Supporting Resilient Conceptual Design Using Functional Decomposition and Conflict Resolution

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Abstract

Concept generation plays a critical role in product design especially in the early design phase when functional requirements are either uncertain or partially known. To cope with the uncertainty imposed by the varying work environment, resilient design has often been called upon to leverage system capacity from the perspective of functional requirements. While the resilient design has been advanced recently, how to design a resilient product structure so to accommodate more functional requirements at the conceptual design phase remains challenging. To tackle this issue, we propose a methodology to support resilient conceptual design using functional decomposition and conflict resolution. To reduce the impact imposed by potential issues and uncertain environments, the overall system functional requirements are defined based on five principles of resilient design. The redundant conceptual scheme that meets functional requirements is given resilience through functional decomposition and conflict resolution. A case study of the conceptual design of a hard rock coring structure present to demonstrate the feasibility of the proposed approach. The results yielded have suggested that the proposed approach can not only support resilient conceptual design, but also leverage design reliability and robustness under uncertainty, especially in terms of varying work environments.

Keywords: Resilient Conceptual Design; Functional Decomposition; Conflict Resolution

1. Introduction

The product development process is a transformation process from customer requirements to a physical structure while considering the various design constraints. Conceptual design is crucial in the design process, especially when the system encounters an uncertain external environment or some functional structures fail[1, 2]. At this stage, the implemented design of product concepts for customer expectations and functional requirements plays critical role in increasing the success of the product in the market[3]. Since the higher the cost and the time spent in modifying a design scheme, the lower the design resilience [4]. The amount of space a product system has to hold more fault tolerance and correction in a changing or multi-interference environment. These changes and interferences are often uncertain or partially known in the design process. In 2009, the American Society of Mechanical Engineers (ASME) defined resilience as a system's ability to rapidly recover to the full function after disruption [5]. Most previous studies agree on the nature of resilience: resilience represents the ability of a system to defy and absorb disturbances and subsequently recover from the damage or impact incurred by disorders [6]. However, the designer's understanding of the key steps in the design process is ambiguous, which pertains to the uncertain environment analysis, functional decomposition and conflict resolution. Thus, integrating functional decomposition and conflict resolution is important for supporting resilient conceptual designs under uncertain or partially known environments.

The general design process consists of design problem definition, functional analysis, solution decoupling elements, etc. [7]. This process is designed to accomplish tasks or missions under abnormal conditions, that is, the absence of partially or uncertain disturbances [8]. Although the related theory of system design has developed extensively, it doesn't remain easy to ensure that the designed products would effectively operate. A system operating in uncertain or harsh environments has a high probability of failure. In addition to improving the adaptability of the system, it also needs to have a specific capacity and self-healing capability. Achieving these gains would require the development of an innovative framework and methodology to endow complex systems with attributes of resilience, enabling these to operate across a range of functional capabilities. This model has a good effect on decomposing uncoupled product functions and can obtain innovative conceptual solutions through conflict resolution.

The investigators aim to develop a resilient conceptual design framework that generates a suitable structure based on changing requirements or evolving environments at the critical stages of conceptual design. This framework can alter the self-tuning capabilities of system operation independence and consistency through uncoupled function iterative mapping and conceptual guidance under the guidance of thinking. The framework can help improve product self-regulation capabilities through uncoupled function iterative mapping and solution conflict resolution. Then, this can be aligned with functional requirements (FRs) and conceptual design parameters (DPs), and increase structural redundancy. Accordingly, this can make the design space focused, allowing to identify better multi-concept solutions. The framework adopts an open innovative design approach and an iterative improvement strategy to build a design logic system since system self-repairing and capacity under uncertain environments can be enhanced. A case study of the conceptual design of a hard rock coring structure was reported to demonstrate the feasibility of the proposed methodology.

The study is organized as follows: A review of related studies present in Section 2. A framework that supports the resilient conceptual design present in Section 3. Section 4 introduces the framework and describes its steps and main application methods in solving resilient conceptual design problems. The technical challenges and blueprints for the implementation of the framework discuss in Section 4. Section 5 describes the application of the proposed framework and methodology in the design of a hard rock coring scheme. The present study aims to demonstrate the capabilities of resilient product performance in dealing with extremely uncertain underground work conditions. The discussion and conclusion are presented in Section 6 and 7, respectively.

2. Related Work

2.1 Overview of Resilient Design

Resilient design is a developing frontier technology, which is an evolution of traditional system security and execution efficiency in engineering practice. A system designed by resilience technology can continue to work after a major mishap or in the presence of continuous stress, mainly because it can adaptively protect and maintain its operation[9]. The foundations of the resilient design were built upon the lessons learned from the interplay between biological science and complex systems engineering[10]. Those learned from the biological system, such as cell division for functional repair and brain plasticity[11].

Some scholars have developed different approaches to deal with the problems caused by changes in the environment and requirements, such as adaptive design and the environment-based design (EBD). Adaptive design was introduced by Gu et al. and further developed by many researchers[12, 13]. It mainly originated from the idea of replacing multiple products with one adaptable product with a set of add-on accessories or attachments[14]. Adaptable products have the advantage of changing and/or adjusting the execution module during the operation stage to satisfy the changing customer requirements. To be adaptable, a product must possess degrees of freedom, which does not mean that it has the ability to perceive malignant disturbances and realize autonomous variants. Although adaptable design is an enabler of resilient systems to achieve resilience[15], it cannot replace resilient design. Zeng eproposed and developed the EBD methodology[16, 17], which was logically derived from the axiomatic theory of design modeling and was founded on the recursive logic of design[18, 19]. Its advantage lies in finding out the key environment components, in which the product works, and the relationships between the environment components through environment analysis. EBD can effectively and progressively identify major design problems and generate related solutions through the analysis of complex design environment.The products designed by this method do not include redundant structures or modules that adapt to sudden changes. It is challenging to deal with the functional loss caused by external environmental disturbances through autonomous variants. The difference between adaptive design and EBD shown in Table 1.

Table 1 Comparison of adaptive design and EBD

Items		Description
Adaptive Design [12-14, 20, 21]	Features	Products must possess degrees of freedom; Three evaluate measures - extendibility of functions, upgradeability of modules, and customizability of components
	Advantages	The design idea of replacing multiple products with one adaptable product satisfies the changing customer requirements.
	Limitations	Module changed and/or adapted under manual intervention; Insufficient consideration of the impact of disturbance on structure; Complex evaluation procedure
EBD [16-19, 22]	Features	Three main activities: environment analysis, conflict identification, and solution generation; Clarify design issues by introducing extra environment components
	Advantages	Through environmental analysis, find out the key environment components and their relationships, and generate solutions founded on the recursive logic of design
	Limitations	Uncertain impacts and environmental changes cannot be completely eliminated; The ability to perceive the environment and analyze disturbances cannot be guaranteed.

Through comparison, it is found that these similar design methods reduce the impact of environmental changes on products from different aspects. Design methods based on environmental analysis, modular design, axiom theory and conflict resolution have been proven effective in improving product applicability to the environment. In fact, the scope of predicting disturbances from the external environment at the design stage is limited. Still,the existing methods are difficult to ensure that the designed product has the ability to recover quickly from change, hardship, or misfortune. In the context of enterprises, Guelfi et al. defined the resilience as the capacity of a business process to recover and reinforce itself when facing changes[23]. Resilient design aims to improve the ability of the product to keep or recover quickly to a stable state, allowing it to continue its operation during and after a major mishap or in the presence of continuous significant stress[9], it can enhance the product's ability to identify and actively correct when encountering irresistible disturbances autonomously.

Resilient design is applied to the design of some complex products in addition to architecture [24], urban and rural planning [25], and biomedical engineering[26]. Zhang et al. considered that the resilient system would be more dependable by categorizing the knowledge of resilience, sustainability, fault tolerance and robustness [27]. George et al. designed an unmanned robotic platform using self-organization and control reconfiguration strategies that avoid error techniques and empirical trials[8]. Liu et al. designed a robot with an under-actuated robotic system that consisted of one type of module [28]. There are many similar application scenarios, especially in the design case of under-actuated robots and modular self-reconfigurable robots [29, 30].

The present literature review correlated to resilient design, it was found that there are many modeling formalisms and design methods for different applications. The fact that products with resilient functions can effectively cope with uncertain or partially known environmental changes remains unquestionable. We define a resilient function as ‘the resilient function-related entities, attributes and their relations which are used to be modeled’. Conceptual design is an important stage in product (resilient) function solving[31]. However, existing research lacks a general framework and the methodology for the entire process of resilient conceptual design, from building the resilient functional decomposition process to the conceptual solution. Hence, the investigators aim to integrate the conceptual design process through design methods and an innovative approach and apply this at different stages to make the design a resilient product structure and accommodate more functional requirements.

2.2 Conceptual Design Process: Functional Decomposition and Conflict Resolution

The key of product design is to set up a conceptual design model for the designer and user in steps of the conceptual design. The model can help designers discover, identify and solve the system conflicts of the product [32]. The product concept design process is a solution process that analyzes functional requirements to generate product solutions, which are innovative, complex and cognitive [33].

Many scholars have conducted several studies on the conceptual design solving process. Huang described a process model to realize a theoretical interaction that can help designers achieve innovative product solutions [34]. Based on this macro-model, Ehud proposed a parameter analysis methodology that centers on the repeated identification of dominant conceptual-level issues and relationships[35]. Fiorineschi completed a literature review of 'functional decomposition and morphology (FDM)', refers to a new conceptual design approach that can overcome the flaws of FDM, and suggested to combine creativity-enhancer tools or methods with the FDM process[36, 37]. Simitsis presented a framework and described the mapping of the conceptual model to the logical model[38]. The previous research conducted by the investigators applied the conceptual design generic model to different products, such as replacing the device of vulnerable parts in a nuclear radiation environment[39, 40].

Therefore, building a general framework or methodology is a common research method to support conceptual design. Among these, functional decomposition and conflict resolution are key technologies to solve resilient conceptual design problems. Functional decomposition is a method of expressing abstract design requirements. Umenda et al. define a product function as 'a description of behaviour abstracted by human through recognition of the behaviour in order to utilize the behaviour', and he proposed the Function-Behaviour-Structure (FBS) framework to support functional decomposition[41]. The researchers proposed a strategy called KRITIK, which simultaneously decomposes the functions and behaviours in a system [42]. Komoto reported a modeling framework that focused on the hierarchical system architecture and used parameters to support the system decomposition[43]. Yuan et al. proposed a hybrid approach to automate the process of functional decomposition using qualitative processing reasoning[44]. Tang et al. presented a formal interpretation of the integration logic between axiomatic design (AD) and the design structure matrix (DSM)[45]. Most functional decomposition methods have focused more on the subjective judgment of the designer, the reasoning process of functional decomposition is usually based on established knowledge.

In general, when designers give incompatible solutions for a given functional requirement, or one designer has a negative critique of solutions asserted by another one, it can say that a conflict has occurred[46]. It mainly includes physical conflict and technical conflict. The complexity of resolving conflict can be increased through imprecise and uncertain product requirements. Chong et al. reported a general best first heuristic algorithm for applications on conceptual design problems[47]. Kouroush et al. proposed a multi-layer graph model that resolves the conflict of experts' opinions and aggregates the layers that correspond to the decision criteria into a single graph[48]. Klashner presented a decision support system (DSS) design model for mission-critical situations [49]. These similar studies are mostly used to judge and assess the source and severity of conflicts. However, innovative design methods are still a practical methodology to guide designers to create conceptual solutions and solve design conflicts by breaking the mindset. The Theory of Inventive Problem Solving (TRIZ) combined with AD, which is an analytical tool that detects and solves problems by eliminating or attenuating conflicts, and generate innovations [50] to solve conceptual design problems. Borgianni attempted to investigate the reasons for the unsatisfactory evolution of the matching hypotheses between AD and TRIZ. In the early stage[51], the investigators also applied TRIZ to solve conflicts in products, such as medical equipment[52], nuclear equipment [39] and obtained a series of innovative solutions. This mainly includes five steps, as shown in Figure 1.

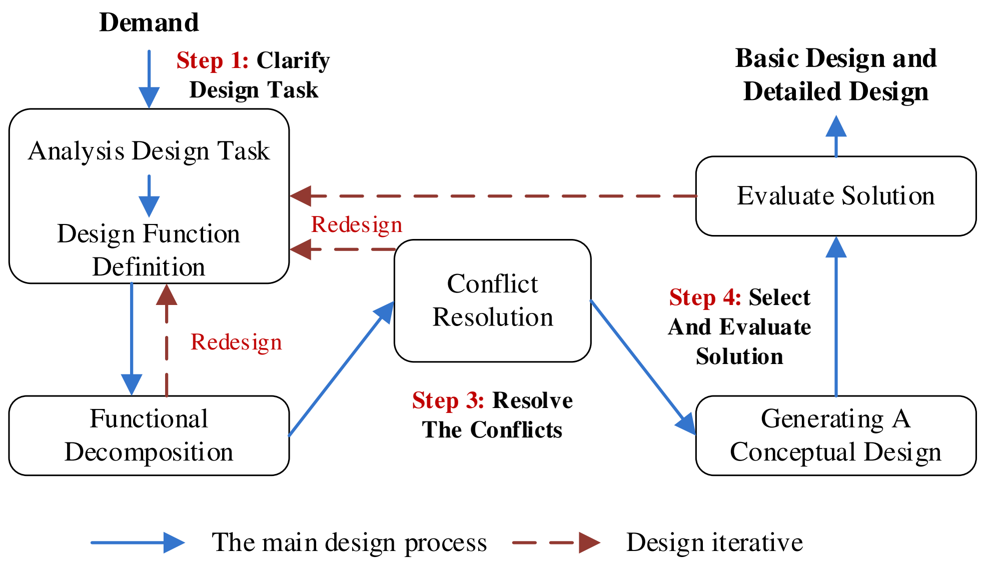


Figure 1. A general model of the conceptual design process[37]

In summary, the investigators scrutinize these vital design activities and methodology in the concept design process that contribute to the effectiveness of products and processes. However, researchers ignored the discussion of the impact of system performance on functional requirements when operating in an unknown or partially known environment. Hence, the investigators propose a framework and methodology to support resilient conceptual design using functional decomposition and conflict resolution.

2.3 A Brief Summary of Resilience and Problem Solving

Although resilient design has recently advanced, determining how to design a resilient product structure to accommodate more functional requirements at the conceptual design phase remains challenging. Several factors hinder the development and adoption of resilient conceptual design:

(1) An unstructured resilient conceptual design process makes each design uncertain, especially when requirement is diverse or the application environment dynamically changes.

(2) Predicting and analysing the potential threats and uncertain environments of the system is an essential prerequisite for the definition of functions in conceptual design. It is also an important guarantee for the redundant structure to meet the design requirements.

(3) Multidimensional conceptual design requirements and redundant solutions need to converge in the process of functional solution. Building a mapping relationship between different design domains can be useful for expressing abstract requirements.

(4) Uncertain or partially known functional environments bring various conflicts to the resilient conceptual design, which is inevitable. Defining and resolving conflicts requires designers to breakthrough design thinking, and be innovative

Although some scholars have investigated the influence of fuzzy front end on resilient design, its incomplete or difficult operation remains as a challenge for existing methods[53]. Thus, a complete structured framework and methodology to support resilient conceptual design using functional decomposition and conflict resolution are needed to solve these above challenges.

3. Supporting Resilient Conceptual Design - A Framework

The focus of the present study was to propose a generic and systematic methodology to support a resilient conceptual design, which includes three parts: driving and defining resilient functions through unknown or partially known environmental changes, refining system functions step by step through decomposition methods, and generating redundant, resilient conceptual solutions through conflict resolution. The proposed framework that supports resilient concepts using functional decomposition and conflict resolution is presented in Figure 2.

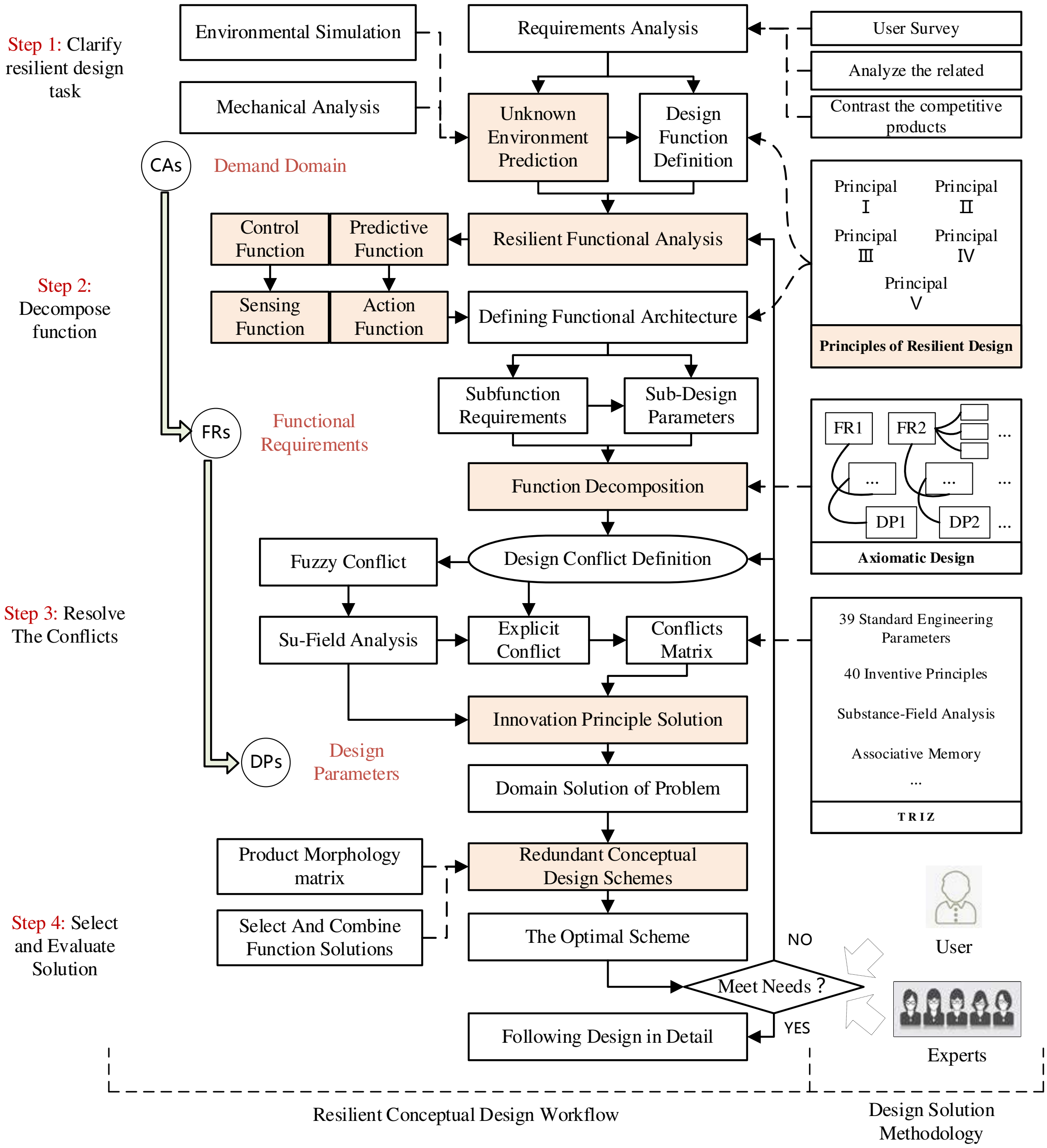


Figure 2. A framework supporting resilient conceptual design

In this framework, three major elements support the resilient conceptual design: the conceptual design process model, the resilient conceptual design workflow, and the methods used to support the design process. To fully design redundant design elements and product concept solutions that meet user needs and can adapt to environmental changes, resilient conceptual design process models were built through four main steps: clarifying resilient design task, decomposing function, resolving the conflicts, and selecting and evaluating. The framework also follows the description of the FBS and AD framework, in which customer attributes (CAs), function requirements (FRs) and design parameters (DPs) constitute the entire design process. This associates the redundant structural elements of the system with uncertain or partially known functional requirements and the behaviour for implementing the requirements. Through this means, various aspects of the process were pulled together with different elements of resilience to make the framework more comprehensive. Based on the proposed approach shown in Figure 2, Section 4 explains the resilient conceptual design flow and its methodology in detail by introducing principles and theory.

4. Methodology

4.1 The principles of resilient design

By learning from the biological system, the design principles of resilient systems were generally considered to consist of the following four axioms [54].

- Axiom 1: In the absence of external intervention, the damaged component of the system cannot be restored to its original state.
- Axiom 2: A component or part of a component used to satisfy function A can be trained to become a system component that adapts to another function B.
- Axiom 3: A component or part of a component can perform one distinct function at distinct times or in a specific environment.
- Axiom 4: System failure is an emergency consequence due to internal vulnerabilities and external mishaps.

Among these axioms, Axiom 1 means that when a component is damaged, it cannot recover itself to its actual physical property. It is precisely the opposite of cell division at the wound after wounding of the human skin, which promotes wound healing. However, some self-healing materials have been copied through this biological property in the material engineering discipline [55]. Axiom 2 makes the system appear to have the ability to train and remember, such as muscle tissue. The premise of this capability is to provide more possibilities for system components during the conceptual design phase.

Furthermore, when placing together Axiom 2 and Axiom 3, resilient system components can meet different functional needs under different conditions, similar to the limbs of the human body. Axiom 4 directly indicates the importance of environmental analysis and the prediction of unknown changes in resilient conceptual design. Through the previous study of the investigators on conceptual design and design thinking, five principles of resilient conceptual design are proposed, as follows:

- Principle I: The more redundancy or functional redundancy the conceptual design has, the better degree of resilience.
- Principle II: An unknown or partially known environment should be analysed by a 'predictor' before the definition of the resilient system function. The more clearly the design requirements are analyzed, the better the system's ability to respond to threats and vulnerabilities.
- Principle III: The more accurate and comprehensive the resilient function decomposition has, the closer the design elements are to the demand.
- Principle IV: A resilient system should be designed to have a controller, which is responsible for function learning and redundancy management, and a sensor, which monitors system functionality, performance, and real-time requirements.
- Principle V: Some system components or actuators responsible for implementing system changes, both in cognitive and physical domains, should be designed after conflict resolution.

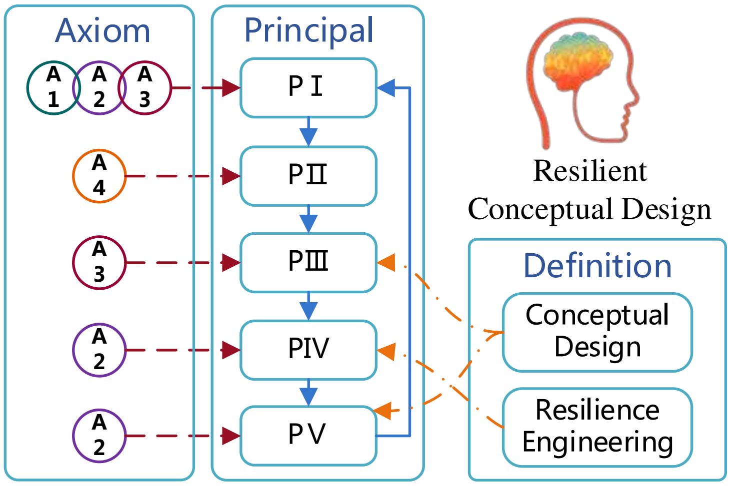


Figure 3. The relationships between the principles, axioms and definitions

These design principles are derived from the axioms and definitions of resilience engineering and conceptual design definitions. Principle I is derived from Axiom 1, 2 and 3. Principle II is derived from Axiom 4. Principle III is derived from Axiom 3 and the definition of conceptual design, particularly functional decomposition. Principle IV is derived from Axiom 2 and resilience engineering definitions, particularly self-management and self-diagnosis. Principle V is derived from Axiom 2 and conceptual design definition, particularly self-organization and conflict resolution. Figure 3 presents the relationship between principles, axioms and definitions, and the relationship among these principles. A system that can be called a resilient system may not necessarily need to have the above five principles.

Figure 4 presents a conceptual scheme of a resilient rewinding machine which includes structures such as servo motors, moving parts and grounding frames. This machine realizes the movement and film transmission through three rollers. The system has a software program for providing commands, driving the motor and controlling motion. Suppose a servo system is partially broken at a certain moment, and can only be used as a constant velocity motor. To ensure that the hybrid actuation system (the system has two servo motors and one constant velocity motor[56]) can continue to operate normally, the software program of the system can be reprogrammed. This is a resilient conceptual design that conforms to principle IV.

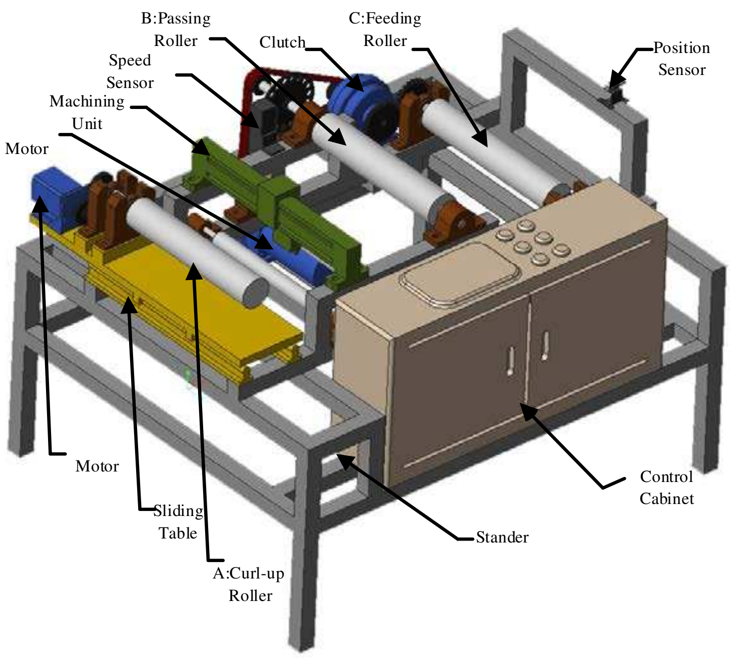


Figure 4. A resilient rewinding machine

4.2 Disturbance or Uncertain Environments (Cas) and Function Definition

The user's demand for the product is the beginning of the conceptual product design, and it is also a key step for the flexible concept design to clarify the product functions. The biggest difference between a product designed with a resilient concept and a product designed with a general concept is its ability to better adapt to environmental changes and potential threats. Therefore, in addition to accurately understanding the needs of users, the product function definition phase also requires further analysis and judgment of possible changes in the product application environment. In a previous study, the 5W2H method used to obtain user demand information, the voice of customer (VOC) method used to collect user demand raw data, and the analytical hierarchy process (AHP) used to represent the relationship among user needs[57, 58].

The specific implementation process is as follows: first, designers analyzed the existing product design to determine the product development stage, and the product was designed by analyzing the related patents and contrast of competitive products. Second, designers use measured or analyzed data to predict unknown or partially known functional environments, and define system functional requirements based on resilient design principles. Third, a resilient system should have a redundant structure that can adapt to and adjust to sudden conditions or changes in the external environment, and the premise of the system to achieve the repair function is to understand the recovery strategy. Finally, according to principles II, IV and V, resilient products should have prediction systems, control systems, sensing systems and execution systems, and these subsystems need not necessarily coexist. With the above four steps, the flexible function of the conceptual design can be determined. This not only satisfies the user's needs for the product but also clarifies the resilient functional attributes from the front end of the design, laying a solid foundation for conceptual design and functional solutions.

4.3 Functional Decomposition Process

Guiding resilient conceptual design through scientific design methods can improve the efficiency of the design process. When designing and analyzing complex systems, it is necessary to decompose resilient functions with a logical tool[59]. Through a literature review, the investigators considered that AD is still a very useful and classic tool. The underlying hypothesis of AD is that the existing fundamental principles govern good design practice [45]. AD theory transforms design based on experience and intuition into a design based on design axioms and avoids the traditional 'design-build-test-redesign' cycle. CAs, FRs, DPs, and process variants (PVs) use to describe the entire design world.

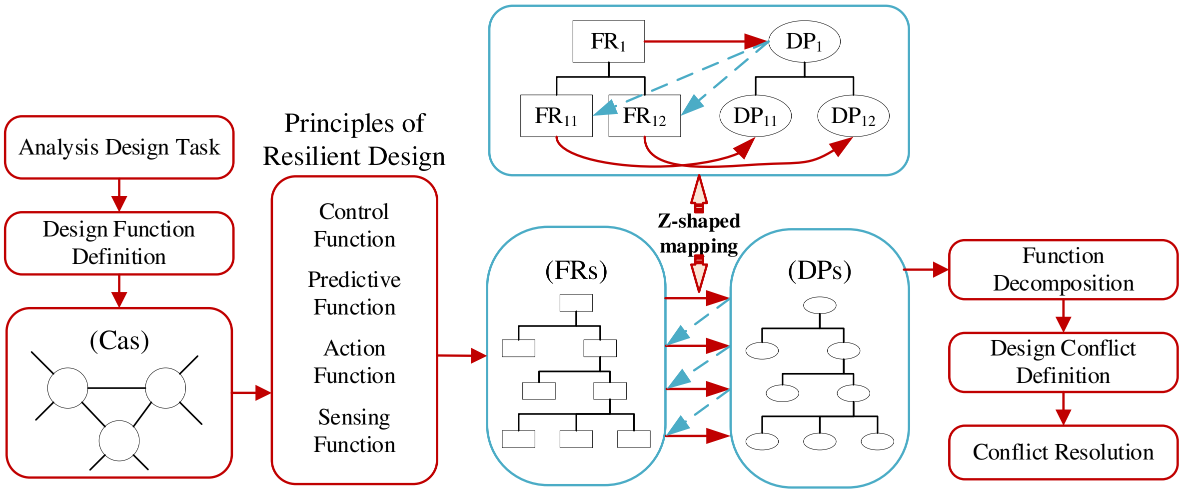


Figure 5. Mapping process from functional requirements to design parameters

The 'Z' -shaped mapping between different design domains provides a top-down conceptual design process. The relationship between these two design domains expresse by two types of mapping: (1) mapping at the same level, and (2) mapping at different levels. These are indicated in Figure 5 by solid and dashed lines with arrows, respectively. Design axioms include independent axioms and information axioms, and the former of which can help designers identify, document and understand functional coupling. The core of the independent axiom is the relationship between FRs and DPs, which can be described, as follows:

$$\{\text{FRs}\}=[\text{DM}]\{\text{DPs}\} \tag{1}$$

$$[DM]=\begin{bmatrix} A_{11} & \cdots & A_{1n} \\ \vdots & \ddots & \vdots \\ A_{m1} & \cdots & A_{mn} \end{bmatrix}, A_{ij}=\frac{\partial FR_i}{\partial DP_j}, (i=1,\dots m \; and \; j=1,\dots,n) \tag{2}$$

Different design matrix forms divide designs into three types: uncoupled (Eq.3), decoupled (Eq.4) and coupled (Eq.5). Among these, in a decoupled design, each FR satisfies exactly one DP. When the design matrix is a lower triangular matrix, a series of methods need to be used for decoupling design. In coupled design, FR cannot be independently satisfied, because it contains a large number of non-zero elements.

$$[DM]=\begin{bmatrix} A_{11} & 0 \\ 0 & A_{22} \end{bmatrix} \tag{3}$$

$$[DM]=\begin{bmatrix} A_{11} & 0 \\ A_{21} & A_{22} \end{bmatrix} \tag{4}$$

$$[DM] = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \tag{5}$$

Based on the principle of resilient conceptual design, functional requirements are initially decomposed through control functions, predictive functions, executive functions and sensing functions. Afterward, designer decomposes functional requirements into sub-functional requirements through behavioural elements, e.g., as action response, message passing and state change, and maps these into sub-design parameters. Finally, the designers assign and decouple the functional requirements based on behavioural characteristics. In resilient conceptual design, AD is only applied in the process of FR to DP decomposition, and the purpose of decomposing the functional requirements is to refine the conceptual design process, identify decoupling paths, and identify design conflicts.

4.4 Design Conflict Resolution Process Based on TRIZ

Ideally, a product is designed to meet the needs of all customers. However, in practical situations, resilience products are difficult to adapt to unknown or partially known environmental changes, and the adaptability and robustness are low. Although functional requirements can be defined and decomposed to the greatest extent, conflicts in the conceptual design are inevitable. The design principle I state that the degree of system redundancy is an important factor in determining its flexibility. As mentioned above, TRIZ is a kind of theory based on knowledge, people-orientation, and a systematic solution to the problem of the invention. This can effectively solve the problems in this design process through its powerful tools, and the most straightforward and most widely known tools are Substance-Field analysis and the resolution of the technical contradictions matrix.

The Substance-Field analysis model is a straightforward and effective method for problem expression and analysis, especially at the subsystem and micro level. This decomposes conceptual functions into two substances (S) and one field (F). Substance A (S1) is the working unit that performs the function, and substance B (S2) is the target object that receives the function [60]. The model that needs to be improved is accompanied by the design conflict. The designer analyzes the original product and selects two parameters (one needs to be reduced, and the other needs to be improved) through the contradiction matrix to obtain the invention principle. Figure 2 introduces the steps of conflict resolution. The above two methods can be separately used or combined together. According to the above information, the designers can not only facilitate the details of resilient products but also design functional module structures by extracting useful user requirements and environmental elements.

4.5 Evaluation Theory of Product Schemes

Selecting and evaluating a resilient conceptual design is an important step in the design process. Designers establish the morphology matrix based on redundant solutions of the product and select one or more solutions for each sub-function randomly, and combine these into a resilient concept design according to the design rules. Among the many methods, the Analytic Hierarchy Process (AHP) is a common multi-criteria decision making method that solving complex decision problems by capturing both subjective and objective evaluation measures.

First, resilient product evaluation indicators include system resilience (contains repair efficiency, monitoring level, structural redundancy, drive speed, communication response speed between modules), technical performance, cost and appearance [22]. These are represented as $E = [E_1, E_2, \dots, E_n]$. Second, a judgment matrix A was listed by the investigators, and the scores ranged from 1 to 9. Among these, 1 means 'two factors have the same importance', while 9 means 'one factor is extremely more important than the other factor.' The a_{ij} used in the matrix indicates the relative importance of $\boldsymbol{E}_{\mathbf{i}}$ to $\boldsymbol{E}_{\mathbf{j}}$. If λ_{max} represents the largest eigenvalue of A and G represents its corresponding eigenvector, then $A \cdot G = \lambda_{max} G$. Through normalization processing, the weighting coefficient of each evaluation index could be obtained. Third, each evaluation index of the selected schemes was user or expert marked using the weighted scoring method. The evaluation index scores of each scheme are presented in Table 2.

Table 2 The evaluation index scores of each scheme (take the case as an example)

Scheme*	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8
I	5	4	4	4	4	3	4	3
II	4	4	2	3	3	3	4	3
III	3	3	3	4	2	4	4	4

*E_1 stands for repair strategies, E_2 stands for monitor, E_3 stands for redundant structures, E_4 stands for drive module, E_5 stands for communication between modules, E_6 stands for technical performance, E_7 stands for cost, E_8 stands for appearance.

Next, the above matrix needs to be checked for consistency. The objective was to determine whether the constructed judgment matrix is logically inconsistent. The specific steps are as follows: calculate the consistency index (C_I), and calculate the consistency ratio (C_R). Among these, R_I is obtained through querying Table 3, and n represents the order of the judgment matrix.

$$C_I = \frac{\lambda_{max}-n}{n-1} \tag{6}$$

$$C_R = \frac{C_I}{R_I} \tag{7}$$

Table 3 R_I values[61]

n	1	2	3	4	5	6	7	8	⋯
R_I	0	0	0.58	0.90	1.12	1.24	1.32	1.41	⋯

Finally, the score matrix W of the resilient conceptual solution evaluation index was obtained. If $R_n (n = 1,2,3 \ldots)$ represents a different design scheme, then:

$$R = W \cdot G = [R_1, R_2, \ldots, R_n] \tag{8}$$

The scheme corresponding to the maximum value among $[R_1, R_2, \ldots, R_n]$ is optimum. Sensitivity analysis of AHP can be used to prove the robustness of the results

5. Resilient Design and Operation: A Case Study

5.1 Case Introduction

In-situ fidelity coring of deep rock with different burial depth is the pioneering science. As it is known, the internal environment of the crust is extremely complicated, and even small changes in whole-rock composition can lead to significant changes in mineralogy at different depths, temperatures and pressures within the crust, and change the density and hardness of the rock[62]. This hardness distribution is very uneven. The loss of an in-situ core storage environment may lead to distortion and irreversible damage of physical, chemical and mechanical characteristics [63]. With the increase in drilling depth and strength of hard rock, there is a big challenge for core blocking during drilling. It is the unknown or partially known functional environment mentioned in the present study.

The exploration of deep rock mechanisms has revealed that the friction between the core and inside of the inner is the key conflict for a high-quality core. On the one hand, the high quality of core should be closely kept at the inner side of the barrel contact core to reduce the release of crustal stress. On the other hand, the close contact between the inner barrel and core increases the friction force and reduces the core length. The impact on the coring mechanism is different in different geological conditions, and this may even cause the system to stagnate due to sudden changes in the external environment. Since coring is completed by a coring drill, the existing drilling method is assumed to be filled with conditions, in which drilling fluid is applied in the borehole. A traditional hard rock coring system and its force analysis are presented in Figure 6[64]. Due to the in-situ stress, there is always a plastic-elastic effect zone.

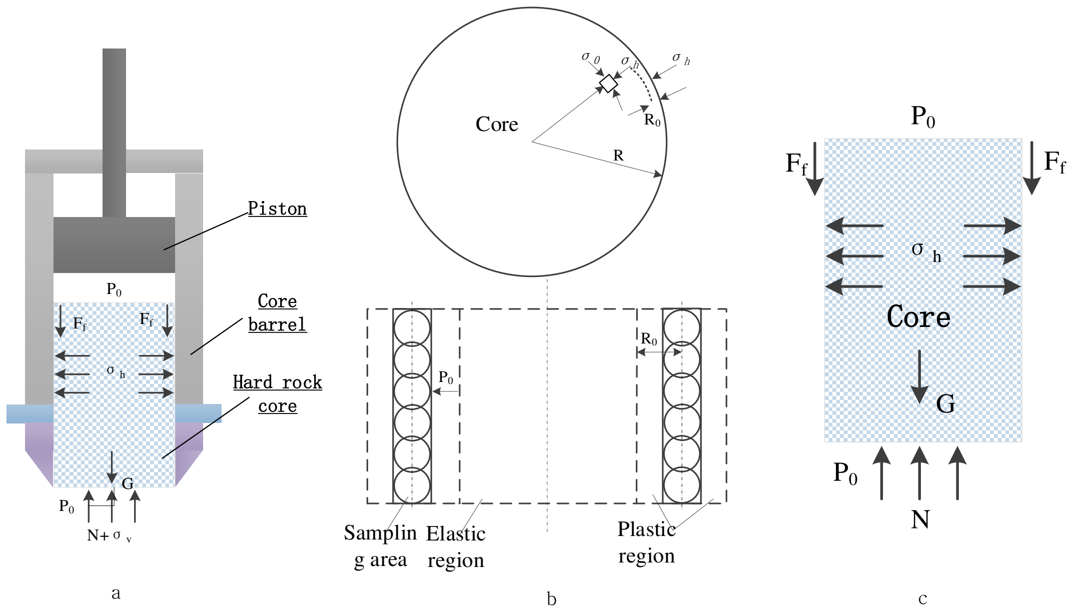


Figure 6. Traditional structure and mechanical analysis of coring system, (a) shows the schematic diagram of the core axial force under the core bit structure, (b) shows the radial force of the core and (c) shows the mechanical schematic diagram of rock core

The general idea of coring with in-situ conditions is to keep the contact between the core barrel and rock core. Therefore, in the case of potential threats and uncertain changes, there is a need to replace the traditional core structure with a resilient conceptual design.

Resilient function definition requires the analysis of the system's environment. The force analysis of the coring device was completed under normal working conditions to understand the reasons that may affect the failure of hard-rocking coring. The core force analysis is presented in Figure 6c. The rock core is connected to the outside, and the bottom of the core is the most vulnerable deformation position. If the lower volume of the rock core reaches the yield strength of the core, the rock core will have a severe plastic deformation when it enters the core barrel. Hence, the entire system would even fail. The limit length of the core rock can enter the barrel, as shown below[64]:

$$l < \frac{4}{d}\left(\frac{\sigma_Y - gh(\rho_R - \rho_w)}{\mu\sigma_h}\right) \tag{9}$$

In the traditional coring device, limestone is assumed for the coring rock in deep underground. The other parameters for rock core conditions are presented in Table 4.

Table 4 The core parameters for the calculation

Core diameter (m)	Compressive strength (Pa)	Acceleration due to gravity (N/kg)	Depth of core (m)	Water density (kg/m^3)	Rock density (kg/m^3)	Friction Angle (°)	Cohesion force (kN)
0.05	9E + 07	9.8	1,000	1,000	2,000	35	55,000

The above parameters were substituted to Equation (9), and a limit length of l < 7.52 mm is obtained. Conducting an unknown or partially known environmental analysis is an important step in resilient conceptual design. It was found that there is very high friction between the hard rock core and core barrel, which is an important cause of system failure. The complex structure inside the crust is much more complicated than the general case in the analysis.

5.2 Functional Decomposition Based on Axiomatic Design

Designing a resilient hard rock coring system and changing the geological environment constitute the customer attributes (CAs). Therefore, designing a system with stable coring and self-repairing functions under complex application environments has become a functional requirement (FRs) of this conceptual design. Similarly, the mechanical structure and control system of the resilient hard rock coring system has become a design parameter (DPs) for resilient conceptual design. According to the resilience conceptual design principle, the resilient system should also have the ability to monitor and drive, and establish communication between the module and the system through communication transmission. Therefore, FRs were further decomposed, as shown in Table 5.

Table 5 FRs and DPs description after decomposition

FR_s	Description	DP_s	Description
FR_1	Allow multiple repair strategies	DP_1	Mechanical system
FR_2	Ability to monitor internal and external status	DP_2	Monitoring system
FR_3	Ability to plan redundant structures	Dp_3	Control System
FR_4	Ability to drive module motion	DP_4	Drive System

FR_5	Ability to communicate between modules	DP_5	Communication system

Among these, the redundant mechanical system enables repair functions. Furthermore, the monitoring system can be used to detect and diagnose fault conditions, the control system processes the information and sends the instructions to the drive system, the drive system can execute instructions and change the system status, and the communication system is used to complete the communication between the module and system. The design matrix (15) is a lower triangular matrix that satisfies the axiom of independence.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \\ FR_5 \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & 0 & 1 \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \\ DP_5 \end{Bmatrix} \qquad (10)$$

Since the rock coring system is a complex, resilient system, the mechanical system was chosen as an example to decompose the function further. FR_1 can continue to be decomposed, and DP_1 is decomposed accordingly.

Table 6 FR_1 and DP_1 description after decomposition

FR_1	Description	DP_1	Description
FR_{11}	Multiple repaired structures	DP_{11}	Redundant structure
FR_{12}	Reduces friction during coring	DP_{12}	Friction reducing structure
FR_{13}	Can realize active drive and passive drive	DP_{13}	Underactuated mechanism
FR_{14}	Modules can be connected	DP_{14}	Docking Agency

The design matrix can be expressed using the following design equations:

$$\begin{Bmatrix} FR_{11} \\ FR_{12} \\ FR_{13} \\ FR_{14} \end{Bmatrix} = \begin{vmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix} \begin{Bmatrix} DP_{11} \\ DP_{12} \\ DP_{13} \\ DP_{14} \end{Bmatrix} \qquad (11)$$

With functional decomposition, the conceptual design process exposes more and more design conflicts. Among these, as the core length increases, the friction between the hard rock coring system and rock increases. The core is located in the fidelity core barrel, which restrains the horizontal deformation, causing the horizontal stress component in the core to change. Therefore, the investigators intend to design a redundant structure that can ensure the core length and reduce F_H, F_N and σ_h at the same time.

5.3 Conflicts Resolution

Taking the above conflict as an example, the Substance- Field model was established. Since the existing structure can only perform core coring operations and its effect on maintaining the original mechanical properties is not obvious, the type of the Substance -field analysis model should be a useful but not sufficient interaction model.

Through the above analysis, 39 general technical parameters in the TRIZ theory was used to define design conflicts, and improve the parameters: No.10 (Force) and No.11 (stress and pressure), and deteriorating parameter: No.5 (the area of moving objects). Then, the conflict matrix was queried, and it was found that the inventive principles can resolve the conflict, as shown in Table 7.

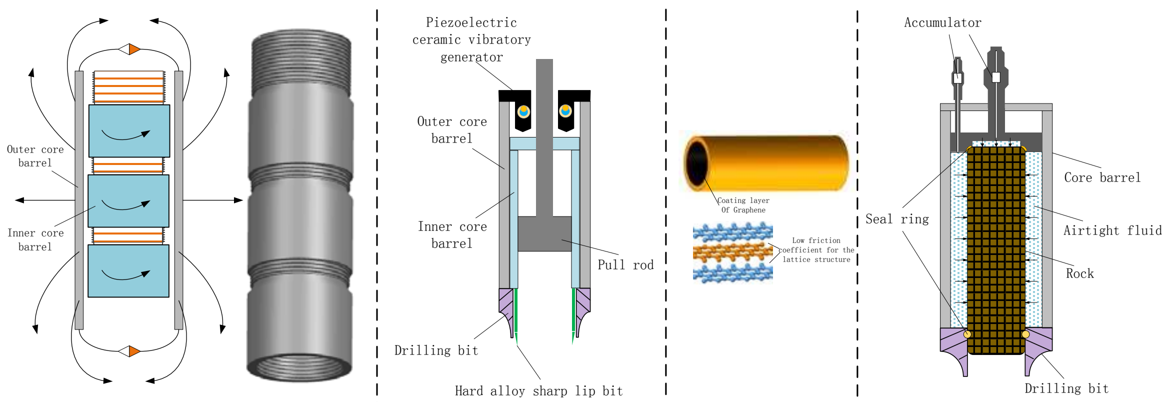
Table 7 Invention principle, standard solution, and conflict resolution

Conflict resolution	Invention principle	Description	Standard solution
Structure 1	19	The periodic effect suggests replacing continuous action with periodic action or impulse action	/
	15	Dynamic characteristics prompt to separate objects, So that their various parts can change the relative position.	/
	/	/	S2.2.2
Structure 2	28	replace with mechanical system Hints for acoustic or hearing systems, electromagnetic systems	/
	/	/	S2.2.5
Structure 3	10	Pre-role prompts the necessary changes to the object (all or at least part of it) in advance	/
Structure 4			/

By considering the invention principle and standard solution guide design, designers can obtain a conflict resolution from four perspectives:

- Structure 1: The core barrel is designed as a segmented structure from the overall structure. The axial pressure is at the bottom frictional force. Each section above the bottom is driven by a magnetic drive and connected by screw threads. Consequently, this can greatly reduce the friction according to the sub-paragraph. The design of the segmented core barrel is presented in Figure 7a.

- Structure 2: By mainly using pressure to change the way to move, the relative movement is a pure sliding friction. Ultrasonic vibration is presently used to reduce friction. As shown in Figure 7b, a piezoelectric vibration generator was arranged above the core barrel to produce an ultrasonic vibration source.
- Structure 3: An improved design of the contact surface of the core and core barrel was made by comprehensive analysis, which can be divided into change contact material and change contact medium. The existing hard rock sampler process is connected to the core and PVC tubes. The PVC material is not the material with the smallest coefficient of friction. Hence, it can be applied to the graphene in the inner surface of the cylinder to reduce the effect (Fig. 7c).
- Structure 4: The special air seal structure in the contact section was designed, which can ensure that the axial contact is only exposed to the air, thereby greatly reducing friction. At the same time, this can also be pre-filled with sealing liquid. Hydraulic sealing pressure can be changed according to the pressure at the bottom of the hole. As shown in Figure 7d. the top and side of the rock in the core barrel are sealed into two partitions by seal rings, with each partition filled with sealing fluid to produce hydrostatic pressure, in order to maintain top pressure and lateral pressure of rock. Furthermore, accumulators were used to maintaining pressure actively.



a b c d

Figure 7. Four conflict resolutions

5.5 Selection and Evaluation

All four structures mentioned above are effective for resolving conflicts. In an ideal state, if structure 1 is divided into 10 parts, the friction is reduced to one-tenth. Structure 2 meets the publicity $F_H = \frac{k}{f} \cdot \mu\pi dl \cdot \sigma_h$ (f is the frequency of the acoustic system, and k is a constant). When f = 1kHz and k = 500, the friction of structure 2 is reduced by half. Since the contact medium changes, the friction coefficient becomes smaller, and the friction between structure 3 and structure 4 is also greatly reduced.

As a resilient system, the above four structures are all derived from the original structure (Structure O). These structures can be used alone or in combination. All functions cannot be used at the same time, and some would only run when the original structure fails. Three combined conceptual design schemes were selected by the investigators: Scheme I (Structure O+1+2+3), Scheme II (Structure O+1+2+4), and Scheme III (Structure O+2+3). Next, there was a need to use the evaluation theory to select the best scheme.

The set of evaluation indexes is [repair strategies, monitor, redundant structures, drive module, communication between modules, technical performance, cost, appearance.], and symbol E = [E_1, E_2,...,E_8] was used to represent this. According to AHP, The experts' opinions of pairwise comparison using the evaluation indexes are summarized and shown in matrix A and will be used to illustrate how AHP works.

$$A = \begin{bmatrix} 1 & 4 & 6 & 5 & 4 & 8 & 8 & 5 \\ 1/4 & 1 & 2 & 3 & 6 & 6 & 3 & 2 \\ 1/6 & 1/2 & 1 & 2 & 2 & 4 & 6 & 5 \\ 1/5 & 1/3 & 1/2 & 1 & 4 & 4 & 6 & 1 \\ 1/4 & 1/6 & 1/2 & 1/4 & 1 & 2 & 2 & 1 \\ 1/8 & 1/6 & 1/4 & 1/4 & 1/2 & 1 & 1 & 1 \\ 1/8 & 1/3 & 1/6 & 1/6 & 1/2 & 1 & 1 & 1 \\ 1/5 & 1/2 & 1/5 & 1 & 1 & 1 & 1 & 1 \end{bmatrix} \quad (12)$$

The eigenvector matrix G = [0.399,0.182,0.139,0.105,0.053,0.033,0.034,0.054] is obtained through matrix A, and the maximal eigenvalue is λ_{max} =8.2296. Then, the consistency check for the judgment matrix was done: C_I=0.0328, C_R =0.080<0.1($R_I = 1.41$ for n = 8). As the C_R is below 0.1, hence, pair-wise comparison matrix is reasonable and acceptable.

The sensitivity analysis of the evaluation indexes ranking is performed using Expert Choice software. The sensitivity analysis is useful to justify the robustness of the results. The analysis is performed by changing the weight of each evaluation index, as shown next.

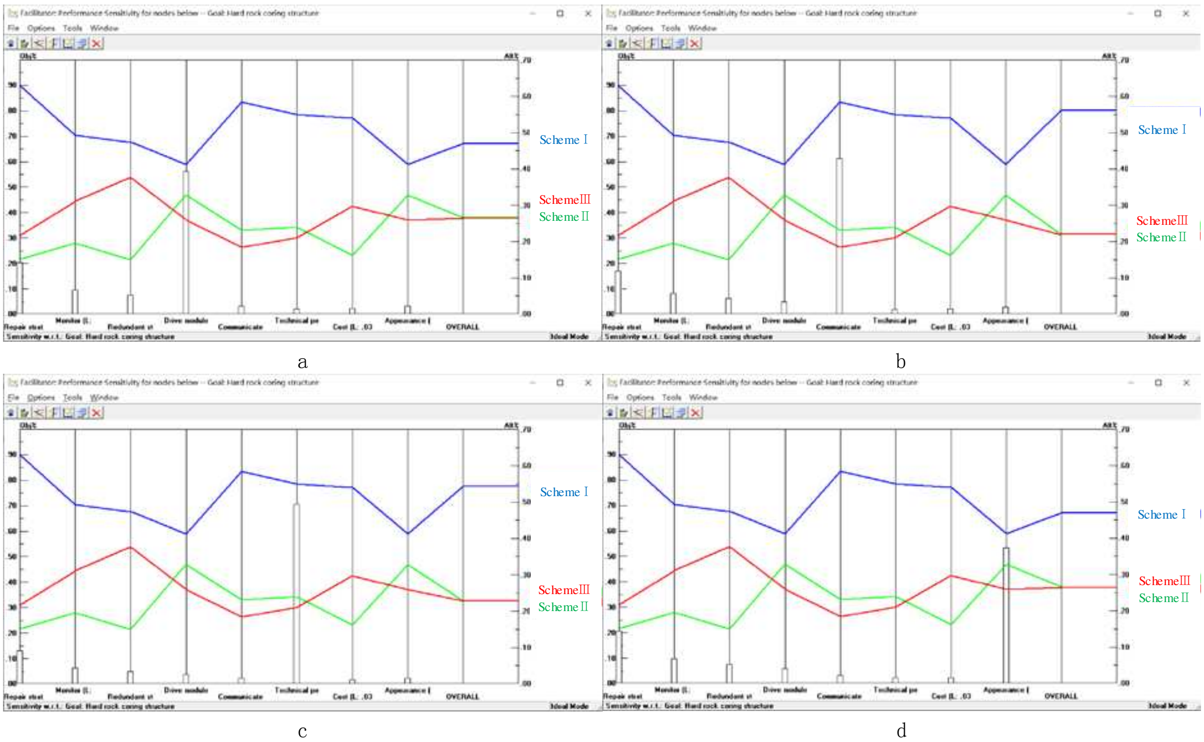


Figure 8. Ranking of schemes based on evaluation indexes

The ranking of the schemes will change from the scheme (I, II, III) to the scheme (I, III, II) when the drive module is 55.4% (the result is mentioned in Figure 8a), or when the communication between modules is 60.7% (Figure 8b), or when the technical performance is 70.5% (Figure 8c), or when the appearance is 52.6% (Figure 8d). The top rank scheme and ranking will not change (robust) regardless of any value of repair strategies, monitor, redundant structures, and cost.

Experts and users scored these three schemes, the matrix R was calculated through the score matrix W based on Table 2.

$$W=\begin{bmatrix} 5\ 4\ 4\ 4\ 4\ 3\ 4\ 3 \\ 4\ 4\ 2\ 3\ 3\ 3\ 4\ 3 \\ 3\ 3\ 3\ 4\ 2\ 4\ 4\ 4 \end{bmatrix} \tag{13}$$

According to Equation 6-8, $R = W \cdot G = [4.308,3.473,3.170]$. The result of the weighted scores for these three schemes is $R_1 > R_2 > R_3$. Therefore, the satisfaction of these three resilient conceptual schemes are as follows: Scheme I > Scheme II > Scheme III. The scheme I was selected as the final resilient conceptual structure.

6. Discussion

There are many methods and strategies to support design, especially conceptual design. Resilient products need to be tested against external risks and unknown environmental changes. A framework supporting resilient conceptual design is proposed to solve the conceptual design problem when demand input is diverse or the application environment dynamically changes In this framework, the resilient conceptual design process was divided into four steps. The resilience of the conceptual scheme has a relationship with the design process, as shown in Figure 9.

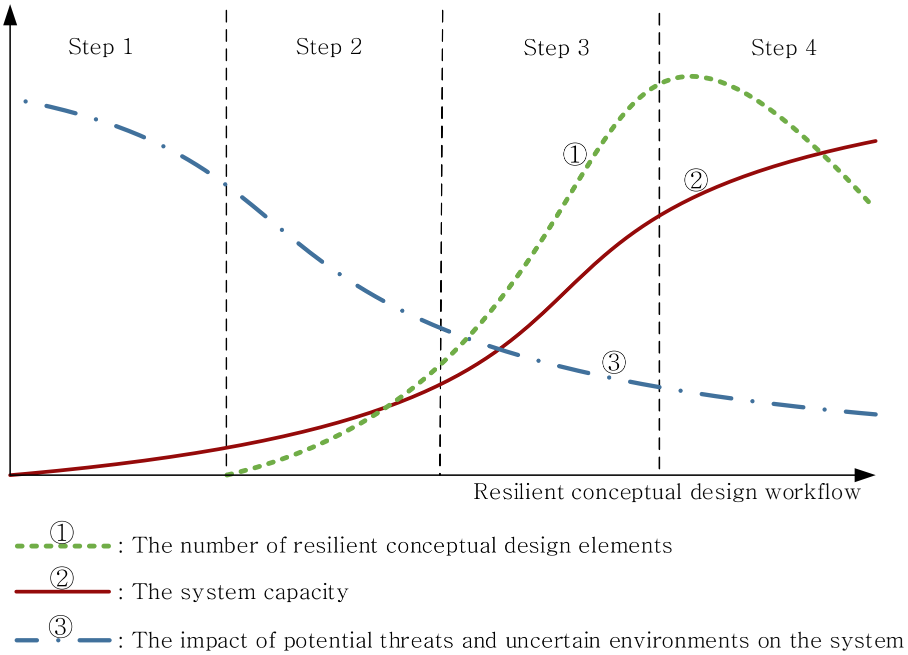


Figure 9. Some changes in the resilient conceptual design process

The objectives of resilient design include preventing requirement occurrences, reducing or eliminating damage severity and quickly recovering from sustained damages. Analyzing potential threats and clarifying functional requirements such as control, prediction, sensing, and action are the main guarantees for reducing the uncertainty of conceptual design. The impact of potential threats and uncertain environments on the system is greatest during the requirements acquisition and environmental analysis phases, and this impact converges as the design process evolves. A resilience system designed through this process would have a better capacity. The conceptual solution is a highly subjective design activity. To reduce design deviations and limitations caused by erroneous experience, the proposed framework limits the design process, and the superposition of AD, TRIZ, and AHP makes the conceptual scheme traceable. Based on the evaluation method, the framework proposes to establish a design feedback and iterative process, which will be the focus of further research.

Functional decomposition can help designers accurately define and refine functional requirements, and map these to design parameters. The number of design elements increased from the second stage. Conflict resolution through innovative design methods provides the possibility for designers to breakthrough design limitations. In the third stage, design thinking diverges, the design elements greatly increase, and the conceptual design redundancy increases. The resilient conceptual design framework adopts selection and evaluation methods to achieve the effective convergence of design schemes, and finally obtain the optimal resilient concept design schemes that meets the design needs, and can withstand certain risks.

However, it should be acknowledged that the proposed design model based on the framework supporting resilient conceptual design is still a conceptual one, which is based on our understanding of the design process, demand analysis, functional decomposition and conflict resolution. In practice, designers do not have to strictly follow the methods in the case for functional decomposition or conflict resolution. For example, a relevant problem analysis model-SAFC can be used to assist designers in identifying the crucial problems of the case. Different design conflicts need different conflict resolution methods. The case in Section 5 only uses TRIZ as an example to introduce a conflict resolution process, which also brings other possibilities for subsequent research. The factors affecting the choice of redundant conceptual design schemes can be qualitative or quantitative. There are many qualitative questions when evaluating whether the conceptual scheme meets the functional requirements, which is different from the detailed design or configuration design. For more difficult factors to quantify, such as service and security, fuzzy AHP, fuzzy TOPSIS and other hybrid technologies can be considered to solve this gap. Meanwhile, vague user requirements still impose a challenge in defining the design problem. It will be more complicated if the environmental disturbance to the product needs to be considered at the beginning of the design. To resolve this, it is necessary to obtain accurate design objectives, for example, by introducing interactive genetic algorithms.

7. Conclusion

Resilient design plays a role in improving the systems' ability to adapt to environmental changes and to lower risks. In the present study, a framework and methodology to support resilient conceptual design using functional decomposition and conflict resolution have been proposed. Our contributions have twofold. Firstly, five principles of resilient conceptual design are proposed from the axioms and definitions of resilience engineering and conceptual design definitions. Secondly, we propose a framework with four related phases to (1) specify the functional requirements for a resilient product that includes control, sensing, predictive and action based on the proposed design principles and environmental analysis, and (2) reduce uncertainty in the design process effectively using functional decomposition and conflict resolutionBased on the proposed framework, designers can proceed with the resilient conceptual design under an uncertain or partially informed design context. To demonstrate its feasibility, a case study of a hard rock coring system design is presented. Results have shown that a suitable conceptual design scheme for different resilience cases can be identified while the redundant structure designed is still placed under control. Such a scheme of resilient conceptual design enables the coring system to mitigate the negative effects caused by potential underground threats, which are critical in supporting product design for the uncertain work environment.

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