small bowl + smelly	Middle
2	VN Tet cuisine = pork bologna + peppercorn + banana leaf + spice + tiny	Inner
3	VN Tet cuisine = ring cut + arrange plates + partly divide + decorate + equal	Middle
4	VN Tet cuisine = boiled chicken + lemon leaf + chop + partly divide + arrange	Middle
5	VN Tet cuisine = lucky + fortune + red + God-of-Wealth money + watermelon	Inner

Step 4: Group-Structured Brainstorming: Collaborative Sketching. With those 5 newly culture-based idea combinations, participants performed one round collaborative sketching in 25 minutes. After finishing, they came out 25 sketches (5 sketches for each of 5 newly culture-based idea combinations) in which they voted for 3 final conceptual sketches for the next phase of Design Thinking Process (Figure 7).



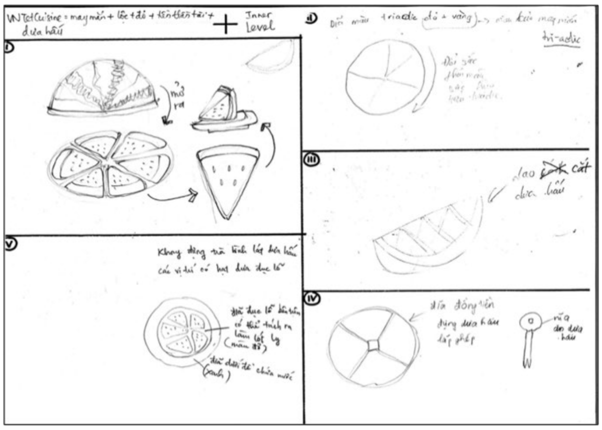


Fig. 7. 5 newly culture-based idea combinations from 25 sketches.

Step 5: Scenario Building: AEIOU & 5W1H, Persona & Storyboarding. From the final conceptual idea from the collaborative sketching (Step 4), with the case Spring Roll Sauce Bowl, participants used 5W1H & AEIOU to get the detailed and imaginative approach to potential customers who might use the product in some situations. In this case, these methods could help students understand more about the possibility and convenience of using the Spring Roll Sauce Bowl with a purpose of avoiding smelly sauce on hand (Figure 8).

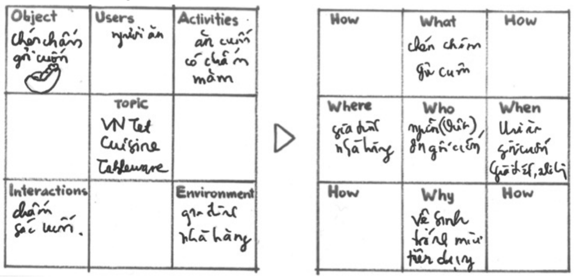


Fig. 8. Using 5W1H and AEIOU to approach to potential customers.

With detailed and contributive information from 5W1H & AEIOU, participants carved more clearly with the personas that would be potential customers of their product design by developing storyboards visually (Figure 9). In this case with Spring Roll Sauce Bowl, they described the scenario in which a young lady named Que Que (who) wanted to eat spring roll in a Vietnamese restaurant (where) for dinner (when). However she was afraid of smelly sauce on hand when holding and eating the spring roll (why), so she used the Spring Roll Sauce Bowl (what).

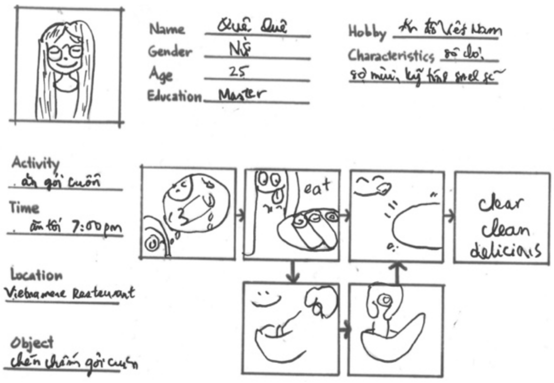


Fig. 9. Using Scenario and Storytelling to have a better imagination of potential customers.

4.5 Phase 5 – Prototype

Participants in Design Team conducted this phase three times to refine the conceptual product whether it could fulfill the customers' needs or requirements as products of culture-based ceramic tableware which easy to use for daily purpose in family, restaurant, and for tourist souvenir as well. Figure 10 would show more about the Spring Roll Sauce Bowl with virtual, quick and 1:1 prototypes.

Fig. 10. Prototypes (virtual, rapid and 1:1 scale) of Spring Roll Sauce Bowl.

4.6 Phase 6 – Test

Participants in Design Team had team discussions twice with virtual and rapid prototypes before taking target customer test with 1:1 scale prototype and Value Opportunity Analysis. (VOA). This phase is to ensure the possibility of conceptual product Spring Roll Sauce Bowl that was persuaded as a product of culture-base ceramic tableware (Figure 12) compared with other designs in the real market (Figure 11).

Fig. 11. Existing commercial products in the market.

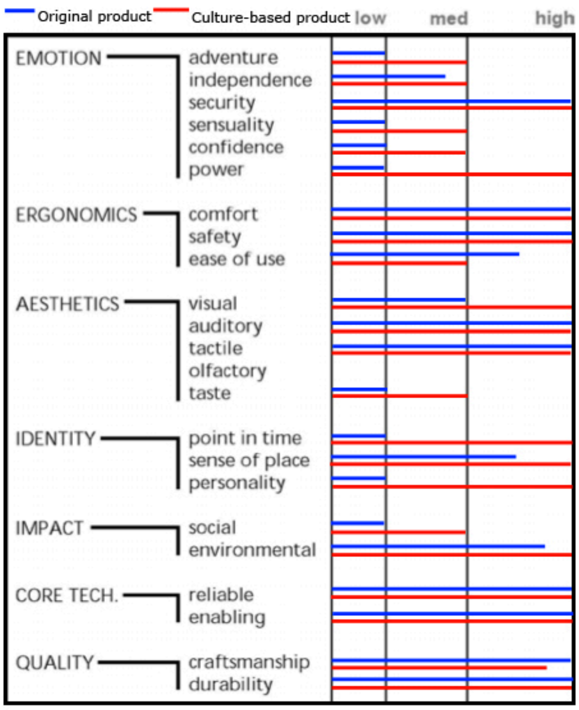


Fig. 12. Value opportunity analysis for the conceptual product Spring Roll Sauce Bowl.

The chosen target customer is a Vietnamese female graduate student also from Ming Chi University. She is 23 years old, and from Industrial Engineering and Management department. She is quite introverted and cautious but interested in Vietnamese traditional folk games and cuisines. Figure 12 shows among many specific Value Opportunities, Emotion and Identify are much more value added for the culture-based product rather than the original product. While other Value Opportunity is almost the same between the culture-based product and the existing commercial product. The target customer also shared her belief on the importance and challenge of storytelling in culture-based products for approaching customers as well as educating for the new culture-based impact.

5. Conclusions

This study generated three spaces in Design Thinking process (Brown, 2008; Brown & Wyatt, 2010) (Inspiration, Ideation, and Implementation) with six Design Thinking phases proposed by Carroll et al. (2010) (Understand, Observe, Point of View, Ideate, Prototype, and Test) and Three Levels of Culture Theory (He, 1992; Leong & Clark, 2003) to develop a systematic framework for transforming cultural features of Vietnamese traditional Lunar New Year cuisine to ceramic tableware. Understand, Observe, and Point of View in the first space (Inspiration) help participants understand the fundamental relevant knowledge on cultural objects, comprehend deeper customers' behaviors, needs and insights as well as contemporary technologies and cultural products on the commercial market, and figured out the customers' needs as well as narrowing down the design problem. In the second space (Ideation), there are many creativity tools such as: Affinity Diagram Method, Lotus Blossom Brainstorming Method, Collaborative Sketching (C-Sketch), AEIOU & 5W1H, Scenario & Storytelling for participants to diverge, converge and develop conceptual idea solutions. Finally in the third space (Implementation), Prototype and Test encourage participants to come out either virtual or physical prototypes (rapid prototypes and then 1:1 scale prototypes) for testing with Value Opportunity Analysis (VOA) to help participants ensure if their design solutions could meet customers' needs. The implication of Design Thinking to Culture-based Product Design Process is a two-dimension framework combined from three levels of culture as the vertical dimension, and Design Thinking process as horizontal dimension. Therefore, the study might produce a different approach in which cultural features still focusing but keeping as the main and strong target for designers to conduct divergence and convergence in more effective ways.

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