Design for Product Resilience: Concept, Characteristics and Generalization

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Abstract:

Potentially high-impact disturbances always disrupt normal product use, cause structural or functional failure, and shorten product life. How to design products with better fault tolerance and recovery capabilities to effectively deal with such complex disturbances will be a key factor in product innovation and intelligence in the future. Resilience is a system's ability to rapidly recover to its full function after disruption, and it is applied across multiple industries. As manufacturing systems and products diversify, this has resulted in an increasing variety of different definitions that threatens to dilute the concept and lead to ineffective implementations of resilient product design. This paper reviews the different definitions and scope of application of resilience in existing research and proposes two general definitions of resilient products from broad and narrow perspectives. On this basis, the author compared product resilience with product reliability, robustness, and adaptability, and proposed four main characteristics of product resilience, including visibility, agility, redundancy, and adaptability. Next, a design principle for product resilience is introduced, and future needs and opportunities for product resilience are outlined.

Keywords: Product resilience; Design for product resilience; Product Resilience Characteristics; High-impact disturbance

1. Introduction

The development of product-centric manufacturing has become an engine of national security and economic strength. It plays a vital role in almost every sector of countries' economies, from health care to aerospace and beyond. New technologies and innovations increase productivity and design efficiency and enable next-generation products. Over the past few decades, due to the increasing level of globalization and a higher rate of innovation, there have been noticeable major changes in the types and principles of products. However, more complex and changeable application scenarios also make products more vulnerable to disruption. As a potentially high-impact (or low-frequency extreme) event becomes more uncertain and severe, it may lead to a full or partial loss of product functions, making it less resilient. That is, they have less ability to recover quickly from unexpected events. Thus, though the new generation of smart products continues to meet people's growing material requirements, they may be applied in more complex environments, which also makes the products easily break.

At present, products have faced challenges such as changing customer expectations and requirements, inconsistent product intelligence, and sudden external interference; adapting to these challenges increases product complexity and results in more instability and unpredictability. With the increasingly harsh and complex service environment and the continuous increase in operation time, equipment often faces more potential threats in operation, and the risk of equipment failure or malfunction is on the rise. Every year, accidents caused by equipment instability, structural failure, fatigue fracture, and other reasons are not uncommon[1-

2]. The Subcommittee on Advanced Manufacturing (SAM) of the United States pointed out in the " 2022 National Strategy for Advanced Manufacturing" that high-impact disturbance is a temporary change caused by external risks that has a serious negative impact on equipment, presenting high complexity and suddenness. China's 20th National Congress report stated that efforts should be made to accelerate the construction of manufacturing power, build growth engines such as high-end equipment and next-generation information technology, focus on improving resilience and security levels, and promote the development of high-end and intelligent manufacturing. The expectation of enhancing the effectiveness of high-end products in resisting and dealing with failures caused by high-impact disturbances is also a concern shared by several countries, including various European countries, Japan, and Australia.

Taking the manufacturing equipment for aviation electronic products as an example, high-impact disturbances such as destructive vibration, physical impact, and multi-material wear can easily cause sudden equipment failures, resulting in long-term interruptions in a workshop production, causing significant economic losses, and seriously affecting the delivery of key models. Such high-impact disturbances are prone to occur in extreme service environments, unmanned service environments, environments with multiple physical field changes, and other operational environments with high uncertainty, including ground subsidence and collapse causing damage to tunnelling shield machines, and storm surges and tsunamis causing impact on underwater navigators. Therefore, with the improvement of product performance, the structural density and the number of components continue to increase, which in turn brings a higher risk of failure. High-impact disturbance has become a major factor leading to structural damage and functional failure of equipment systems, bringing significant challenges to equipment operation safety and service life[3].

Ensuring the safety and stable operation of equipment has become an important research direction in the field of equipment design in recent years. The current design research has to some extent improved equipment reliability and reduced damage risks. The proposed evaluation and design methods have solved the problems of high nonlinearity, large computational complexity, and multiple parameter coupling in the equipment robustness analysis process[4]. The focus of related research is to identify the weak links that cause equipment failures, analyze the gaps between the analysis and actual needs, and provide improvement measures from the perspective of optimized design. Alternatively, maintenance decisions can be used as an important channel to improve product reliability, and preventive maintenance can be achieved through methods such as fault prediction to mitigate or eliminate potential failures[5]. Taking the assembly equipment for electronic products as an example, it has the characteristics of fine process control requirements, customized functional indicators, and stable continuous operation. With the continuous strengthening of external delivery demands, the requirements for assembly quality and production pressure are increasing exponentially. Due to high-impact disturbances such as destructive vibration and abnormal impurities in materials, factors such as servo motor failures, control system crashes, or nozzle foreign object blockages may cause overall equipment failure. Traditional methods such as shutdown maintenance are costly, time-consuming, and difficult to repair. Similarly, high-end products such as high-pressure deep shale gas drilling and production throttling equipment and high-pressure power transmission and transformation equipment have stringent requirements for service life and stable operation quality. If a systemic failure occurs and cannot be quickly restored, it will result in serious economic losses and safety consequences[6]. Designing products with resilience to withstand disturbances and solve structural damage or failure caused by high-impact disturbances through self-restoration and other methods will be an important means of extending equipment service life and a new emerging frontier direction driven by engineering problems.

This paper will research the impact mechanism of high-impact disturbances on equipment failure and resilience triggering, as well as the design concepts and characteristics of resilient products. In the second section, the different definitions and application scopes of resilience in existing research are reviewed, and two general definitions of elastic products are proposed from a broad and narrow perspective. The third section proposes the characteristics of product elasticity, including adaptability, agility, redundancy, and visibility. The fourth section briefly describes some principles for conducting resilient product design activities. The fifth section is the conclusion.

2. Definition of Product Resilience

2.1. Resilience definitions in the literature

Resilience engineering is an emerging discipline, which can be viewed as an evolution of traditional safety and survivability engineering practices[7]. It comes from the Latin word ‘resilio’, which means ‘spring-back’ applied in physics. Holling et al. first applied resilience in the field of ecological research and described resilience as the ability to absorb change and disturbance and maintain relationships between populations and state variables[8]. Since then, resilience has been applied in other disciplines, such as psychology, geography, sociology, earthquake hazards, engineering, medicine and supply chain management. To gain a more comprehensive understanding of the concept of resilience and its characteristics, the authors have listed some representative academic articles from different periods in Table 1. It is found that most researchers agree on resilience as a recovery process during disruption. Besides, combined with other disciplines' features, researchers in different disciplines have defined resilience differently.

Table 1 The definition of product resilience in different periods of literature

Time	Author(s)	Scope of Research	Definition of Resilience	Key Techniques	Reference
1973	Holling, Crawford S.	Ecology	Resilience is a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables	Adaptive management, panarchy, regime shifts, etc.	[8]
2003	Michel Bruneau, etc.	Urban Planning	The ability of social units to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways that minimize social disruption and mitigate the effects of future disturbance.	Probability and consequences of failure, recovery time	[9]
2006	Odin Hjemdal, etc.	Psychology	The protective factors and processes or mechanisms that contribute to a good outcome, despite experiences with stressors shown to carry a significant risk for developing psychopathology	Resilience Scale for Adolescents	[10]
2006	Folke, Carl, etc.	Sustainability Science	The capacity of a system to cope with change and continue to develop	Social-ecological systems, resilience indicators, adaptive governance, etc.	[11]
2010	Cimellaro, Bruneau, etc.	Engineering	The ability of a system to withstand, respond to, and recover from disruptive events while maintaining an acceptable level of service and functionality	Risk assessment, performance-based design, redundancy, etc.	[12]

2012	Henry, Ramirez-Marquez	Ecology	The capacity of a system to absorb disturbance and reorganize while changing to retain essentially the same function, and structure.	Absorb disturbance, reorganize, retain	[13]
2015	Gu Xi, Xiaoning Jin, Jun Ni, etc.	Manufacturing System	The ability of a system to withstand potentially high-impact disruptions, and is characterized by the capability of the system to mitigate or absorb the impact of disruptions, and quickly recover to normal conditions	Withstand and absorb disruptions, restore to normal conditions.	[14]
2017	Blanchet, Ramalingam, etc.	Medicine	The resilience of a health system is its capacity to absorb, adapt and transform when exposed to a shock such as a pandemic, natural disaster, or financial crisis and still retain the same control over its structure and functions	Retain the same function, absorb shock	[15]
2017	Brusset, Xavier, Christoph Teller.	Supply chain	An operational capability that enables a disrupted or broken supply chain to reconstruct itself and be stronger than before.	The perception of supplier risk, the perception of external risks	[16]
2022	Yang, Bofan, Lin Zhang, etc.	Manufacturing System	the capacity of complex equipment systems to avoid failures, and to maintain and recover system performance if a failure occurs.	Avoid failure, recover from failure.	[17]

Researching product resilience can effectively solve the impact of high-impact disturbances on products[18]. The higher the resilience of a product, the less time and cost it takes for the product to repair itself after being damaged or impacted. From some existing research, it can be seen that the theoretical basis of resilience comes from the fields of biological science and system engineering. Although the concept of product resilience was proposed earlier, related research has achieved good results in fields such as economics, sustainability science, urban planning, and biomedical engineering. However, previous studies have lacked research on intelligent electromechanical products as the object of study, and there is a lack of understanding of the risk of product failure and internal interruptions (such as equipment failures or irregular shutdowns) under high-impact disturbances. The operating rules of equipment self-recovery and functional structure compensation after failure are not yet clear[19]. Hence, there is still a considerable gap in guiding the development of cutting-edge foundations and solving engineering practical problems in the engineering field.

Different academic articles provide different definitions based on their respective perspectives.

These differences mainly focus on two aspects. Firstly, the need to unify and standardize the naming of different stages of resilient products. For example, some scholars believe that the "adaptation stage" should be present throughout the entire product lifecycle[20], while others think that it should only be demonstrated after high-impact disturbances occur[21], and some consider that it should occur after system recovery[22]. Secondly, the question of whether the system performance can be restored to its pre-high-impact disturbance state or even improved after the resilient mechanism of the product is triggered and self-repaired. The time span of resilience covers the entire process of equipment operation and maintenance, and how equipment withstands disturbances and self-recovers, as well as the conditions that trigger resilience, are significantly different from previous research objects[23]. Existing achievements provide insufficient support for improving equipment resilience, and the essential issue is a lack of understanding of the connotation of equipment resilience. Therefore, a more comprehensive and targeted definition of product resilience would help further research its stage characteristics, trigger conditions, and better guide the design activities of such products.

2.2.Definition of product resilience from a broad and narrow sense

To better understand product resilience and apply the concept of product resilience to the design, manufacturing, and service of next-generation products, this section will explain product resilience from two dimensions: a broad sense and a narrow sense. Figure 1 illustrates the performance changes and response mechanisms of resilient products under three disturbance conditions. The product is in a robust state when no disturbance is present. Under moderate disturbance, although the system performance is not impaired, effective learning mechanisms can promote the product's ability to resist risk. After experiencing high-impact disturbance, the product's performance can be restored and learning achieved based on resilience mechanisms. The figure identifies the two scopes of product resilience, broad and narrow.

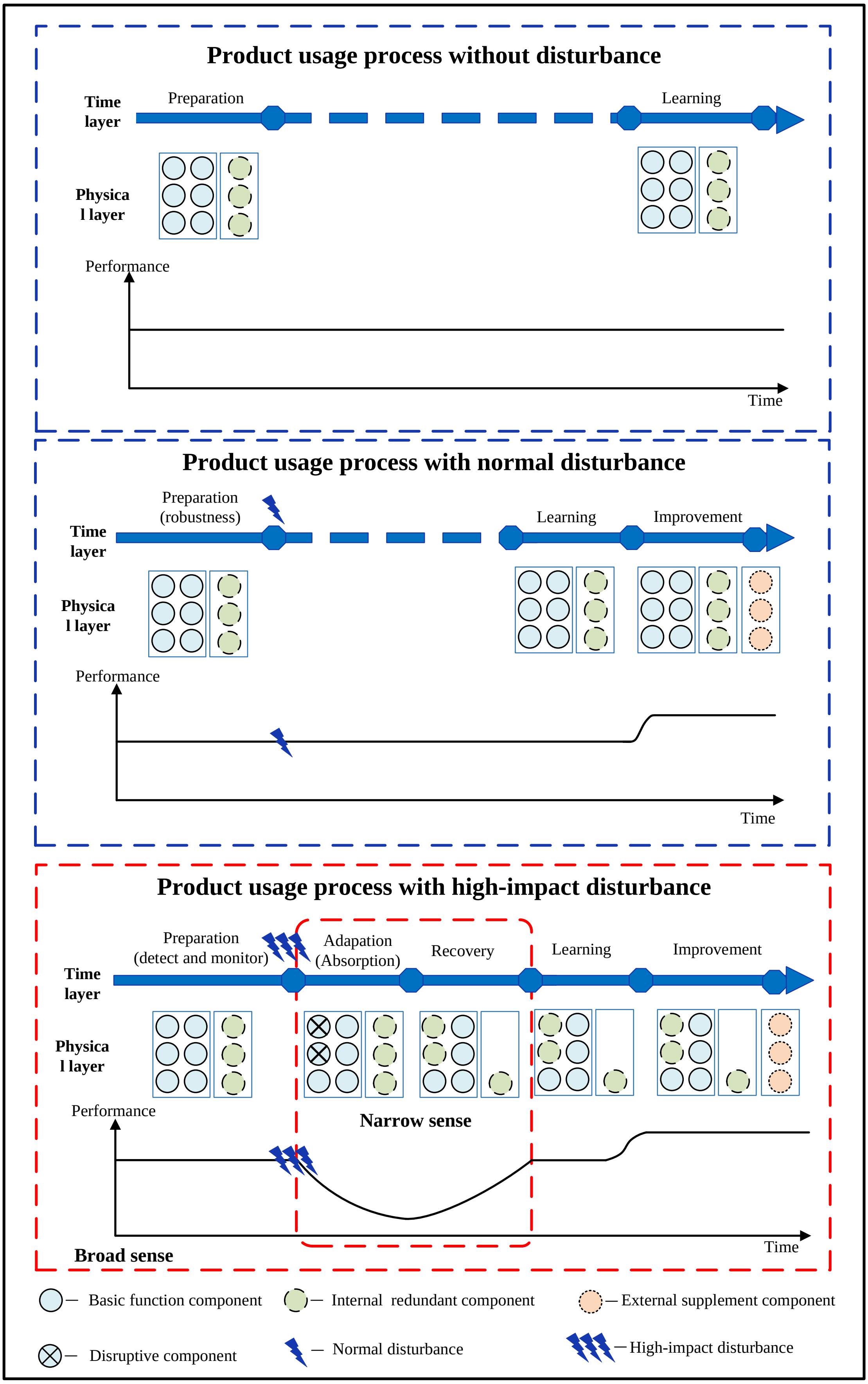


Figure 1. Product resilience expression, definition and scope

- **Broad definition**: product resilience is that during the whole process of product use, the system can anticipate, avoid or withstand potentially high-impact and unexpected disturbance; and in case of disruptions, it can quickly maintain or recover to normal conditions and learn from experience.
- **Narrow definition**: product resilience is that under high-impact disturbance, the product or system can not withstand shocks, conditionally absorbs or soothes the effects of adverse events for continuous change and disturbance, and rapidly recover from the disruptive events to the desired state.

In fact, the difference between the broad and narrow definitions lies in the different stages of product operation they cover. The broad definition focuses on the entire life cycle of product operation, while the narrow definition pays more attention to the stage from the occurrence of high-impact disturbances to the recovery of product performance. The narrow definition is similar to the focus of most researchers, focusing on the process of self-recovery after product damage, while the broad sense describes the whole process of product resilience performance. The specific analysis is as follows.

Starting from the broad definition, product resilience emphasizes three factors. First, based on shocks that have been experienced, the product can anticipate high-impact and unexpected disturbances. Secondly, the product can withstand disturbance within a certain range to avoid damage, and recovery measures will be taken when disturbance reaches a certain degree which disrupts the product. Thirdly, after recovery, the product can better cope with the next similar situation by learning from this process and supplying external maintenance resources.

In contrast, analyzing product resilience from a narrow perspective focuses more on the question of "how to absorb high-impact disturbances and quickly recover", which requires attention to the following three aspects. First, the product component has been disrupted by a high or unknown disturbance, and the resilience of the product will stimulate the corresponding recovery mechanism. Secondly, the product can absorb continuous disturbance and reduce the impact of subsequent shocks. Finally, the product can recover quickly from disruption.

3. Product Resilience Characterization

3.1. The main stages of product resilience

When a product is subjected to high-impact disturbances and fails, resilience is triggered and self-recovery is achieved through redundancy or training of similar structures. In order to better interpret the basic laws of the entire process of resilient product operation, this section will discuss the different stages of product operation separately, and propose the operational laws of resilient products from disturbance to performance recovery. As shown in Figure 2, the process of triggering resilience in products can be divided into a preparation period, adaption/absorption period, recovery period, learning period and improvement period. These periods of the resilience product are described below.

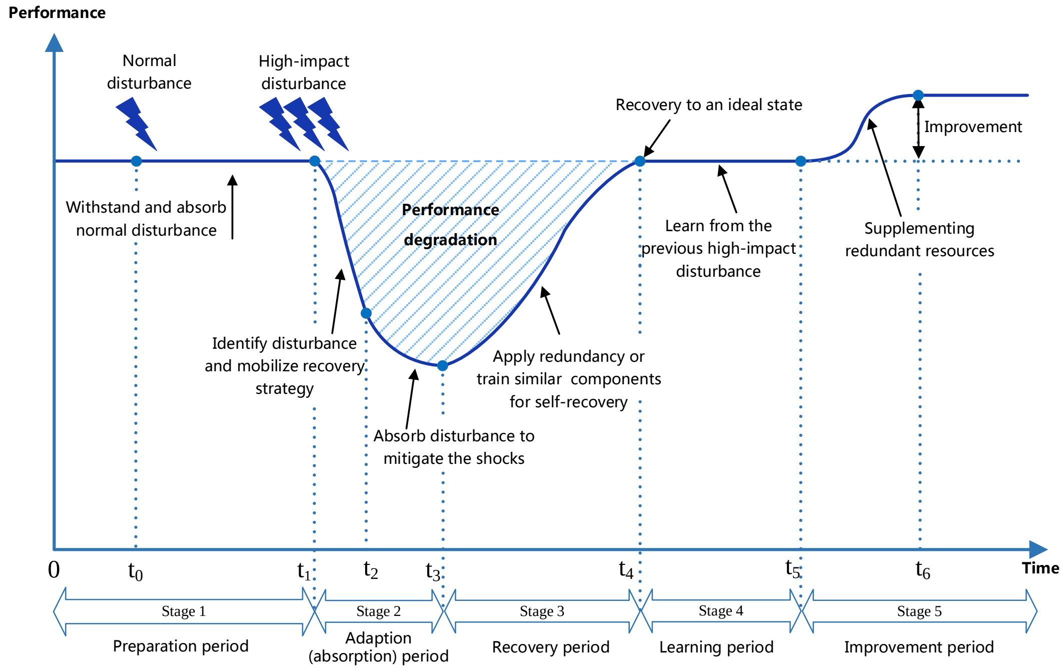


Figure 2. Performance curves for resilient products at different stages

Stage 1 (Preparation period). The system withstands or takes measures to avoid external shocks without structure degradation or function loss, monitors external disturbance at all times which is assumed as a steady state, and predicts high-impact and unexpected shocks based on monitoring data.

Stage 2 (Adaption/absorption period). When the occurrence of the high-impact disturbance disrupts the product components which manifests in product performance degradation, the system recognizes the disturbance and mobilizes corresponding recovery strategies according to its current situation, such as using redundant resources, self-maintenance and rescheduling. The purpose of absorption is to weaken the sustained impact of a high disturbance on product performance. The absorption period does not occur every time the resilience mechanism is triggered but rather depends on the duration of the high disturbance.

Stage 3 (Recovery period). The product can be restored to a desired state applied by the backup structure or similar components. On the one hand, make use of the backup structure designed in advance, that is, redundant resources, to restore the system damaged by high-impact disturbance to its normal state. On the other hand, for the objective structure or function which need to be restored, the other product components with similar function can be trained to restore the target part to the desired state.

Stage 4 (Learning period). Once the product has recovered from the disturbance and returned to its ideal state, it can use mechanisms such as data analysis and deep learning to learn from the previous high-impact disturbances and prepare for possible similar disturbances in the future.

Stage 5 (Improvement period). After going through the aforementioned five stages, the internal redundant resources of the product are depleted. In order to further improve the performance of the product and its ability to resist disturbances in the future, it may be necessary to improve the product's resilience by supplementing external resources or conducting product optimization design.

3.2.Further discussion on the operating rules of resilient product

The operating rules of resilient products are based on in-depth research on the adaptive and self-recovery capabilities of products when facing high-impact disturbances. This rule is of great significance for improving the anti-disturbance performance of products, promoting the stable and reliable operation of products.

Firstly, resilient products should have a comprehensive mechanism for fault prediction and evaluation, which evaluates the potential impact of possible high-impact disturbances. At the same time, during the absorption and recovery stages, products should be able to quickly and accurately locate faults, determine their severity, and take appropriate measures. As shown in Figure 3, reasonable adaptation and absorption mechanisms can delay and weaken the impact of high-impact disturbances on product performance. The activation of the absorption mechanism can reduce the performance loss of the product from P_1 to P_2. Therefore, the product can consume fewer resources on recovery.

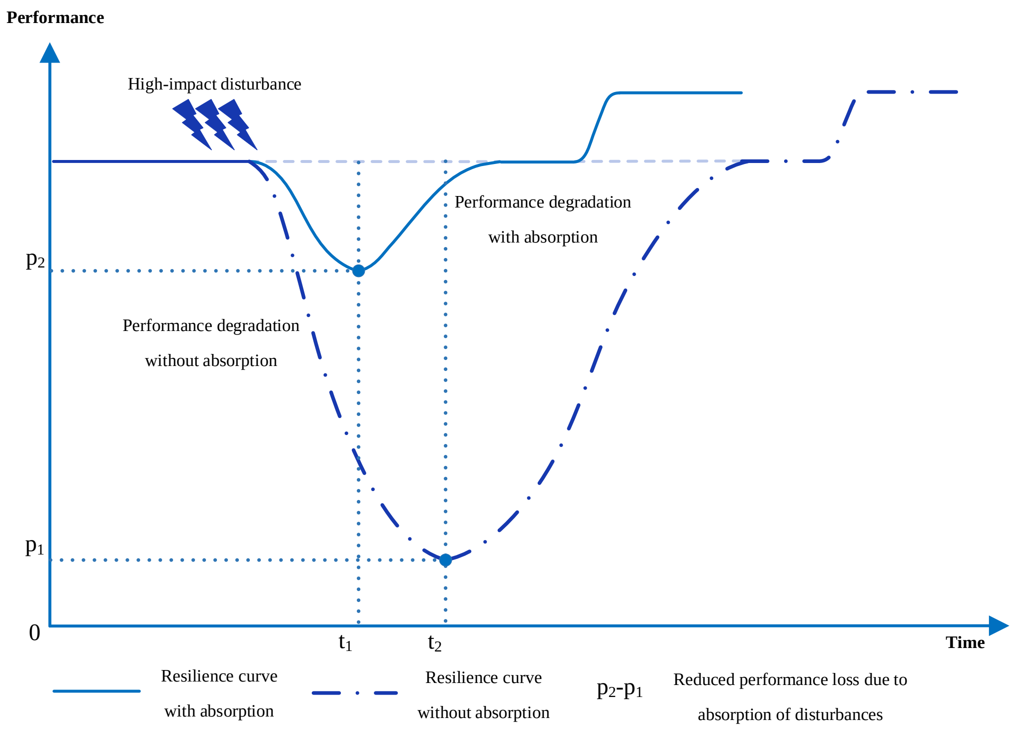


Figure 3. Influence of the absorption period on the product resilience curve

Secondly, the degree of disturbance damage is directly related to the failure mode and resilience-triggering conditions of the product. The self-recovery after the shock-induced failure is within a certain range, rather than unlimited. Specifically, if the product's monitoring system, execution system, or redundant structure is also within the range of failure, it will be difficult for the product to recover to ideal performance without external intervention. In addition, the duration of high-impact disturbances is also a key factor that affects the resilience of a product. It includes both instantaneous disturbances and sustained disturbances, and the resilience curve of the product will vary depending on the type of disturbance. The impact on the product's performance will also be different, as shown in Figure 4. If an instantaneous disturbance occurs, the product may have difficulty adapting and absorbing the disturbance promptly. However, if the interference is persistent or applied slowly, the product can first trigger absorption mechanisms to counteract or mitigate subsequent similar interferences. While absorbing and adapting, if conditions permit, the product can also trigger self-recovery mechanisms in advance to shorten the recovery period.

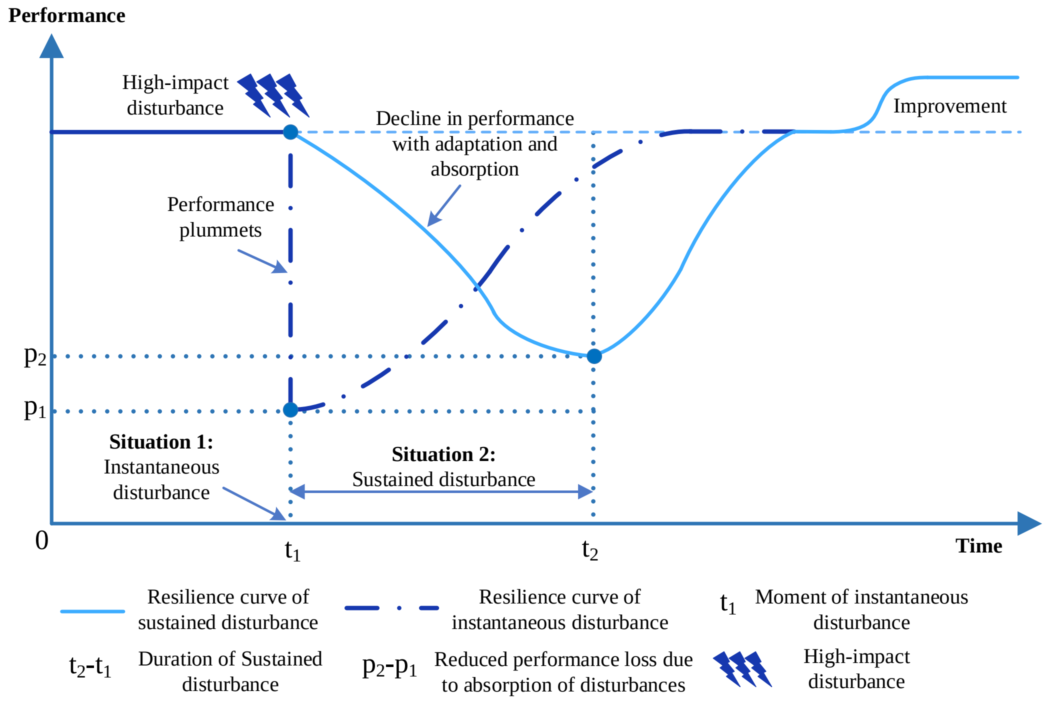


Figure 4. Product resilience curves under instantaneous and sustained disturbances

Thirdly, because basic function, internal redundancy and external maintenance components exist, product resilience can play a key role in functioning properly. When a high-impact disturbance occurs, the product's basic function component is disrupted and needs to be restored by consuming internal redundancy components, which is a process of product recovery but product resilience decreasing. External maintenance components are supplied to improve product resilience. As the frequency of high-impact disturbance increases, resilience can be continuously consumed. As basic function components and internal redundancy components are exhausted, the product is destroyed which means there is no resilience in the product in Figure 5.

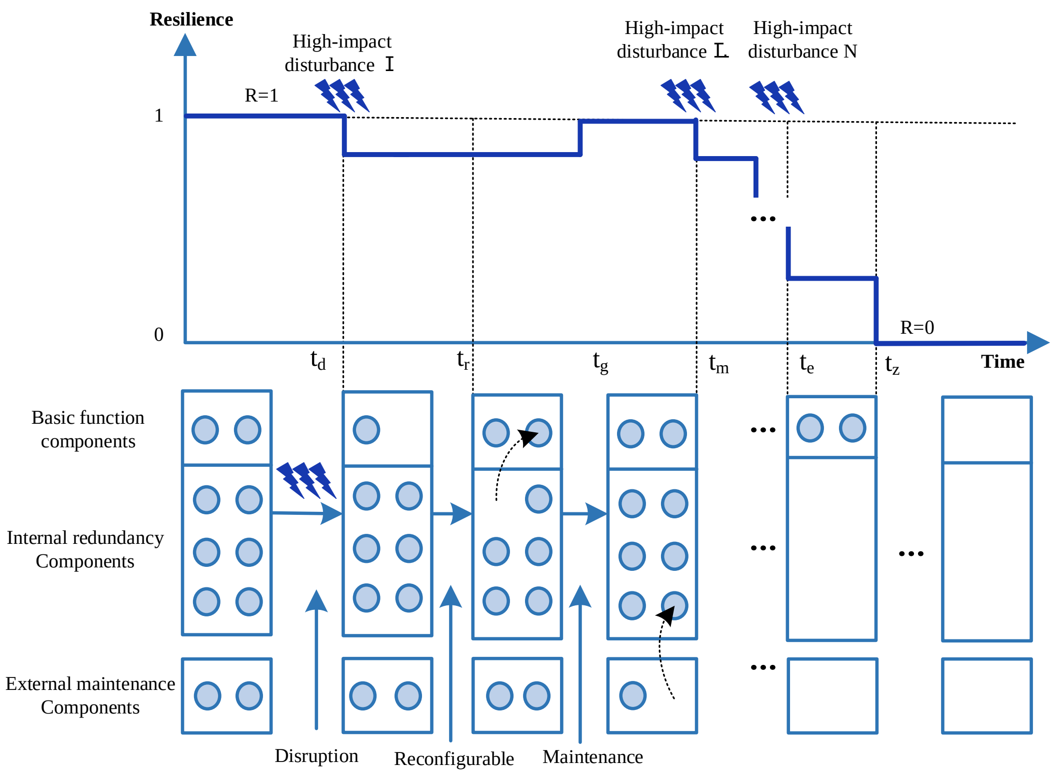


Figure 5. Changes in product resilience under multiple high-impact disturbances

Finally, resilient products should have self-learning and optimization capabilities, and through analysis and summary of historical failures, improve their ability to resist disturbances and fault handling efficiency. At the same time, products should be able to respond to user feedback promptly, collect and analyze user data, and continuously optimize product performance and user experience. In summary, the operating rules of resilient products need to be continuously improved and enhanced through continuous practice. Only through continuous optimization and improvement can the ability of products to respond to disturbances and reliability be continuously improved, and meet the needs and expectations of users.

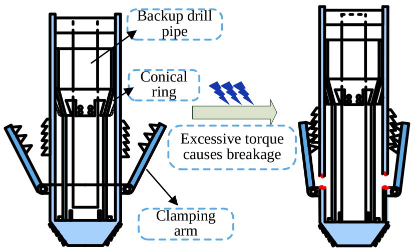
3.3.The main characteristics of product resilience

As described in the definition, product resilience emphasizes the ability of a product to respond to high-impact disturbances, as well as the measures taken to recover from and learn from disturbances. Resilient products possess four key characteristics that contribute to their ability to withstand and recover from disturbances: agility, redundancy, adaptability, and visibility. These characteristics enable products to effectively respond to and mitigate the impact of disruptions, ensuring their continued functionality and performance, as shown in Figure 6. Agility reflects the product's capacity to respond rapidly and easily to high-impact disturbances. Redundancy emphasizes the presence of duplicated or similar functions or components, which serves as a crucial condition for system recovery following failures. Adaptability refers to the product's ability to change its operating mode to maintain performance continuity even under high-impact disturbances, preventing it from entering an unsafe state. Finally, visibility highlights the product's ability to perceive its operational state and understand the forms of failure caused by high-impact disturbances. In the following paragraphs, each of these characteristics will be elaborated upon in detail.

Characteristic 1: Agility

Agility reflects the quick and easy response of resilient products to high-impact disturbances. This is evident throughout the entire process, from absorption to improvement.

Example：Resilient gas drilling equipment



When drill bit breaks and falls:

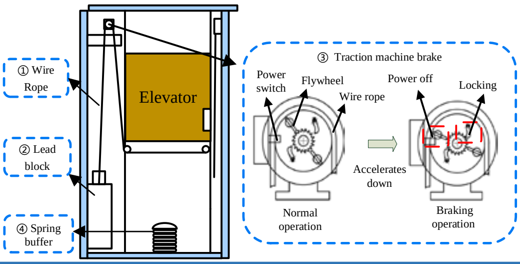
1.Clamping arm bites into the tooth surface of pipe and the conical ring is embedded in pipe to quickly ensure that it does not fall.

2.The backup drill pipe is quickly spun into the drill bit to ensure that the drill bit continues to drill.

Characteristic 2: Redundancy

Redundancy reflects that resilient products have certain functions or components with similar or identical backups, which is one of the primary conditions for system recovery after a failure occurs.

Example：Resilient elevator



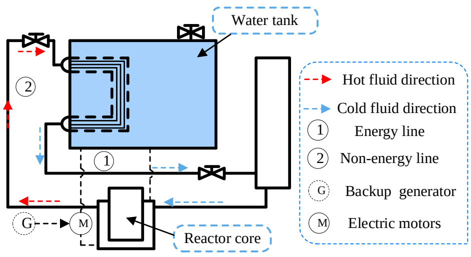
Structural redundancy: The backup lead block (1) and steel wire rope (2) ensure the smooth operation of the elevator.

Functional redundancy: When the elevator experiences a rapid descent, the ratchet mechanism of the brake (3) locks the traction machine; and when the elevator reaches the bottom, the spring buffer (4) functions to decelerate and provide cushioning.

Characteristic 3: Adaptability

Adaptability refers to the ability of resilient products to change its operating mode in order to maintain the continuity of product performance and avoid entering an "unsafe" state under high-impact disturbances.

Example：Resilient cooling systems for nuclear power plant cores



To adapt to the problem of core cooling system failure caused by sudden shocks, two recovery strategies are employed:

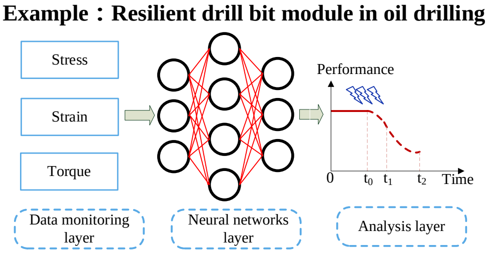
1. Initiating multiple emergency generator units to provide energy supply and core cooling.

2. Constructing a non-energy line based on the height difference and temperature difference, utilizing gravitational potential energy to achieve core cooling.

Characteristic 4: Visibility

Visibility reflects the ease with which resilient products possess the ability to understand high-impact disturbances and their forms of failure, as well as perceive their own operational state.

Example：Resilient drill bit module in oil drilling equipment



During the operation of the drill bit, a built-in visibility monitoring system is incorporated to provide monitoring and feedback.

The system utilizes torque, stress, and strain as input data and employs a neural network to establish a predictive model for the drill bit. This allows for real-time monitoring of the drill bit's status and overall performance changes.

Figure 6. Four main characteristics of product resilience

- **Agility.** Agility embodies the characteristic of a product being able to recover quickly from disturbances. Specifically, when a product encounters high-impact disturbances, it can quickly react, identify and absorb the disturbances, and rapidly mobilize the corresponding repair mechanisms (training of existing structures or mobilisation of redundant modules).
- **Redundancy.** The implementation of redundant characteristics can be achieved in two ways. First, by replicating or backing up some of the structures or components of the product. When the original structure is destroyed by high-impact disturbances, the backup structure replaces the failed structure. Second, when there are two similar structures or functional components, they work independently under normal conditions. If one of them fails, the other replaces the failed structure through training mechanisms.
- **Adaptability.** Adaptability reflects the product's characteristics to accurately identify disturbances, weaken the sustained impact of disturbances, and learn from experience. During the self-repair process of the product, external resources can be appropriately supplemented to mitigate the impact by updating the environmental changes and product failure level. After the product is restored to its ideal state, the learning mechanism can effectively weaken or even eliminate the impact of the same type of disturbance on the product.
- **Visibility.** Visibility determines which high-impact disturbances a product can respond to and to what extent. It includes Visibility in the design phase and visibility in the operation phase. During the design phase, designers should conduct rational redundancy configuration for different failure modes. During the operation phase, the product should

be equipped with the ability to monitor the environment and predict the impact of different degrees of disturbances on itself.

3.4. Differences and relationships with reliability, robustness, and adaptability

In order to meet the requirements of stable performance and continuous safe operation of products, scholars at home and abroad have conducted research on product reliability, robustness, and adaptability technologies. Computer modelling, simulation methods, and digital twins are applied in the design stage to conduct safety analysis and evaluation of the overall structure or key components of the product under quasi-realistic working conditions. This extends the robustness requirements of product design in order to reduce the risk of failure and downtime. To better clarify the concept and characteristics of resilience, and to apply it to guide the design process, it is necessary to further compare and explain the differences and relationships between the concepts of resilience, reliability, robustness, and adaptability. A review comparing the main content and characteristics of reliability, robustness, and adaptability is shown in Table 2.

Table 2. An overview for comparing reliability, robustness, and adaptability

Items		**Description**
Reliability	Main content	(1) the reliability of a system is the probability that this system uninterruptedly performs certain (accurately) specified functions during a stated interval of a life variable, on the condition that the system is used within a certain specified environment[24]. (2) System reliability is generally defined as the probability that a system performs its intended function under operating conditions for a specified period of time[25]. (3) Reliability is the ability of an item to perform a necessary function, under environmental and operational conditions over a defined period[26].
	Characteristics	(1) The system perform a necessary or specified function during system life. (2) The system is within a certain specified environment and a given period.
Robustness	Main content	(1) The capacity of product to maintain performance under adverse conditions[27]. (2) Continue its normal operation even when faced with disruptions[28]. (3) Resist disturbances without interruptions while continuously delivering desired

		outputs[29].
	Characteristics	Product resists, absorbs disturbance without damage and operates properly.
Adaptability	Main content	(1) The ability of a product to adapt to new requirements and the reuse of a product and design when requirements are changed[30-31]. (2) Adaptable design is conducted through the replacement of multiple products with one adaptable product with a set of add-on accessories and/or attachments[30-31]. (3) The ability of a system to be changed to fit diverse circumstances and the changed requirements[32].
	Characteristics	(1)Products with adaptability meet user benefits and environmental friendliness, and save in development time, design and production costs. (2)Users can utilize the same product under different conditions, by replacing different functional parts or upgrading current parts.

From Table 2, it can be seen that reliability emphasizes that the probability of the designed product working normally should not be lower than the minimum allowable reliability value[33]; robustness emphasizes that the designed product is less sensitive to environmental changes and has small performance fluctuations[34]; adaptability emphasizes that the designed product can be replaced or adjusted by manual intervention in order to meet different user needs and changes in environmental factors[35]. Relevant research has improved the ability of products to withstand and absorb interference, providing a theoretical basis for how to address the problem of absorbing adverse interference in resilient product design.

As product resilience emphasizes when, how, and under what conditions to quickly achieve self-recovery from failure, these definitions and characteristics are different from reliability, robustness, and adaptability. However, the mechanisms of product resilience can be improved through the development of reliability, robustness, and adaptability. The stronger the robustness of a product, the greater its ability to withstand and absorb disturbances, while adaptability can help the product avoid disturbances and adapt to unknown or uncertain environments.

Reliability is beneficial for the product to have a more stable working state and longer working time. Based on these foundations, how to use the definition and characteristics of resilience to guide designers to analyze and predict the relationship between different disturbances and failure modes during the design process, and to design corresponding functional structures to achieve self-recovery of product performance under high-impact disturbances will become a research focus in the future.

4. Design for Product Resilience

Product design essentially entails a mapping from 'What we want to achieve' to 'How we want to achieve it'[36]. A resilient product should be designed to be able to adapt to and absorb high-impact disturbances, suffer minimal performance losses during product failure or interruption, and quickly recover to a stable state after each interruption. Therefore, to research resilient product design, it is necessary to clearly articulate the design problems and solution spaces represented by "what" and "how" and guide designers to make correct design decisions in the mapping between these two spaces through more applicable design methods and models.

Resilient product design of a product is the process of solving the entities, attributes, and relationships related to resilience in product design. It is a developing frontier technology, which is an evolution of traditional system security and execution efficiency in engineering practice[37]. Currently, many scholars have conducted extensive research on the diversity theory of the product design process[38], design-solving models[39], design scheme generation process[40], scheme-solving and decision-making[41], and other aspects. The author and team have also proposed product design deployment models[42], knowledge configuration methods[43], innovative design collaborative evolution models[44], and other design theories, providing reference ideas for product design solving. However, there is still insufficient support for how to design resilient products to withstand high-impact disturbances that may lead to irreversible structural damage and product failure.

Therefore, based on the definition and characteristics of resilient products under high-impact disturbances, it is necessary to establish a structured design model that meets the rules of design thinking and knowledge inference logic and satisfies the functional-structural reasoning of the product scheme under disturbance constraints. The study of the evolution mechanism of design intent towards design solutions will provide a theoretical basis and methodological support for designers to carry out resilient equipment design. According to previous studies on product design and the product resilience characteristics mentioned above, the author proposed five principles of product resilience design in the early stage, as follows[37]:

- 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 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.

To minimize the impact of high-impact disturbances on the stable operation of the product, the first task is to clarify the possible failure modes that different disturbance levels may cause to the product and to clarify the basic connotation of product resilience and the triggering conditions. Quantifying the probability of the impact of different levels of disturbances on the robustness of the product and the degree of loss of product functions caused by high-impact disturbances are key issues and difficulties. The process of resilient product design should ensure that the solution meets the requirements of resilience and function-structure mapping under disturbance constraints, which is the prerequisite and foundation for improving the accuracy of design solutions for such products.

Different forms of product failures and their corresponding self-recovery strategies increase the uncertainty in understanding design intent. To impart resilience to equipment while meeting functional and performance requirements, it is necessary to clarify how resilience affects the entire design process. Moreover, although physical redundancy in product configuration can effectively improve equipment resilience, this kind of redundancy backup largely affects the spatial layout of the original design, bringing new limitations to traditional design solutions. Therefore, enhancing the understanding of resilience design intent, reducing subjective experience or the fuzzy judgment of fixed knowledge on solutions, and integrating design thinking, design methods, cross-domain knowledge, and resilience capability assessment is the core and key to improving the accuracy of product resilience design solutions.

5. Conclusions

With the increasing challenges that products are facing, such as large changes in demand, complex and changing operating environments, and multiple overlapping sources of disturbances, designing resilient products has become increasingly important. In practical work environments, as external risks pose greater threats of high-impact disturbances to products, equipment may be subjected to more severe shocks, inevitably leading to failure events. It is therefore urgent to accurately quantify the degree of disturbance during the design stage, analyze equipment failure modes, and achieve solution-solving. Among these challenges, the mechanisms by which high-impact disturbances affect equipment failure and trigger resilience, as well as the constraints of equipment resilience on the design solution process under high-impact disturbances, have become key issues in tackling the challenges of resilient design.

In this article, the author reviews the application and evolution of resilience in different fields from the mechanism of product resilience. The definition of product resilience is introduced from two dimensions, namely, broad sense and narrow sense, and their boundary ranges are defined. The entire process of product resilience is composed of a preparation period, adaption/absorption period, recovery period, learning period and improvement period. The author explains the changing patterns of product performance in different stages and further discusses them. Agility, redundancy, adaptability, and visibility are considered the four main characteristics of product resilience, and the author introduces and analyzes them. To better meet the requirements of product performance robustness and sustainable safe operation, enhance the equipment's ability to withstand and absorb interference, and guide designers to analyze and predict the relationship between different disturbances and failure modes during design, the author also proposed key technologies and design principles in resilient product design, and introduced the challenges in resilient product design research.

To better manage high-impact disturbances and improve resilience, further research can be conducted in the following areas: (1) exploring the essence of product resilience, revealing the impact relationship of high-impact disturbances on equipment robustness and the triggering mechanism of resilience; (2) establishing a product resilience design methodology that meets functional reasoning and structural configuration under high-impact disturbance constraints; (3) while meeting the requirements of product resilience, balancing resilience with cost, performance, energy consumption, and sustainability; (4) it is necessary to establish better systems and tools to use knowledge and information, integrating design thinking, design methods, cross-disciplinary knowledge, and resilience capability assessment, in order to better manage and respond to the risks of disturbances and improve the accuracy of product resilience design solutions.

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