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Importance Measure-based Maintenance Management: Review, Methodology and Perspectives on Resilience

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Abstract: In recent years, frequent natural or man-made disturbances have accelerated the study of resilience management. As an important source of system resilience, maintenance activities need to be managed effectively. Meanwhile, importance measures have become an effective tool in maintenance management. However, there are still some challenges in the studies of importance measure-based maintenance management. A comprehensive review and discussion can serve as a useful reference for the future research. This paper firstly reviews the definitions of importance measures, maintenance, and resilience and then examines their interrelationships. It then analyses the roles of importance measures in maintenance management for resilience improvement. Finally, it proposes future research directions.

Keyword: Importance measure; Maintenance management; Performance; Resilience

1. Introduction

In the past decades, natural disasters and artificial disturbances have greatly affected the operation of many infrastructures [1]. For example, in February 2021, three severe snowstorms knocked out the energy infrastructure in Texas, leading to shortages of water, food and heat and leaving more than 4 million homes without power. Similar malicious events seriously affect the performance and safety of many communities. The development of society has brought various infrastructures and relevant networks together. A negative hazard can even cause a system to collapse [2]. In response to the rapidly changing environment, resilience has become a key performance indicator of many infrastructures systems [3, 4]. As a comprehensive measure, resilience is concerned with both the preparedness and recovery ability of a system in the face of disturbances [5]. Resilience management can provide engineers with an intuitive way to evaluate the ability of a system to meet specified performance requirements after the occurrence of disturbances.

Reliability importance measures are developed in reliability and maintenance for ranking the importance of components of an engineering system. They can provide a powerful method to support system analysis from various perspectives [6]. For example, the component reliability importance measure can help engineers to identify weak components/parameters and providing guidance in system improvement and the component criticality importance measure provides the probability that a component is critical for the system and is failed at a time when the system is failed. There are various importance measures that have been developed for improving resilience management. In addition, maintenance activities have a significant impact on a system's capability to maintain or restore its performance [7]. This capability is also one of the important sources and optimization objectives in resilience management. The allocation of preventive maintenance resources, the decision of condition-based maintenance strategies, and the scheduling of post-disturbance emergency maintenance have all become resilience-oriented maintenance problems. With the increase of governments' attention to resilience management, research on importance measures and maintenance optimization for enhancing resilience is increasingly abundant [8].

There are some debates on the definitions of system resilience and the applications of importance measures in resilience management [9, 10]. Due to the different levels of attention and research subjects, there are huge differences between maintenance strategies to optimize resilience. Meantime, importance measures are also one of the key tools in maintenance management. It follows that there is a complicated coupling relationship between resilience, importance measures, and maintenance optimization. Furthermore, although many scholarly papers on importance measures and maintenance management oriented to resilience management have different foci, there are similarities among them. A comprehensive review and discussion will provide a helpful reference for future research. Therefore, this paper firstly reviews the definitions of importance measures, maintenance, and resilience and then examines their interrelationships. It then analyses the roles of importance measures in maintenance management for resilience management. Finally, it proposes future research directions.

The reminder of the paper is as follows. Section 2 provides an overview of resilience, importance measures, and maintenance management and then examines the relationship among the three concepts. Section 3 introduces the application of importance measures in maintenance management oriented to resilience. Section 4 wraps up this paper and identifies on-going and upcoming research directions.

2. Relationship between resilience, importance measure, and maintenance

2.1 Overview of resilience

The word "resilience" originated from the Latin word "resilier", which means "to bounce back". Before 1973, the word was often used to describe a characteristic of some materials [11]. In 1973, Holing pioneered the concept of resilience as a measure for systems to absorb changes to its state and driving variables [12]. With globalization and connectivity, the impact of natural and man-made disasters may no longer be limited by geography. Destruction has also become more unpredictable and frequent. The concept of resilience is therefore also gradually applied to areas like engineering industries and other businesses [13]. It has been widely adopted in many research fields such as ecology, psychology, sociology, and public management [14]. For example, Leveson [15] laid the foundation of resilience engineering by proposing an accident occurrence model based on system safety engineering. For its connotation, Hosseini [5] delineated and defined the concept of resilience in four domains: organisational, social, economic, and engineering. Moreover, some scholars proposed a general definition of resilience across multiple disciplines. Pregenzer [16] defined resilience as a measure of a system's ability to absorb sustained and unpredictable changes and maintain its vital functions. Henry and Ramirez-Marquez defined system resilience as a quantifiable metric related to time [13]. To adapt to the specific system and scene, some authors have made further enrichment and explanation of "resilience". Table 1 provides the definitions of resilience in different areas: engineering, socio-ecological, organizational, economics, and psychology.

Table 1 Summarize of focus of attention in different fields

Field	Focus of attention	Reference

Engineering	The ability of a system to maintain and recover the system's function with external and internal disruptions.	[17-19]
Socio-ecological	The ability of a system to resist interference and reorganization after experiencing external shocks	[12, 14, 20, 21]
Organizational	The needs of enterprises, organizations, and supply chains responding to a rapidly changing business environment	[22-24]
Economics	The ability of a system to withstand market or environmental shocks without losing the ability to allocate resources efficiently	[25-27]
Psychology	A dynamic process by which an individual exhibits positive behavioral adaptation when they experience adversity	[28-30]

It is not difficult to see that the "resist", "adapt", and "recovery" for functionality or performance are the key aspects of system resilience. Hence, the current research on resilience metrics is focused on system performance degradation and recovery, which can be divided into two categories: deterministic metrics and probabilistic metrics [31, 32]. There is still no consensus on the definition of resilience. But research on the optimization, design and analysis of resilience is evolving. Similar to the well-known concept of *reliability*, resilience is also a critical characteristic of a system. The two have great similarities but are different, and many studies have tried to distinguish the relationship between them [33]. It is generally believed that resilience analysis considers the reliability of the system under disturbed conditions [34]. Reliability optimization and analysis methods, such as importance measures, can provide strong support for the development of resilience.

2.2 Overview of importance measures

Importance measures are studied in reliability engineering. Birnbaum [35] first introduced the concept of importance analysis methods for binary state systems and defined three types of importance measures: structure importance, reliability importance, and lifetime importance. For example, Lambert [36] established a critical importance analysis method for two-state systems in 1975. In 1983, Vesely et al. [37] introduced the concepts of Risk Achievement Worth (RAW) and Risk Reduction Worth (RRW), which were applied to probabilistic risk assessment in risk information regulatory systems. Si et al. [38, 39] studied the theories and methods of importance measures for multi-state and reconfigurable systems oriented to the whole life cycle. At the same time, importance measures are applied to various fields. For example, in the aerospace field, [40] extended the integrated importance measure to find the most important components for a propeller plane system. Marseguerra et al. [41] used the differential importance measure to analyze the impact of changes in the random characteristics of components on a nuclear reactor system. In recent years, maintenance, cost, and many other factors are integrated into the significance analysis, which greatly enhances its practical significance and application scope [42-44]. For example, in [45], the impact of external factors such as temperature, vibration, etc., was considered and a novel importance measure for multi-state system lifetimes with renewal functions being proposed to prioritize weak components (or states) of a system. Based on the reference [6, 35-39, 46], the common importance classification methods, application fields, consideration factors and application stages are summarized as shown in Fig. 1.

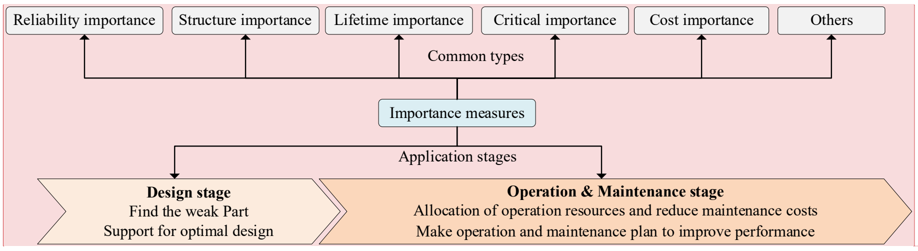

Fig. 1 A summarize of importance measures

As shown in Fig. 1, the application field of importance measures is becoming wider, and the factors considered, such as performance, cost, etc., are becoming more comprehensive. Because these factors have a significant impact on the system to maintain efficient and economical operation. Importance measures play an important role in the whole life cycle of a system, including design, and operation and maintenance stages. Based on their applications, importance measures can be categorized into reliability importance measures, lifetime importance measures, structure importance measures, cost importance, and so on. Take performance analysis for a multistate system as an example, the contribution of the performance of components can be measured by an importance measure to identify weak parts of the system at the design stage. It can be seen that importance measures may serve as one of the indexes to

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evaluate the sensitivity of the system from different aspects. In recent years, importance-measure-based analyses are becoming a popular topic. A widely used example is the increasing number of importance-based resilience measures, especially criticality importance measures [47], published in academic journals. In addition, reliability and resilience are closely related to maintenance, which has attracted more research towards importance-measures-based maintenance management to enhance system resilience.

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2.3 Overview of maintenance management methods

Maintenance is one of the most important and effective means to improve the safety, reliability, and resilience of an engineering system. Maintenance can be corrective maintenance and preventive maintenance [48]. Corrective maintenance refers to restoring a system to its working condition upon its failure [49], which is a commonly used maintenance policy[50]. This type of maintenance is generally unanticipated as it can have serious consequences for system functionality. Emergency maintenance or restoration upon a shock on a system of resilience management is one type of corrective maintenance [51, 52]. To alleviate the impact of serious damage to the system, preventive maintenance has been extensively studied. Preventive maintenance is a method that performs inspection or repair actions according to a planned or specific schedule to keep the system in a predetermined working condition [53]. The earliest models of preventive maintenance can be dated back to the sixties of the twentieth century [54]. In the past decades, various maintenance strategies, such as condition-based maintenance, opportunistic maintenance, selective maintenance, etc. are proposed [55, 56]. In order to deal with the suddenness and harmfulness of the disturbance, a special maintenance mode called emergency repair is proposed in resilience management.

Of course, not all maintenance strategies are related to resilience management, [57] defined the concept of resilience-based maintenance, including can corrective and preventive maintenance. Ineffective or inefficient maintenance not only does not significantly improve the performance of systems but may also incur excessive costs. Therefore, it is necessary to implement different maintenance actions at the different phases in the lifetime of a system. Reliability-oriented maintenance methods have improved tremendously over the past few years [61, 62]. Among them, there is a lack of maintenance management research based on importance measures. In many studies, a resilience process has three phases: normal phase, disturbance phase, and recovery phase [60]. In these three phases, preventive design, condition-based control, and recovery arrangement are carried out, respectively.

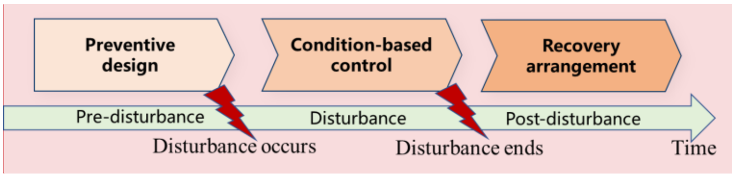

Fig. 2 Maintenance management in different stages

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According to the time-driven management characteristics shown in Fig. 2, common management activities include redundancy design, preventive maintenance, group maintenance, emergency maintenance and so on. These maintenance activities play different roles in different stages of resilience management because of their own characteristics. The specific maintenance activities and adaptation stages are shown in Fig. 3, in which the cells in columns Management and Activities contain the sections that the associate content will be discussed.

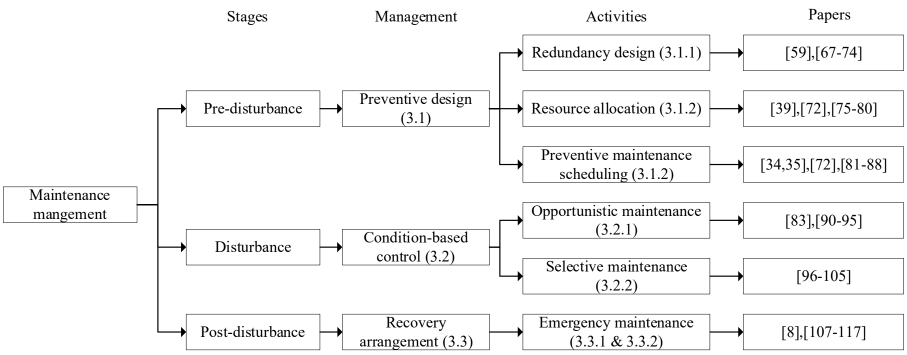

Fig. 3 Classification of common maintenance strategies related to resilience

Maintenance management in a broad sense refers to a series of activities in order to reduce the probability of failures, reduce the impact of failures, and improve the maintenance effect [58]. Therefore, some proactive preventive measures, such as redundancy design and logical switching, are also considered as special maintenance methods [59].

- Redundancy design and resource allocation aim to ensure that the system can respond to disturbances by adding additional components or protective resources, etc.

- Preventive maintenance refers to the maintenance of parts before they fail to improve the system's ability to resist disturbances.
- Selective maintenance and opportunistic maintenance are group maintenance. In addition, when a condition-based maintenance is performance, engineers may use this opportunity to perform preventive maintenance on other components in the system.
- Emergency maintenance is a special maintenance way in resilience management, which is carried out only when either an inspection or breakdown maintenance has identified its necessity.

The papers shown in Fig. 3 are all correlated with importance measures and the following are respectively elaborated.

2.4 Relationships among the three concepts

Resilience, like reliability, is one of the quality characteristics of a system, and there is a close relationship between it and maintenance. Likewise, effective maintenance management is an important source of system resilience [57]. Maintenance activities can help a system maintain or restore its performance, which is the goal of resilience management. As an effective tool of maintenance and resilience management, importance measures have been widely studied in recent years.

Routine preventive maintenance work keeps a system in its healthy working condition before the disturbance arrives. In addition, preventive design efforts, such as redundancy design and resource allocation, can be developed to reduce the damage caused by disturbances [63]. In this phase, importance measures can guide engineers to identify weak parts of the system, make a reasonable preventive maintenance plan, and contain the risk of system performance degradation. During the disturbance phase, the reliability of some components decreases, or the system fails eventually because of the degradation of system performance. At this time, importance-based maintenance activities can be performed to sustain the system’s performance. Moreover, to make full use of resources, some relatively novel maintenance modes such as group maintenance and selective maintenance can also be carried out under the guidance of joint importance measures. The dependence between components, such as cost dependence, structural dependence, and other measures need to be considered comprehensively [64]. This is very similar to the condition-based maintenances described above, so we refer to them as condition-based maintenance without causing ambiguity. After a disturbance ends, the performance of the system generally reduces to a certain level, and the emergency maintenance work needs to be carried out. Importance measures can be used to determine the order of recovery and the method of allocating resources to support a rapid and efficient recovery of the system to an acceptable level. Both heuristic and ranking methods are used here. To sum up, the relationship between the three is shown in **Error! Reference source not found.**.

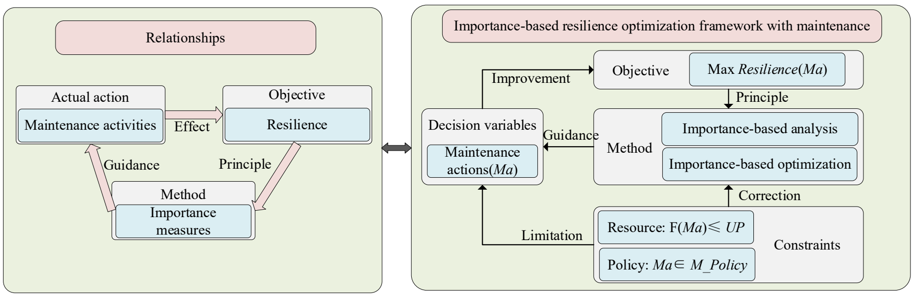

Fig. 4 Relationship between resilience, maintenance, and importance measure

As mentioned above and shown in Fig. 4, resilience, maintenance, and importance measures play the roles of the objective, action, and method, respectively. Maintenance is the actual action to sustain or restore the system's functionality; and importance measures provide guidance for maintenance management. In the pre-disturbance phase, as the disturbance has not arrived, preventive maintenance is more concerned about critical components. To reduce the great influence of disturbance on system operation, importance measures usually are used for redundancy design, resource allocation, and maintenance planning. In the disturbance phase, some of the components failed as a disturbance arrives, and the degradation of system performance may not have been significant because of the preventive maintenance. To ensure that the system can continue to operate, condition-based maintenance is applied in this phase. Considering the dependance of components, such as: cost, structure, etc., researchers proposed importance measures to improve the economy and effectiveness of maintenance. In the post-disturbance phase, disturbance has caused great damage to the system and emergency maintenance is necessary. With respect to resource consumption and recovery contributions, importance measures can guide the designation of maintenance plan to maximise system resilience. For the characteristics of these three resilience phases, this paper takes importance measures as the analysis methods guide the optimization process and establishes the optimization model of the maintenance strategy to maximize the resilience of the system.

3. Importance-based maintenance management oriented to resilience

Having sorted out the relationship among the three concepts, we turn our attention to the specific application methods. Maintenance management is essentially an optimization problem, aiming at rationally arranging maintenance activities. Resilience oriented maintenance management is a special optimization model considering disturbance conditions.

3.1 Importance-based maintenance management in the pre-disturbance phase

Pre-disturbance maintenance management is a design-stage job, which has a significant impact on the retention and recovery of system performance. Generally speaking, we can use prior information to predict the disturbance scenario [65]. Then, under the condition of considering the disturbance, some maintenance plans and resources should be rationally arranged to reduce the risk of system operation [66]. Through some attempts, a more resilient system can be obtained.

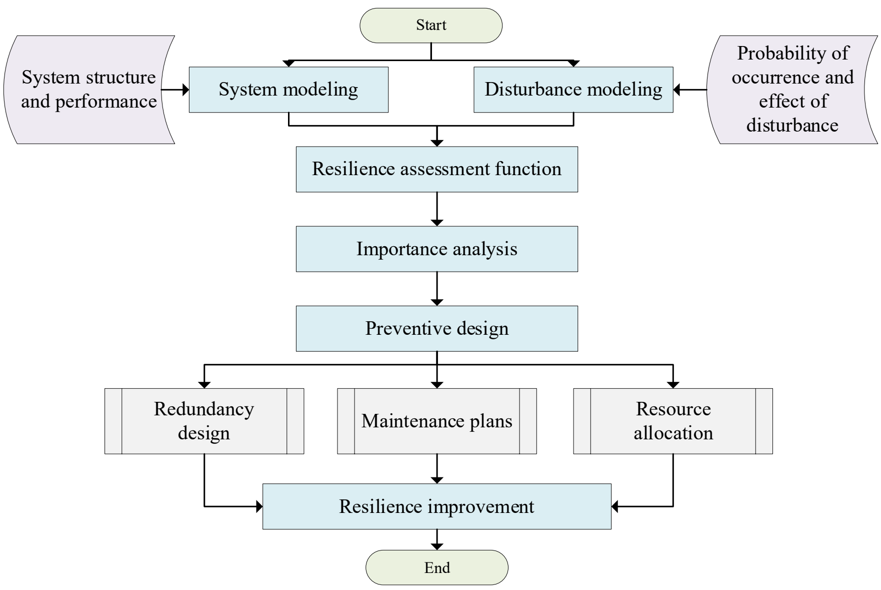

Fig. 5 Maintenance management process in the pre-disturbance phase

As shown in Fig. 5, resilience modeling consisting of system models and disturbance models should be developed first. In real situations, if a system is in a complex environment with various threats, predictive resilience measures with disturbance models are more realistic [18]. System models and resilience functions will directly affect the identification of critical components. To reduce the impact of disturbance on system performance (or improve the robustness of a system), the work of preventive maintenance design, such as redundancy design, resource allocation and maintenance planning, can be carried out in this phase. The specific application of these works is discussed in Section 3.1.1, Section 3.1.2, and Section 3.1.3. However, constraint by the cost or other resource, some critical components should be found to maximize the effect of resources. Importance analysis is used to identify critical components to support the design and properly allocate resources or plans.

3.1.1 Redundancy design

For many systems such as unmanned aerial vehicles (UAV) swarms, components are the source of system self-recovery and self-adaptation ability [67]. When a disturbance occurs, the failure of critical components may greatly reduce system performance or even cause a system to fail [68]. Replacement of redundant components or switching of logic to maintain the ability of the system to function [69, 70] is therefore needed. In terms of logic, [71] makes redundant design for key modules to improve the resilience of a control system. [72] proposed a redundancy importance measure by analyzing the impact of the number of backups of a component on the resilience of the system, which is used to determine whether a component is worth redundancy or not. A UAV swarm itself is a typical redundant system, which relies on its collaboration with more UAVs to complete a specific mission [68]. In [73], an importance measure considering the effect of the number of different types of UAVs in a heterogeneous UAV swarm on the phased-mission is presented, which provides useful guidance to the decision of redundancy composition of UAV. Redundancy design, as a special preventive approach, maintenance activities are taken into account before the disturbance arrives, which is becoming a hot topic [74].

3.1.2 Resource allocation

Proper allocation of resources helps increase the reliability of a system and thus maintains system performance in the face of disturbances. Especially for a network system, the protection of key nodes or edges has become a mature method to improve the resilience of the system. Network features such as the degree of nodes, centrality, and H-index are often studied in the area of importance analysis, and some evolutionary features such as network seepage are also usually taken into account [75]. [72] proposed a reinforcement importance to select critical components and improved their component resilient limit. In [76], performance loss is more concerned in finding important nodes of a wind power generation system for protection. In addition, risk factors are often considered in finding critical nodes in infrastructure investments [77]. [78] proposed a resilience-based component importance measure with a Bayesian kernel model. [79] indicated that microgrids can be used as a resource of a power system to improve system resilience. To satisfy the need of maintenance, based on the integrated importance measure proposed in [39], a spare parts storage configuration method was given in [80]. When there are resources available for allocation to improve system resilience, how to allocate the resources reasonably provide a broad platform for the development of importance. This has great influence on the follow-up maintenance activities or operation modes and should be paid attention in the future research.

3.1.3 Preventive maintenance plan

To maintain the performance of a system and improve its resilience in complex environments, the main task of preventive maintenance management is to decide when and on which components maintenance activities should be performed. Adequate preventive maintenance can reduce operational risks and improve system resilience [81]. It's not hard to see the objective of resilience and reliability are similar in this phase [34]. In terms of the "when", time-dependent importance measures can give some guidance [82]. The Birnbaum importance measure is just the importance of a component oriented to reliability in a given time [35]. In [76], the resilience measure was defined as a function of time and components, which presented the change of component importance with time. Moreover, in opportunistic maintenance, when a component fails, it is also a good time to repair other components [83]. The goal is also to reduce the cost of downtime, which is somewhat similar to the concept of "group maintenance" [84], where the objectives (or constraints) include performance improvement [85], cost reduction, maintenance time shortening, and other practical factors often be taken into account [86]. For example, a cost-based importance is proposed to select proper components for maintenance in [87]. In [88], combing the advantages of time-dependent and time-independent lifetime measures, two types of importance measures were proposed to determine objectives of the optimization should be optimized simultaneously. Compared with the two above mentioned methods of preventive design, importance-based preventive maintenance decision has been relatively well-established.

3.2 Importance-based maintenance management in the disturbance phase

Maintenance activities during a disturbance phase are not easily defined. It has similarities to the post-disturbance phase in terms of maintenance because there are failed components at both phases. The difference is that the state of a system at the disturbance phase is still degrading continuously. To intervene at the initial stage of a disturbance to reduce the influence and avoid causing greater losses is therefore needed [89]. In fact, reasonable and timely maintenance actions at the disturbance phase can reduce the need of more maintenance works in post-disturbance phase or even avoid large-scale breakdown maintenance.

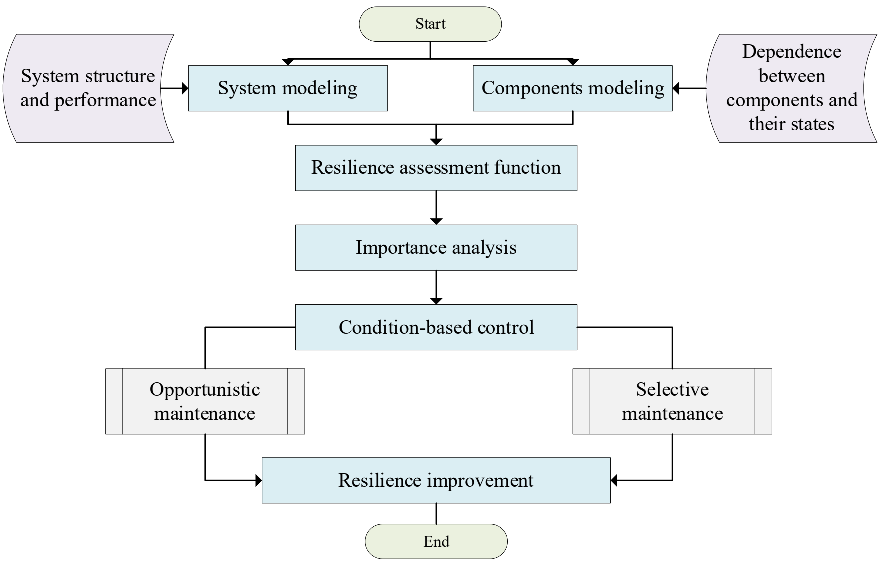

Fig. 6 Maintenance management process during the disturbance phase

In this phase, a disturbance may cause a small-scale failure of the system and some impact of the disturbance is offset by maintenance. Maintenance activities are subject to specific failures and operation conditions, so condition-based maintenance is applied at this phase. Some maintenance activities may be needed to restore some functions. Based on the system model, the operation state and dependance between components should be described. Importance measures are used to identify the components worthy of repair and condition-based maintenance, such as opportunistic maintenance, selective maintenance. Specific applications are shown in Section 3.2.1 and Section 3.2.2.

3.2.1 Opportunistic maintenance

To enhance system performance, corrective maintenance upon failures and preventive maintenance for reducing the probability of future failures can be performed simultaneously on repairable systems. To improve the system availability or reduce cost, one may adopt the following method: if a component fails, preventive maintenance is carried out on a number of the other components while the failed component is being repaired. This idea is commonly referred to as opportunistic maintenance and sometimes as group maintenance [90, 91]. [83] proposed an importance measure to presenting the component maintenance priority for normal components when some components were failed. Similar to this idea, constrainted by the limited budget, an extended joint integrated importance measure was proposed in [92] to determine which components have opportunity for preventive maintenance. [93] Considering the maintenance cost and system structure, group importance measures were designed to find the optimal maintenance strategy in [94]. [95] established a model considering economic and structural dependences to make a maintenance plan based on the mean remaining lifetime and Birnbaum's importance measure.

3.2.2 Selective maintenance

Selective maintenance is the process of identifying a subset among sets of desirable maintenance actions [96]. This process mainly includes two parts: (a) Determine which parts to take maintenance actions and (b) determine what type of maintenance actions to take. The goals of the decision include improving system performance, reducing costs, and reducing downtime [97-99]. Although the resilience oriented selective maintenance strategy has not yet been proposed, we believe that its goals are similar to those described above. [100] developed a two-phase model: at the first stage, the yield-cost importance measure was used to find the appropriate component; at the second stage, the optimal maintenance level was decided by the value of maintenance actions. Similarly, [101] addressed the joint selective maintenance and repairperson assignment problem based on importance measures in [102]. For multi-state production systems, [103] proposed a total throughput importance measure and the maintenance effect importance measure, which can answer the questions about the criticalities of different components and the long-term effects of successful maintenance activities. To our knowledge, importance measures have not been mentioned much in the research of solving selective maintenance problems. But it is interesting to note that the idea of importance measure is discussed in many articles [104, 105].

3.3 Importance-based maintenance management in the post-disturbance phase

Maintenance management in the post-disturbance phase is mainly to help a system to recover to an acceptable performance level quickly and efficiently. Based on maintenance management before and during a disturbance, post-disturbance damage must be minimized as much as possible. At this time, more attention has been paid to the restorative features of the resilience concept, such as the speed or degree of recovery. The results of the first two phases of work directly affect the work of this phase, effective measures can even make the system always within the acceptable performance range and do not need the work of the current phase [56] [106]. Unfortunately, the randomness of the disturbance leads to damages that are often unavoidable. It is necessary to imply emergency maintenance in post-disturbance phase.

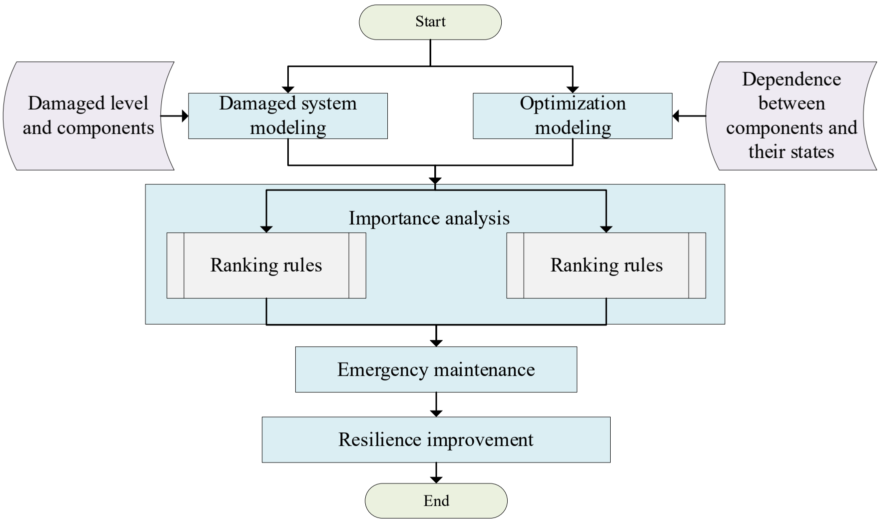

Fig. 7 Management framework at the post-disturbance phase

As shown in Fig. 7, a system is assumed to be damaged in the post-disturbance phase and emergency maintenance is then carried out. The damaged system consisting of damaged subsystems and components should be modeled firstly. Then optimization models can be developed to consider resource limitations and resilience levels. Importance measures are used to guide the emergency maintenance, which includes determining the maintenance priority and scheduling tasks. In the process of guidance, ranking rules and heuristic methods are two common ways. The applications are given in Section 3.3.1 and Section 3.3.2 respectively. According to different objectives, maintenance management can be divided into three types. The specific classification is shown in Table 2.

Table 2 Classification of maintenance management in the post-disturbance phase

	Characteristics of problems	Objectives of problems	Papers
Maintenance management in post-disturbance phase	Specified recovery degree	Minimize time	[107]
	Specified recovery time	Maximize performance	[108]
	Specified proposed resilience metrics	Maximize or minimize metrics	[109,110]

It can be seen in Table 2, different characteristics of maintenance problems correspond to different resilience optimization objectives, which is determined by the function of systems. For example, it is critical to restore to an acceptable performance for active distribution system [107]. On the contrary, [108] proposed a two-phase algorithm to maximize system performance in a short time. Meantime, there were also many scholars tend to propose a proprietary resilience metric and then used optimization methods for maintenance management [109, 110]. In the post-disturbance phase, it is critical to analyze the recovery impact of failed parts on the system to guide the maintenance management. Resilience-based importance measures are also widely used in this phase.

3.3.1 Ranking rules

Importance measures can be used to determine the criticality of components [6]. Applications and research of importance measures are extensive in the field of maintenance management oriented to resilience [111]. Guided by objectives and constrained by constraints, new importance measures are proposed to determine component maintenance priorities. For example, a novel resilience importance measure is developed to obtain the optimal maintenance efficiency for irrigation networks under the influence of droughts in [112]. Under the guidance of two stochastic resilience-based component importance measures, [113] provided a method to determine the order in which disrupted links in the inland waterway network should be recovered for improved resilience. In order to optimize the resilience of maritime transportation systems, [114] proposed an importance measure based on the residual resilience to determine the maintenance priority of ocean ports. From a seismic resilience perspective to water distribution networks, [115] represented a dynamic ranking method to maximize the resilience based on importance measures. Compared with other phases and heuristic methods, research on the methods of ranking is very rich [116, 117]. As a result, the resilience and performance measurement of the system has become a key issue in this direction.

3.3.2 Heuristic methods

Heuristic methods are also commonly used importance measures along with reliability optimization [118, 119]. Therefore, some authors also attempted to apply heuristic methods in studying maintenance management. For example, a novel resilience importance measure was

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Commented [刘12R11]: Heuristic methods combined with roulette wheel selection to form the initial maintenance plan for pigeon-inspired optimization in [8], which can help improve the effectiveness of resilience optimization. Based on two modified importance measures (approximate measure and rate measure), a heuristic policy for maintaining multiple multi-state systems was proposed in [120]. Fang et al. [121] proposed two metrics to quantify the priority with which a failed component should be maintained and the potential loss in the optimal system resilience due to a time delay. Then the stochastic ranking approach based on the Copeland's pairwise aggregation is used to rank components importance. In order to find the critical nodes set and improve the resilience of cyber-physical power systems, a gene importance based evolutionary algorithm was proposed in [122]. [123] proposed two project priority measures as the likelihood of a bridge being selected for repair when the budget is fixed and the uncertainties governing the performance of the transportation network are considered. Compared with the ranking rules, importance-based heuristic methods are more flexible and can be used to solve more complex problems.

4. Perspectives for future development

Following the above analysis, we identify the following perspectives for future research.

4.1 Multi-attribute importance measures based on resilience management

As a comprehensive system characteristic, resilience itself contains many kinds of perspectives, such as robustness, recovery, and so on. In recent years, there also has been an increasing trend in the research of multi-objective optimization. However, it can be found that the design attributes of studies in Section 3.1 and optimization objectives of studies in Section 3.2 and 3.3 are widely researched. It is not desirable to ignore other operational or design attributes of the system while ensuring resilience. For example, the relationship between system resilience and reliability mentioned in [34], a system with a high resilience may have a low reliability and vice versa. While we expect a high level of both undisturbed system reliability and disturbed system resilience. In addition, Moreover, as real-world optimization problems become more complex [124], time, cost, performance, and many other criteria are widely concerned in maintenance management. Therefore, multi-attribute importance measures in resilience management should be given more attention to dealing with more complex maintenance problems.

4.2 Resilient operation strategies based on importance measures

On the one hand, according to the discussion in Section 3.2, most condition-based maintenance methods aim to improve system performance or reliability.. However, research on resilience-oriented maintenance is still needed for the disturbance phase, as many objective functions in these studies are not related to resilience directly. On the other hand, maintenance models based on importance measures focused on physical maintenance in the existing literature. Nevertheless, resilient operation strategies are attracting more and more attention and have been proven an effective method [59, 125]. To the best of our knowledge, there is still little research on system maintenance based on importance measures from operational logic or mode perspectives. What's more, the development of path set importance measures has provided us with some inspiration for system operation design [126]. Therefore, it may be an interesting topic to use importance measures to develop resilience-oriented operation strategies considering disturbance conditions.

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