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When the digital twin meets the preventive conservation of movable wooden artifacts

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Abstract

To achieve sustainable heritage conservation, preventive conservation has gradually taken precedence over curative conservation, because it can inhibit the damage caused by various environmental factors and maximizes the preservation life of the artifacts. Due to susceptibility to environmental factors, preventive conservation has been used in the conservation of movable wooden artifacts to further protect them. Recently, digital twin technology, as a concept that transcends reality, can be mapped in virtual space to reflect the full lifecycle process of the corresponding entity, which is a superior characteristic that makes it valued and researched for health monitoring and health management of heritages. This paper proposes a health management method mainly for preventive conservation of movable wooden artifacts, integrating digital twin technology into the health management process. Using the Quanzhou Ship as a typical representative, several important components of health management are specifically analyzed, such as the five-dimensional model of the digital twin, the data interaction process of the digital twin, and the identification and assessment of risks. In particular, the process of preventive conservation of the stern based on the digital twin is presented in detail. This method provides a basis for future preventive conservation of movable wooden artifacts and has implications for the use of digital twin technology in the field of heritage conservation, especially for movable wooden artifacts.

Keywords Preventive conservation, Digital twin, Movable wooden artifacts, Health management, Risk assessment, Stern

Introduction

The development and connotation of preventive conservation

The early heritage conservation was achieved through careful planning of the interior environment to avoid as much as possible the effects of moisture, insect and pest problems [1, 2]. In the seventeenth century, a set of guidelines for the maintenance of the interior environment of museums and galleries was developed in the Italian region [2]. In general, there was no systematic concept of heritage conservation and restoration before the eighteenth century [1]. Between the mid-18th and the end of the nineteenth century, the onset of the industrial revolution led to environmental degradation, and the widespread attention was drawn to the gradual damage caused by environmental factors such as lighting, temperature, humidity and pollutants [1, 2]. Subsequently, the two World Wars brought serious environmental threats to heritage collections, and people began to control and research the indoor environment of artifacts [3]. The preventive concepts such as routine maintenance, environmental control, and permanent maintenance became the consensus for the conservation management of collections [4]. The concept of preventive conservation was first introduced in 1930 at the first International Conference for the Study of Scientific Methods for

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the Examination and Conservation of Works of Art [5]. Between 1930 and 1950, the traditional logic of "remedial conservation" of heritage in emergency situations was gradually replaced by a new logic of "prior prevention" or "systematic maintenance" through the research of conservators and scientists [1, 6]. From the 1960s to the 1990s, research into preventive conservation was in full swing, with preventive conservation frameworks, standards, rules, guidelines and training becoming a major focus of research [3, 7]. Preventive conservation was led to further development as the application of risk assessment models and the dynamic monitoring of environmental factors in the field of preventive conservation [8]. ICCROM outlined preventive conservation as the measures and actions necessary to delay any form of damage to a heritage that could be avoided without jeopardizing its authenticity in 2008 [1, 9].

The core connotation of preventive conservation is the implementation of effective quality management, monitoring, assessment, regulation, and intervention in the environment of heritage conservation, and a series of maintenance measures are adopted to inhibit the hazards of various environmental factors to heritage. In addition to the analysis and diagnosis of existing hazards, preventive conservation also requires the prediction of potential defects and threats in order to prevent or reduce the possible future deterioration and damage to heritage [1, 10].

This concept of preventive conservation had transformed heritage conservation from reactive restoration to proactive prevention [11], which not only greatly reduced the probability of deterioration under conditions of time, environment, force majeure and other factors, but also maximized the preservation life of heritage [3, 10, 12].

Digital twin and preventive conservation

The concept of the digital twin was first introduced by Grieves [13], and a real product or device can be represented by creating a digital twin used as a basis for simulation testing in a virtual environment, which was first used in the military and aerospace sectors [14]. With the development of emerging technologies, digital twin has been used in different industries including: production processes [15], smart manufacturing [16], and particularly in health monitoring [17], health management [18], diagnosis and prediction [19–21], digital twin has a unique advantage, which is a superior characteristic that makes it valued and researched in preventive conservation of heritages [10, 22, 23]. The use of digital twin for the health management and monitoring of heritages requires real-time data support, and it is a good way to build CAD models as digital twin models to monitor and record heritages using sensors mounted on physical objects [24]. Of course, digital twin not only can remotely monitor the health status of heritages, but also can predict potential risks by simulating. Funari used the parametric scan-to-FEM method to build a digital twin model of the church in an FE environment and verified the ability of the digital twin model to simulate past and future damage scenarios of the cultural heritages [25]. In addition, Marra used the laser scanner survey to build a digital twin model of two sculptures for estimating their stress regime and dynamic properties, and the result highlighted the great advantages resulting from the digital twin in the field of conservation of museum collections and heritages [23]. It is particularly noteworthy that digital twin had also been used in the field of movable wooden artifacts. Due to the variability of wood, Lorenzo used a series of non-invasive experimental observations and instrumental analyses to construct a hygro-mechanical predictive model (Digital Twins) of Leonardo da Vinci's Mona Lisa panel, which allowed a deeper understanding and prediction of the physical structure and behavior of the wooden artifacts itself [26]. It can be seen that the combination of digital twin technology for remote monitoring, prediction of potential risks and real-time control has tremendous advantages for preventive conservation of movable wooden artifacts [10].

Wooden artifacts and preventive conservation

Due to many negative factors in the environment, such as air pollutants, temperature, humidity, micro-organisms, human factors, wooden artifacts are highly vulnerable to damage and corrosion [27, 28]. To enhance the surface protection of wooden artifacts, Coating on the surface is an effective means of protection, such as constructing organic–inorganic composite coatings on the surface of wood to give it UV resistance and self-cleaning properties [29]. Besides, adaptive adaptations to the original coating material are also included. As an important coating material [30], Shellac adding appropriate ZrO_2 and ZnO nanoparticles improves its properties such as the hardness and UV ageing resistance of the coating [31]. However, the detrimental effects of cracks and holes cannot be effectively addressed by the coating, but filling is a more superior option. Due to changing environmental conditions and biodegradation, the filling compounds being used to fill the cracks and holes in wooden artifacts need to be able to adapt to changes in wood dimensions in response to changes in humidity [32], and filling compounds in combination with bio-friendly preservatives can also prevent degradation of the wood [33]. Both the control of environmental conditions and the implementation of protective measures can be effective in preventing damage to wooden artifacts. It is obvious that the development of guiding method for preventive conservation of wooden artifacts is extremely important to mitigate the deterioration of artifacts contained special cultural value [34].

Research aim

This manuscript aims to propose a method for preventive conservation of movable wooden artifacts and to take full advantage of the benefits of digital twin in preventive conservation and health management of heritages. The main advantage of this method is that not only can analyze and diagnose existing damages, but also realistic scenarios can be simulated to predict potential risks and threats through digital twins, and the simulation, assessment and revision of treatment measures provide high-quality references for realistic health management, greatly delaying decay and limiting the potential impact of deterioration factors, which reduces and prevents unnecessary heritage damage and cost losses.

Method

Lucchi presented a method for EEP (environmental and energy performance) assessment in museum buildings, using the SOBANE strategy (screening, observation, analysis, expertise) as a strategic approach to organize efficiently, economically, and durably the risk management [35, 36]. Demas proposed a planning process method, and the process was divided into four main steps: identification and description, assessment and analysis, response, and periodic review and revision [37]. Pierre proposed a framework to support preventive conservation, divided into four main steps: analysis, diagnosis, therapy and control [10]. However, detailed preventive conservation method for movable wooden artifacts are still not well defined and the way in which risks are predicted and assessed still needs further improvement. Synthesizing previous research findings, this research proposes a digital twin-based method to the health management of movable wooden artifacts, which introduces the more specific process for preventive conservation of them and further details the way in which digital twin can be used in the health management process, taking full advantage of the digital twin: analyzing and diagnosing existing damages, predicting potential risks and threats, allowing for treatment measures to be simulation, assessment and revision.

Overall planning

The main objective of the overall planning stage is to investigate the detailed information of movable wooden artifacts comprehensively, including various aspects such as environment, diseases, vital components and background, and to format and arrange the scope, resources, expected goals, methods and means of health management [38], as shown in Fig. 1.

Environmental factors are the main cause of damage to artifacts [10, 39]. Before the overall planning, the

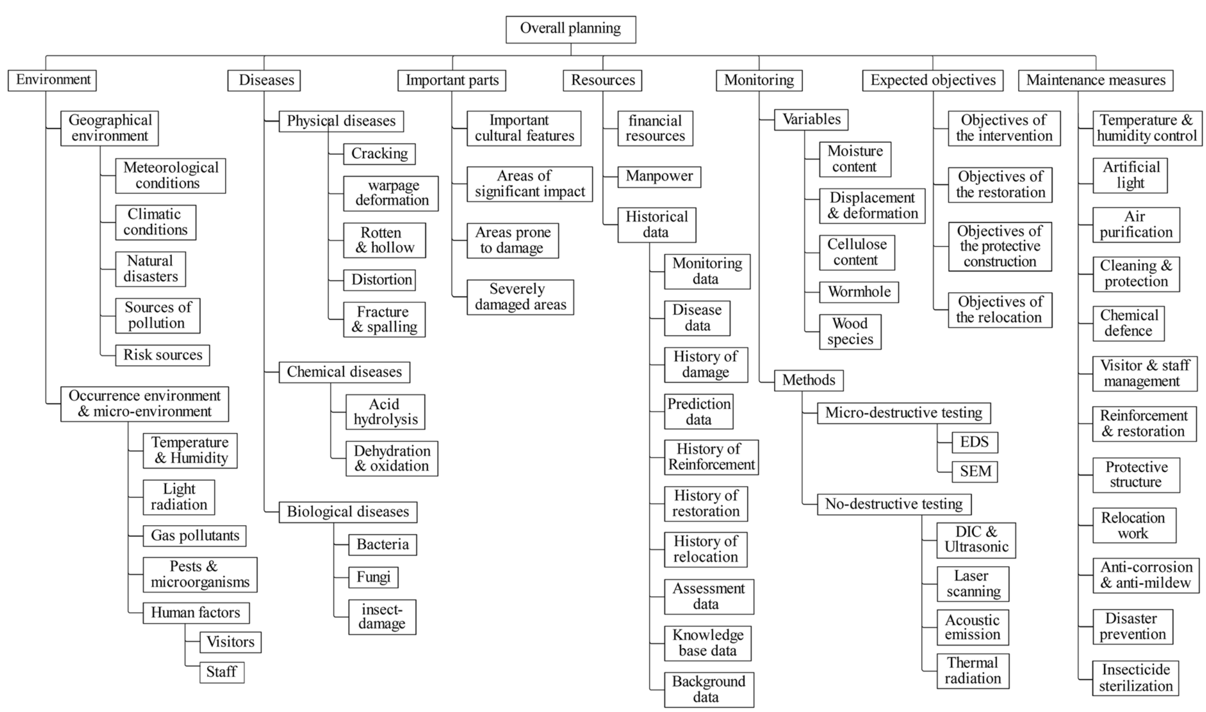

Fig. 1 Overall planning of the digital twin-based health management

environmental conditions of movable wooden artifacts, consisting of the geographical environment, the occurrence environment and microenvironment, should be analyzed in detail [40]. The geographical environment mainly includes: whether or not the meteorological and climatic conditions in the area are suitable for the conservation of movable wooden artifacts [41, 42]; whether or not it is in an area with frequent natural disasters such as earthquakes, tsunamis, landslides, etc. [43, 44]; whether or not there are pollution and risk sources such as factories nearby [45], etc. The main factors involved in the occurrence environment and microenvironment are temperature and humidity [46], light radiation [27, 29], gas pollutants [47], pests, microorganisms [48] and human factors [49], etc.

According to the preservation status of movable wooden artifacts and analysis of the causes of damage, determine the main types of diseases, involving physical diseases, chemical diseases, and biological diseases. The physical diseases mainly refer to cracking, warpage deformation, rotten hollow, distortion and fracture and spalling of wood [50, 51], etc. The chemical diseases, generally produced by the moisture, the harmful gases, the dust and the dirt in the environment, are mainly manifested as the appearance of movable wooden artifacts becoming yellow, brittle or even chalking [52], etc. The most intuitive biological diseases, being from the insect-damage leading to insect holes left on the surface or inside, make the wood soft and mechanical strength significantly declined [53, 54]. Moreover, the erosion from bacterial and fungi is also an important cause of damage to wooden artifacts [55, 56].

Combining the four aspects of cultural value, scope of influence, sensitivity and degree of damage of each part of movable wooden artifacts, assess their various components comprehensively. In general, the important protection parts mainly include: important cultural features, parts of important influence, parts prone to damage and parts with serious damage [57, 58], which provides a reference for the priority of the health management of each part of movable wooden artifacts.

The available resources, including financial resources, human resources and historical data, are systematically collated, and it is necessary to add that historical data consists of historical monitoring data, diseases data, history of damage, history of reinforcement and restoration, history of relocation, assessment data and domain knowledge base, etc.

To ensure the effectiveness of the monitoring of wooden artifacts, it is importance to ensure the reliability of selected monitoring indicators. Following reasonable procedures and principles makes monitoring indicators more reliable. Firstly, comprehensive information, consisting of historical monitoring data, damage records, intervention records such as reinforcement and restoration, etc., is collected on movable wooden artifacts, then their main problems, types of damage and mechanisms are analyzed based on research and observation, and finally a comprehensive analysis is carried out to determine the monitoring indicators and ensure their reliability. The monitoring indicators, including moisture content, displacement and deformation, cellulose content, and wormholes, etc., are used to assess the damage to movable wooden artifacts. To ensure efficient monitoring and minimal damage, the monitoring methods used can be divided into micro-destructive methods [59, 60] such as EDS and SEM and non-destructive methods such as digital image correlation [61], thermal radiation [62], ultrasonic [63], acoustic emission [64] and laser scanning [65].

Based on the information already mastered, the expected objectives for the health management of movable wooden artifacts are determined and appropriate maintenance measures are prepared for the types of identified diseases, such as temperature and humidity control equipment used to control temperature and humidity, artificial light sources used to prevent light radiation, air purification, cleaning and protection, visitor and staff management, reinforcement and restoration measures, protective structure, and relocation, etc.

Diagnosis

Based on the types of diseases and the data monitored, the main objectives of the diagnostic phase are to analyze, predict and assess the damage to movable wooden artifacts and to propose reasonable and effective plans and measures, as shown in Fig. 2.

Firstly, the damage and its impact are analyzed to determine the damage mechanism and information and to create a damage archive. In addition, combining damage mechanisms and information to identify indicators for monitoring, define thresholds for monitoring indicators and trigger values for preventing potential damage, and identify methods and tools for capturing, tracking, and storing the information. After defining the monitoring indicators and thresholds, the digital twins of movable wooden artifacts are created and virtually simulated on a virtual platform based on the data from the monitoring indicators, predicting the potential future risk and its possible negative impact on important parts [25], and storing the resulting predicted data in a historical archive. In addition, existing and potential risks and impacts be demanded to assess, including mainly the likelihood of the risk occurring and its potential impact. The former is to determine the probability and frequency of occurrence of the risk and the latter is to determine the

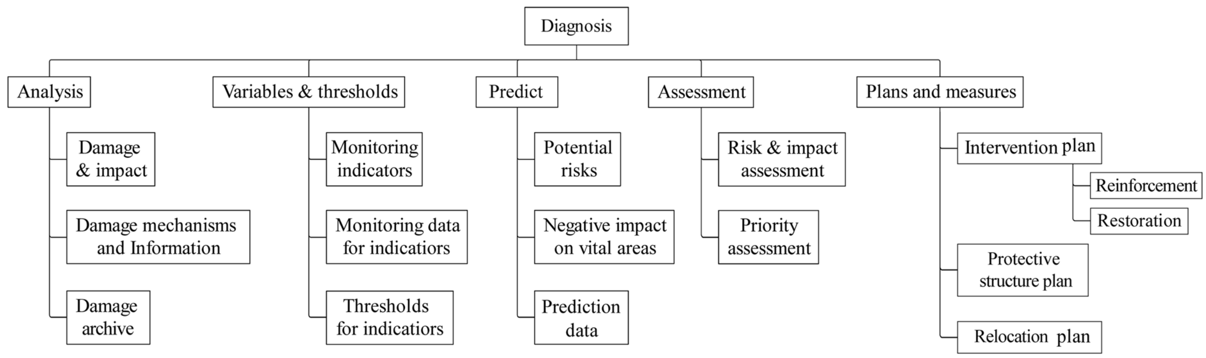

Fig. 2 Diagnosis of the digital twin-based health management

negative impact of the risk on the relevant part [43, 66]. 3D modelling software such as SOLIDWORKS, CATIA, 3D MAX, Pro/E and AutoCAD, reverse modeling tools such as laser scanning, LiDAR scanner and Kinect sensor, and some advanced technologies such as VR, AR, and MR were widely used in the creation of digital twins, and combined with tools such as ANSYS, ABAQUS and Hypermesh, dynamic mathematical approximation simulation and simulation analysis on digital twins are carried out for virtual simulation and prediction[67, 68]. In this way, prioritize the implementation of treatment measures for the various risk parts of movable wooden artifacts and develop a rational and efficient treatment plan.

Treatment

Intervention, protective structure, and relocation are three important forms of treatment for movable wooden artifacts, and the intervention is divided into reinforcement and restoration. Reinforcement are measures to support or strengthen structures or components that are unsafe in order to return them to a safe condition [69–71]. Measures such as grouting, repointing [32, 33, 72], coating [29, 31] or structural reinforcement [73, 74] are undertaken to a structure or its components when prevention has not been effective in solving the problem. These measures are commonly used on heritage and therefore attention should be paid to avoid new damage due to redistribution of stresses. For protective substances such as coatings and grouts applied to a surface or injected to strengthen a damaged section, the feasibility of protective materials should be considered, such as avoiding any damage to the original fabric [69]. Restoration most frequently involves rectifying components that are deformed, displaced or collapsed, repairing damaged elements, removing additions that have been assessed as inappropriate, repair or replacement of damaged and key missing components, and returning a structure to a stable condition [69, 73, 74]. Restoration should, as far as possible, preserve the structures. Protective structure is a preventive measure to eliminate natural or man-made factors that cause damage to heritage sites and helps to avoid or reduce direct interventions on heritage sites, including the installation of protective facilities and the erection of protective shelters on the sites. If the natural environment changes or irresistible factors, movable wooden artifacts are difficult to preserve in situ, relocation is a more appropriate method of protection, but special attention needs to be paid to the relocation of the new site environment should be as similar as possible to the environmental characteristics before the relocation [75, 76]. Environmental remediation refers to the adjustment, removal or replacement of movable wooden artifacts around the geographical environment and occurrence environment of unfavorable facilities, the removal of factors that may cause disasters, to stop production and social activities that may affect the safety of heritages, to prevent damage to heritages caused by environmental pollution [69, 77]. Different types of damage to movable wooden artifacts can be treated in an appropriate way, and the principles of selection should ensure that the original appearance and characteristics of the heritages as far as possible. In addition, the ease of treatment, high feasibility, low cost, and short treatment period should also be taken into consideration.

As shown in Fig. 3, after identifying the important areas to be treated and their priorities, the specific treatment plan is refined while following the treatment principles. To determine treatment methods, the digital twins of movable wooden artifact was built and treated on the virtual platform with treatment plan, which produces virtual treatment data saved in historical data. The treatment assessments are carried out, including an assessment of treatment effectiveness, an assessment of treatment risk, an assessment of the impact on the relevant parts, and an assessment of costs and benefits. When the results of the treatment and assessment of the digital twins are reliable,

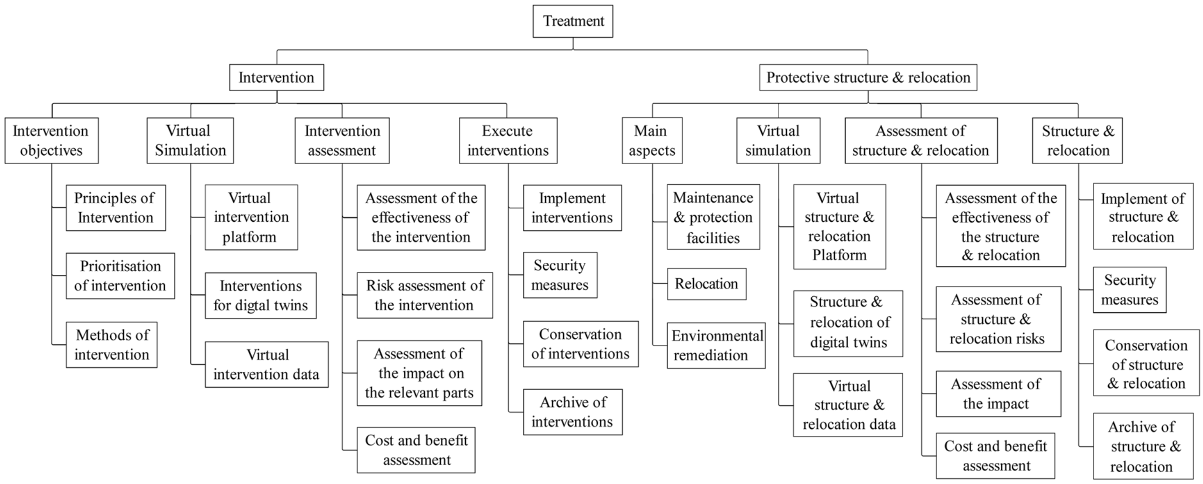

Fig. 3 Treatment of the digital twin-based health management

the actual treatment of movable wooden artifacts is then carried out with security measures. It is also vital to take good maintenance after treatment and to keep treatment data in the treatment archive.

Feedback

As the final stage of health management for movable wooden artifacts, the feedback stage involves the assessment and revision of the effectiveness of the treatment, as well as the generation of historical data that is synchronized to the database and the various stages of health management, as shown in Fig. 4.

The assessment about the effectiveness of the treatment, consisting of the effectiveness of intervention, protective structure, relocation, and the assessment of diseases, is the first step in the feedback phase. The diseases involved in movable wooden artifacts should be assessed in three areas: the types and distribution of diseases, the effectiveness of diseases treatment and the creation of diseases archive. At the same time, with the monitoring equipment monitoring the indicators, the assessment is updated in real time. Based on the monitoring data and assessment data, the digital twins continues to be simulated on the virtual platform during the assessment, through which inappropriate treatment measures are detected in time. When risks are identified and alerts are generated, appropriate reviews and adaptive treatment revisions are made to mitigate the impact of the risks. In addition, timely storage of revised data and assessment of the results of treatment revisions make the database richer and more reliable. Such assessment and revisions make it easier to identify successful treatments and to generate historical data

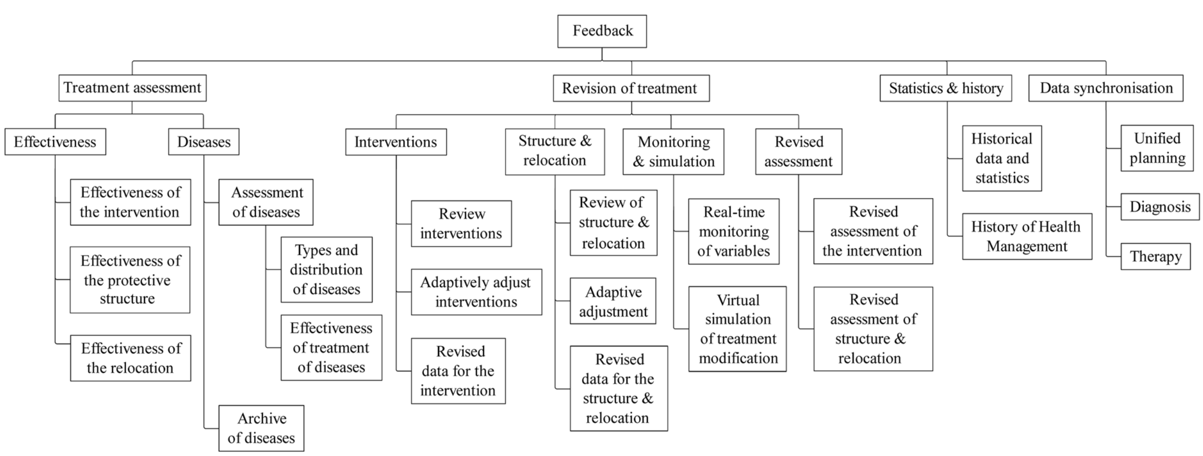

Fig. 4 Feedback of the digital twin-based health management

and a complete history of health management of movable wooden artifacts [10].

As shown in Fig. 5, this digital twin-based health management method for movable wooden artifacts has the advantage of universal applicability, but the specific details still should be adapted to the specific application scenarios. In addition, this health management method can be viewed as data transfer and continuous cycle of the four stages including overall planning, diagnosis, treatment, and feedback.

Result and discussion

In 1974, after more than 700 years buried in the marine clay off Quanzhou Bay (24°37N, 118°37E), the Quanzhou ship was retrieved from the seabed and has been preserved at the Quanzhou Maritime Museum ever since [78]. The structurally intact ancient wooden ship on the seabed carried important historical, archaeological, social, and scientific information. The challenges during the conservation of the Quanzhou Ship were mainly the non-uniform degradation of the wood and the seasonal variation of relative humidity in the museum [79]. From a conservation or structural perspective, ancient wood differed from modern wood in that it has been degraded by various irreversible changes in physical, chemical and biological processes in the marine environment [80]. As a result of uncontrolled water-absorption process, ancient wood was subject to slumping, shrinkage, deformation and surface distortion (twisting, warping, cracking and splitting), disintegration, precipitation of salts and corrosion products [81]. These changes resulted in a very porous material and the formation of cavities and cracks causes a significant loss of mechanical strength. In addition, processes such as shrinkage and warping could also lead to further localized deformation and subsidence of the wooden ship, especially in the stern.

The Quanzhou ship is a typical representative of movable wooden artefacts, and this section integrates the digital twin into the monitoring and health management of the Quanzhou ship, specifically analyzing several important aspects of health management, such as the five-dimensional model of the digital twin, the data interaction, the digital twin process, the identification and assessment of risks, and detailed process of preventive conservation of the stern based on the digital twin.

A digital twin five-dimensional model of the Quanzhou Ship

The five-dimensional model of the digital twin, including physical entities, virtual entities, twin data, services, and the connections between the components [14, 82], is applied to the Quanzhou Ship [78], establishing a five-dimensional model of the digital twin of the Quanzhou Ship, as shown in Fig. 6.

The physical entity, consisting of the various components of the Quanzhou Ship and the deployed sensors, serves as the foundation for digital twin five-dimensional model of the Quanzhou Ship [83], including the sensor acquisition equipment and its acquisition of data. The establishment of the digital twin five-dimensional model is based on the accurate analysis and effective maintenance of the physical entity [14, 84].

The virtual entity, also known as digital twins, that is the core layer of the digital twin five-dimensional model of the Quanzhou Ship is built on the virtual platform by abstractly describing the various elements of the physical entity of the Quanzhou Ship [14], including geometric model, physical model, behavioral model and rule model [14, 84, 85]. Advanced digital tools were used to provide a more detailed knowledge of the Quanzhou ship and to track its current condition for future comparative analysis. A laser scanner survey was performed aiming at obtaining high-resolution spatial data for accurate geometrical representations [86, 87]. With the assistance of this powerful digital tool, a valuable reference 3D model featuring 2641995 points, and stern of the model featuring 42161 points and carrying precise volumes of information of the ship was obtained and herein exploited to build the geometry of its digital twins. The software industry, such as Geomagic Studio, is presently focusing on the definition of parametric-based modelling approaches, which enable performing in no time the transition from half-raw survey data (point clouds) to 3D geometrical entities[25, 86]. The point cloud data obtained by laser scanning was processed by the software to obtain a 3D model of the hull. The 3D model was then processed to obtain digital twins of the Quanzhou ship.

The twin data called the driver for the operation of the five-dimensional model is used to effectively connect the physical entities, virtual entities and services of the Quanzhou Ship [88]. The twin data consists of physical entity data, virtual entity data, service data, knowledge base data and their interactive fusion-derived data [84]. The fusion-derived data is obtained after data processing and fusion, reflecting more comprehensive information and enabling information sharing and value addition [85, 89], as shown in Fig. 7.

The connection involves a combination of six connections specifically between the physical entity, virtual entity, service and twin data of the Quanzhou Ship [14], which is used to ensure data interaction and synchronization in operation. At the same time, the data generated by the physical entity, virtual entity and service of the Quanzhou Ship is deposited into the twin data in real time to drive the operation of all three [84, 85].

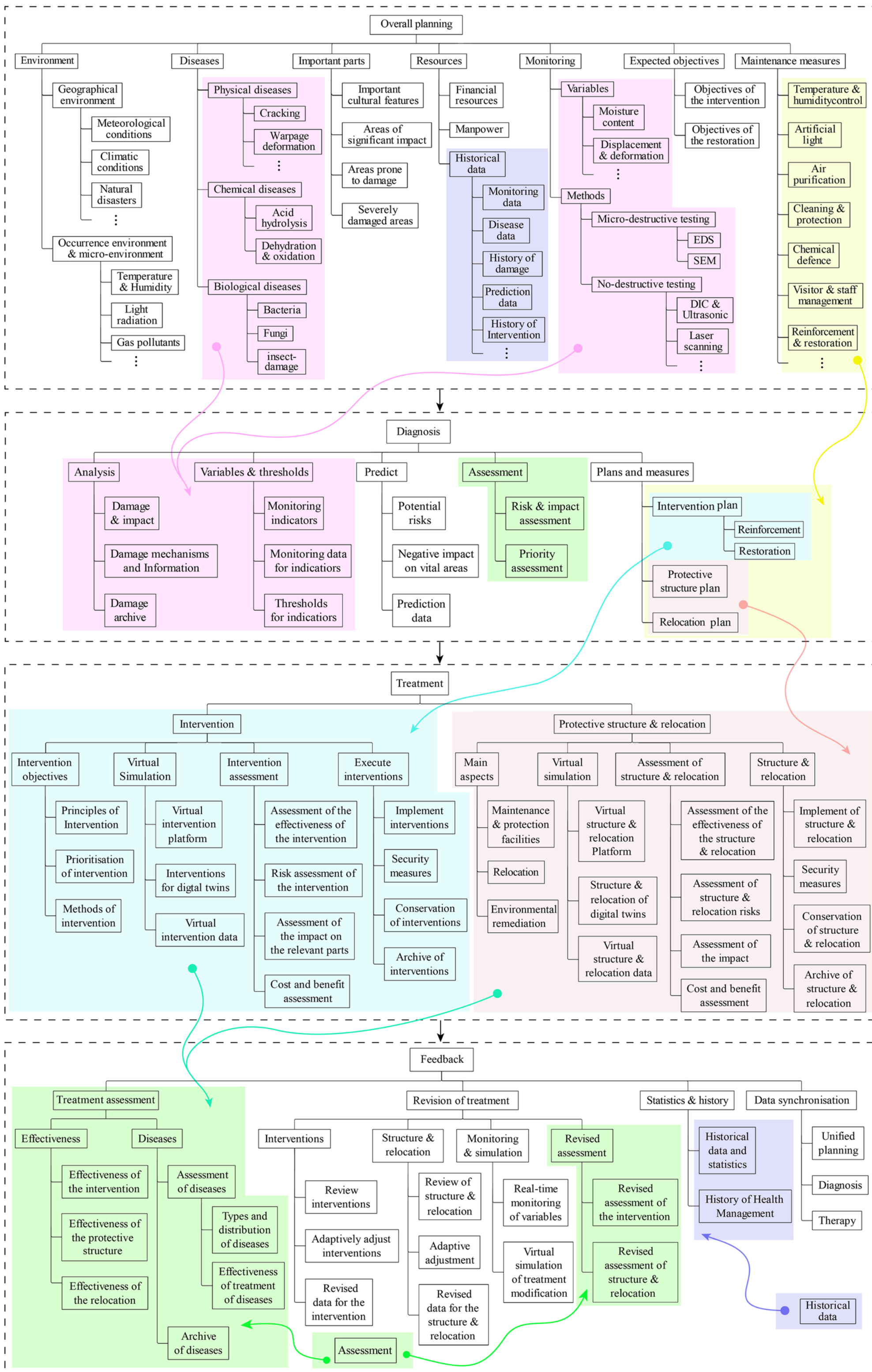

Fig. 5 A digital twin-based method for managing the health of movable wooden artifacts

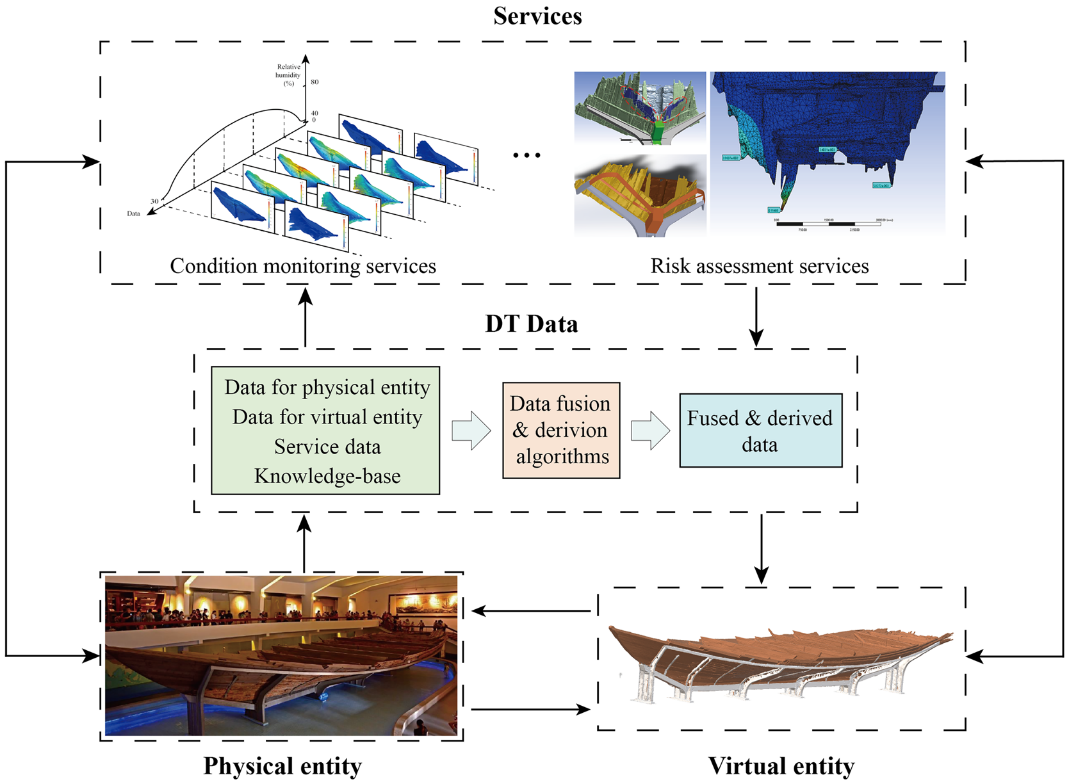

Fig. 6 The five-dimensional model of the digital twin for the Quanzhou Ship

The interaction of the virtual entity (digital twins) with the physical entity, twin data and services are particularly crucial in the preventive conservation of the Quanzhou ship, and the high quality of the interaction directly provides an important reference for the realistic health management of the ship. Firstly, the real-time data collected from the physical entity is transferred to the virtual entity through protocol specifications such as OPC-UA, MQTT and CoAP for updating and correcting various digital models [90]. The data collected, such as the simulation and analysis of the virtual entity, provides the basis for real-time control of the physical entity. Furthermore, through database interfaces such as JDBC and ODBC, the simulation and related data generated by the virtual entity are stored in real time in the twin data. At the same time, the dynamic simulation of the virtual entity is driven by reading the fused data, associated data and lifecycle data of the twin data in real time. Additionally, two-way interaction between virtual entity and services can be achieved through software interfaces such as Socket, RPC, MQSeries, etc. to complete direct command delivery, data sending and receiving, message synchronization, etc. [14, 91].

As the top layer of the digital twin five-dimensional model of the Quanzhou Ship, the service can be divided into three areas including the physical entities, the virtual entities and the managers, completing the monitoring [24], management [19], prediction [92], early warning, treatment [93] and others, which optimizes the various stages in the health management of the Quanzhou Ship and contributes to the health management of the Quanzhou Ship for managers [14].

As shown in Fig. 8, the digital twin framework for Quanzhou Ship is established based on the five-dimensional model of the digital twin. The damage to the physical entity of the Quanzhou Ship and the changes in environmental monitoring indicators will be analyzed and processed through the twin data center and fed back to the virtual entity in real time, which will generate corresponding updates in real time according to the changes in monitoring indicators to achieve a dynamic and continuous mapping of the physical world. The treatment and adjustment of the virtual entity by the relevant personnel will be fed back to the equipment associated with the physical entity through the same path, and the physical entity of the Quanzhou Ship will change in real time, which realizes a two-way real-time mapping of the physical dimension and the information dimension. It provided a new interactive detection and management method for the Quanzhou Ship, and the full-time

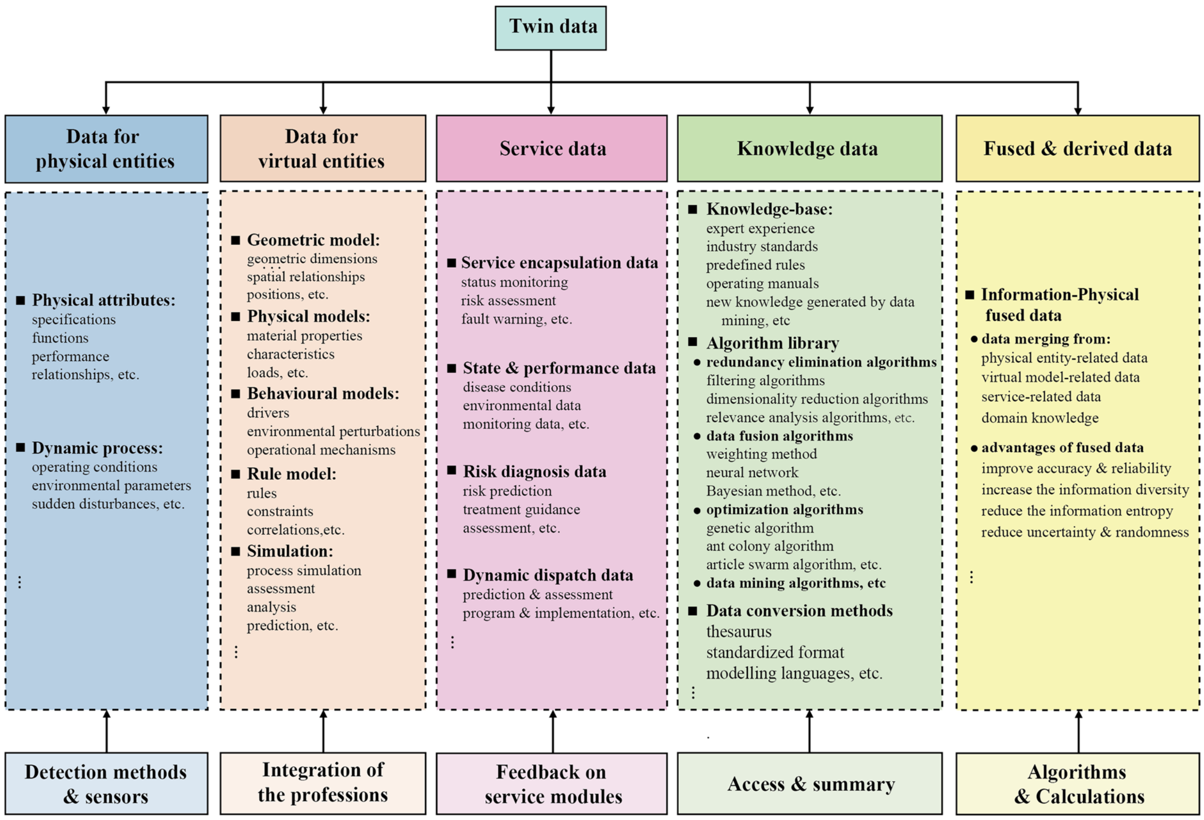

Fig. 7 The components of twin data

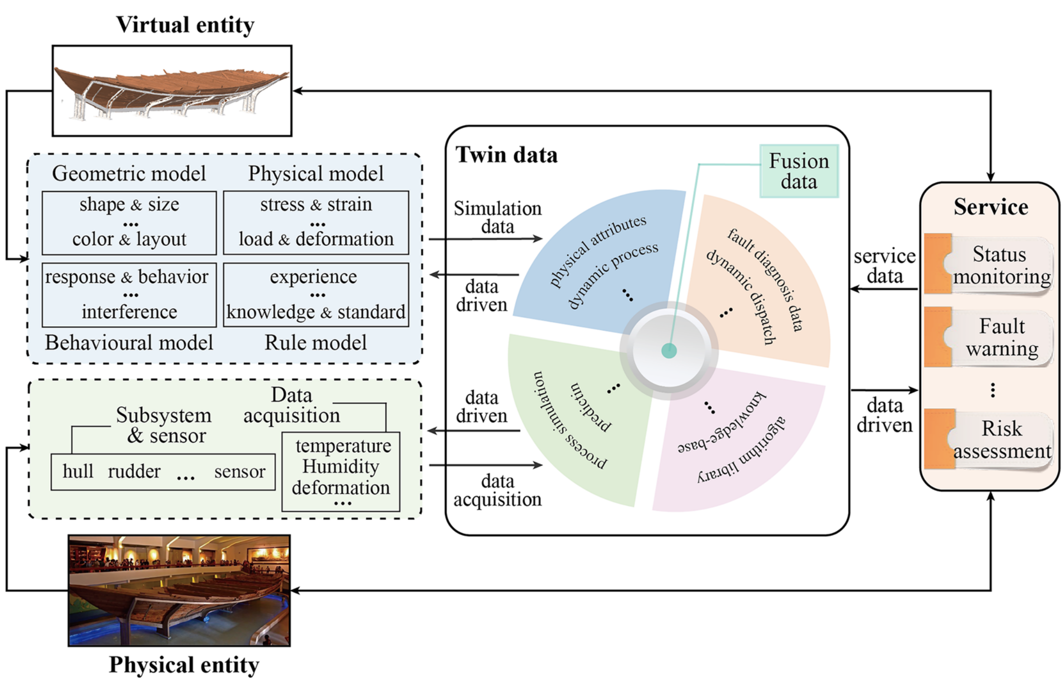

Fig. 8 A digital twin frame for the Quanzhou Ship

situation of the Quanzhou Ship and their surroundings can be grasped in real time through remote monitoring of the digital twins, which can identify potential risks at an early stage and provide an effective basis for the conservation of ancient ship without disrupting exhibitions.

The data interaction and digital twin process of the Quanzhou Ship

In the process of the digital twin of the Quanzhou Ship, the geometrical characteristics, attributes, and environmental data of the Quanzhou Ship are collected through a sensor network distributed around the Quanzhou Ship and specific variables are monitored in real time. Based on monitoring data, the digital twins of the Quanzhou Ship can be created on the virtual platform so that risks can be detected at an early stage, and the preventive and therapeutic measures can be implemented in time. Besides, the digital twins of the Quanzhou Ship can be treated virtually on the virtual platform, providing a reference for the actual treatment based on the virtual treatment results. In addition, the real-time monitoring of specific variables and the assessment of treatment effectiveness is ensured efficiently. The simulation of the digital twins on the virtual platform is accompanied with the whole process of assessment to identify inappropriate treatment measures in time, and adaptive treatment revisions are made to mitigate the effects.

In the process of the digital twin of the Quanzhou Ship, the data input is divided into static data and dynamic data, effectively connecting the physical entity of the Quanzhou Ship, the virtual entity of the Quanzhou Ship and the services. In addition to the obvious short-term benefits, the long-term storage of data monitored through sensors contributes to a better understanding of the disturbance between the artifact and its environment by analyzing the data from different phases and the interaction of various data.

Static data and dynamic data

Static data that does not change with the state of the Quanzhou Ship or its digital twins, as shown in Fig. 9, mainly includes historical data and knowledge data. Although having no direct impact on the health management of the Quanzhou Ship, the static data that acts the subsidiary information is of great importance for the construction of virtual platforms, virtual model building, virtual treatment, and assessment.

Dynamic data refers to the data that changes with the state of the Quanzhou Ship or its digital twins, as shown in Fig. 9, mainly including real-time data and virtual data. These data directly reflect the health state of the Quanzhou Ship and provide the data basis for the treatment measures of the actual Quanzhou Ship. Therefore,

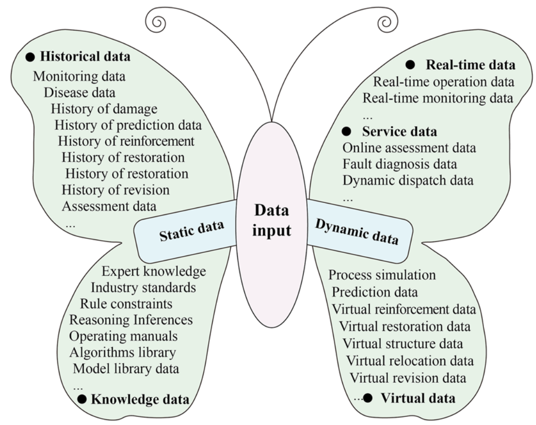

Fig. 9 The composition of static data and dynamic data

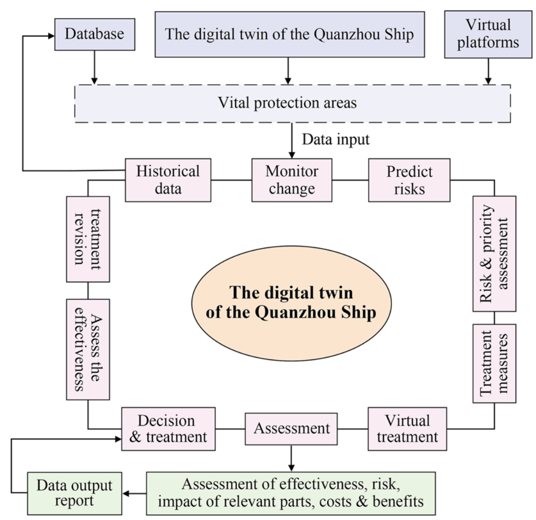

Fig. 10 The digital twin process for the Quanzhou Ship

the dynamic data that is required with high timeliness plays a more important role than static data in health management.

The digital twin process

The main objective of the digital twin is to create digital twins of the Quanzhou Ship with the data monitored on a virtual platform, and the virtual simulations for risk prediction, treatment assessment and treatment revision are carried out to guarantee the health management of the Quanzhou Ship.

As shown in Fig. 10, based on the monitored data, a virtual simulation of the digital twins is performed on the virtual simulation platform to predict the potential risk and to complete risk and priority assessment. Based on the priority of the protected areas, the treatment plans are developed, and virtual treatment is performed on the digital twins of the Quanzhou Ship, whose effectiveness. Risk, impact of the relevant areas and cost–benefit are assessed, and data reports are output to the managers. when the results of output report are highly reliable, the actual treatment can be carried out on the Quanzhou Ship, and the treatment effectiveness is required to be monitored and assessed in real time. The assessment process continues with the simulation of the digital twins on the virtual platform to identify inappropriate treatment in time, and adaptive treatment revisions are made to mitigate the impact of the inappropriate treatment. Historical data can be derived progressively, providing the system with data from field experience to adjust and improve the efficiency of prediction and assessment.

Identification and assessment of risks

Identification of risks

A network of sensors is set up on the Quanzhou Ship to monitor specific variables, and based on the monitored data, potential risks that are deteriorating are identified for preventive conservation. Firstly, during long-term monitoring, a wealth of history data is stored in a database, based on which thresholds for the occurrence of risks are determined. The risk occurring under specific conditions may depend on multiple variables, which makes the thresholds determined by a single parameter or a combination of parameters, and the determined thresholds can be analyzed and simulated for risk on the digital twins, assessing their efficiency and making timely revisions.

Assessment of risks

Risk assessment of the Quanzhou Ship aims to assess the probability, frequency, impact, fraction susceptible and loss of value of risks, and thus to determine the type and priority of preventive conservation. The quantitative approach to assessing risk proposed by Paolini et al. focused on the risk assessment of archaeological sites and suffered from the problem of not explaining the weights of the assessment indicators, which is certainly not applicable to movable wooden artifacts. However, it is worth mentioning the creation of a risk assessment method applicable to Quanzhou Ship through refinement. Considering that the conservation object is movable wooden artefact, the refinement mainly consists of enriching and amending the various assessment criteria, especially the impact of risk, and providing a more refined analysis of the scoring system for each risk criterion [94]. As shown in Fig. 11, the method calculates the level and degree of risk based on four criterions:

$$\text{Risk} = \text{A} \times \text{B} \times \text{C} \times \text{D} \quad (1)$$

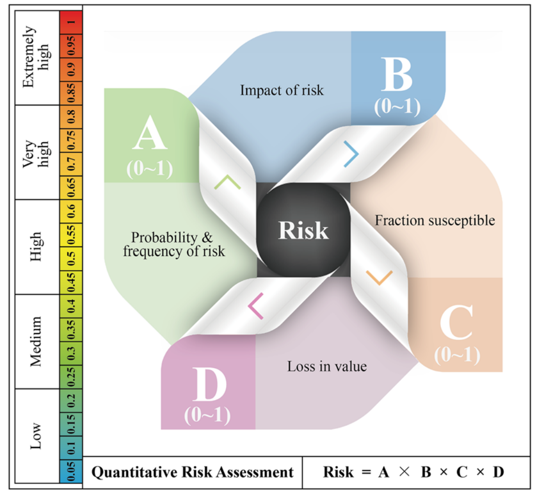

Fig. 11 Quantitative assessment method

A: Probability and frequency of risk happening.
B: Impact of risk (Severity of the risk and the threat level of the risk; Impact of risk on assessed and relevant parts; Speed of spread of risk).
C: Fraction susceptible (Sensitivity and resilience in the face of risk).
D: Loss of value due to risk (Historical value, artistic value, scientific value, etc.).

Criteria A: This criterion is an estimation of the probability that a specific risk will happen. For continuous risk, it is a typical example that deformation and sinking is produced due to its own factors at the stern of Quanzhou ship. There could be deformation and sinking on the stern every moment, but physical effects that attract attention on the stern will not be found every moment. In this case, the question to be asked is 'how soon would damage occur?' For drastic risks and threats such as earthquakes and other objective factors, the question to be asked is 'how often is there an earthquake at that location?' In this way, a score is awarded to A.

Criteria B: As shown in Fig. 12(b), the value of B represents the impact degree of a specific risk, which mainly includes assessment involving four aspects, including the severity of the risk, the threat level of the risk, the impact of the risk on assessed and relevant parts, and speed of spread of risk, and the assessment levels are classified as high, middle, and low. The impact degree of a specific risk is assessed according to the quantitative distribution of the assessment levels of these four aspects, and a score of B is finally assigned.

Criteria C: This criterion includes primarily the sensitivity and resilience of the assessed part exposed at risk. As shown in Fig. 12(c), sensitivity that plays a leading role

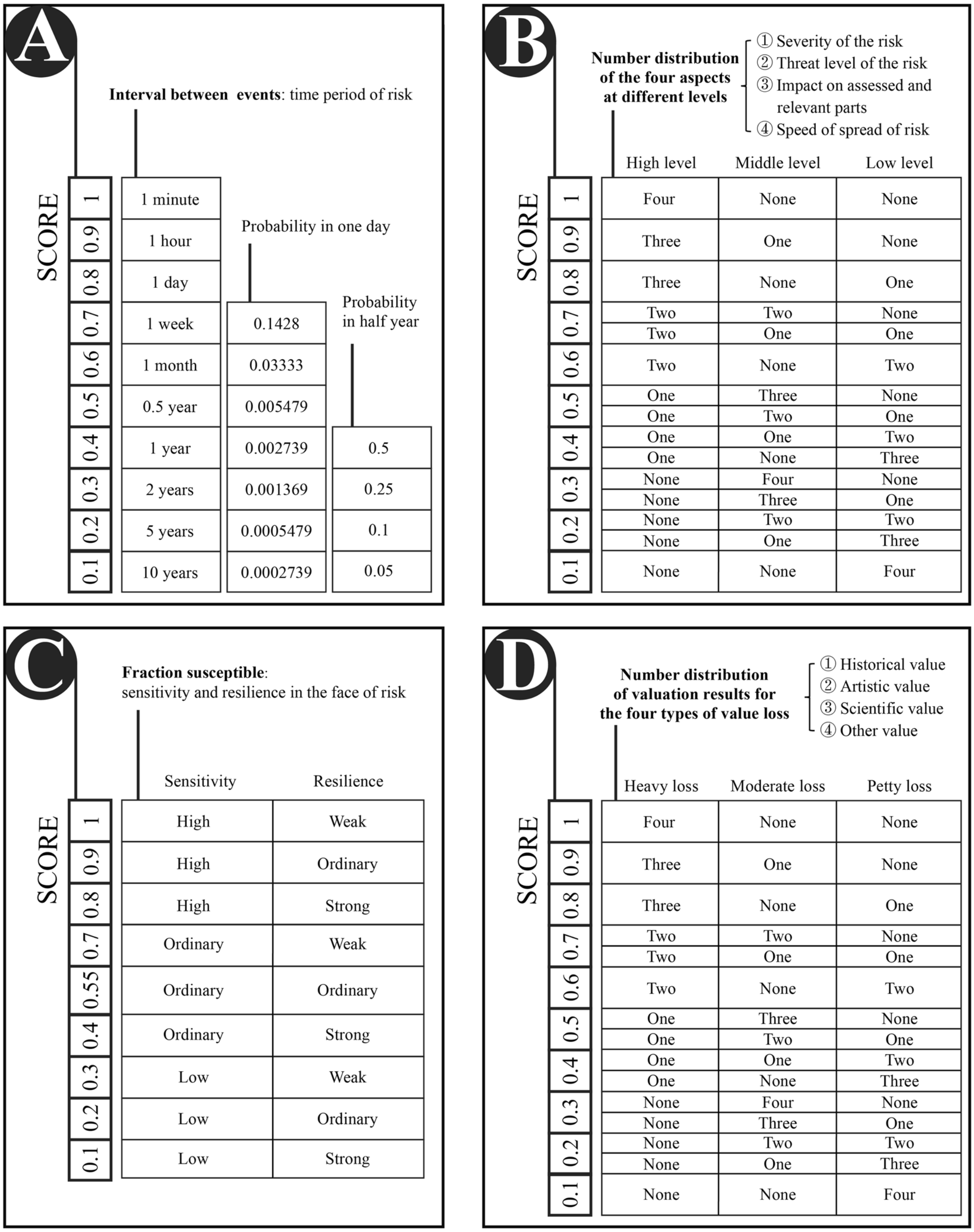

Fig. 12 Scoring system of four criterions

refers to the likelihood of damage to the assessed part in the face of risk, sensitivity of the assessed part and ability to resist risk and protect itself from damage. Resilience refers to the ability of the assessed part to recover from the damage. A score of C is assigned based on the assessment levels of these two aspects.

Criteria D: As shown in Fig. 12(d), the D represents the loss of value of the assessed part if it suffers damage, and the degree of loss of value is the direct effect of a risk on the overall significance of the heritage element or the heritage. The loss of value can be assessed based on the loss of four aspects: historical value, artistic value, scientific value, and other values. The impact of the risk to the assessed part is assessed according to the quantitative distribution of the assessment levels of these four aspects, ultimately assigning a score of D.

Each criterion is assigned a value at risk to obtain a quantitative result according to Eq. (1), and the risk is ranked and managed in a hierarchy based on the quantitative result and higher priority is attached to those with a higher risk level. As shown in Fig. 12, each of these criterions (A, B, C and D) can be assessed based on a scoring system from 0 to 1, and the product of the assessment scores for A, B, C and D represents the level of risk. The advantage of this method is that the scoring system not only enables an assessment of a specific risk, but also provides a basis for comparison of different threats, which makes it easier to compare the impact and prioritization of threats.

Taking the stern of the Quanzhou ship before reinforcement as an example, the risk assessment module assigns values to A, B, C and D and produces the risk value according to Eq. (1). The deformation and sinking of the stern of the Quanzhou ship are continuous risk and the score of 0.92 is assigned for A. The deformation and sinking of the stern have a severity of middle level, a threat of high level, a severe impact on relevant parts such as the hull and a faster speed of spread, and the impact on relevant parts and speed of spread of risk are assessed as high level. Therefore, a score of 0.93 is assigned for B. Due to the non-uniform degradation of the wood and the seasonal variation of relative humidity in the museum, the stern with high sensitivity to risk and poor recovery ability is vulnerable to irreversible damage. So, the score of 0.97 assigned for C. The Quanzhou ship, as a merchant vessel returning from ocean-going trade, has a complete boat shaped and sailing track, and is of very high historical, artistic, and scientific value, hence the score of 0.99 is assigned for D.

$$\begin{aligned}\text{Risk} &= \text{A} \times \text{B} \times \text{C} \times \text{D} \\ &= 0.92 \times 0.93 \times 0.97 \times 0.99 \\ &= 0.82163268\end{aligned} \tag{2}$$

In summary, the value of Risk is 0.82163268 according to Eq. (2). As shown in Fig. 11, deformation and sinking of the stern have a very high risk, which could easily result in further deterioration of the stern damage or even adverse effects on the relevant parts.

Preventive conservation process for the stern based on the digital twin

Risk prediction and analysis through digital twin

As shown in Fig. 13(a), the stern is composed of stern rudder and hull, and their materials are camphor wood and Chinese fir respectively. In order to better protect the stern structure, digital twins of the stern was established to predict potential risks based on the current protection conditions. As shown in Fig. 13(b), the deformation of the digital twins of the stern was simulated under the current protection conditions, and the points A, B, C, and D marked in the figure are four representative points with large deformation. It can be seen from the deformation field of the stern that the farther away from the support end, the greater the deformation. The deformation near the support end is the smallest, about 0.028 mm. Within one meter from the support end, the deformation is about 0.028 to 0.057 mm. But the deformation of the stern has a significant rise in the range of 0.057 to 0.113 mm along with the increase of the distance from the support end. Comparing the deformation of points A, B, C and D, the phenomenon of uneven deformation on the left and right sides of the stern is easy to be found, which is manifested in the larger deformation on the left side and the slight left tilt at the stern. In addition, under the pressure of the stern rudder, the ship plate near the

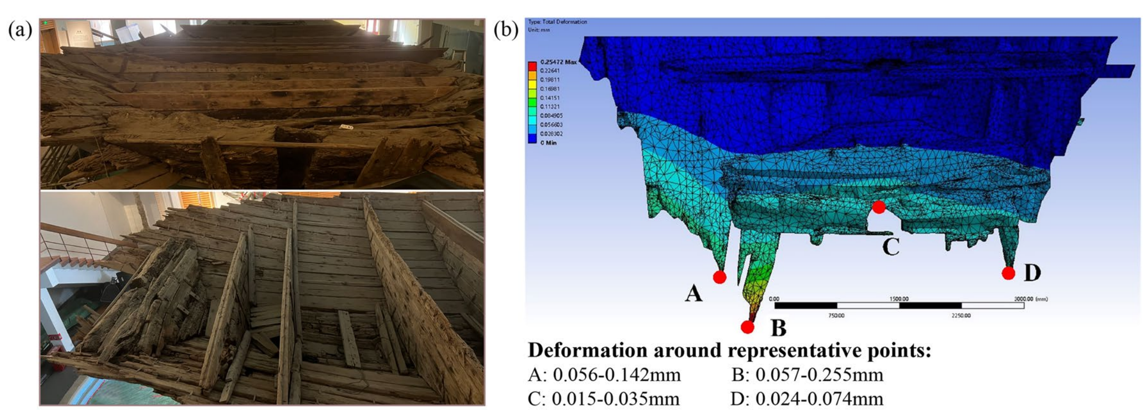

Fig. 13 **a** Actual diagram and **b** deformation of the digital twins of the stern

stern tends to expand to both sides in addition to downward deformation.

Treatment scheme and assessment in the digital twin

The ideal structural interference for shipwreck stern designed by the system is to add support on both sides of the stern (Fig. 14(a)), which based on the prediction results of the digital twins. Figure 14(c) shows the structural intervention for stern with digital twins.

Figure 14(b) shows the deformation prediction of stern after structural intervention. Compared with nonintervention, the maximum deformation of the stern decreased from 0.254 mm to 0.115 mm, and the maximum deformation of the stern rudder decreased from 0.084 mm to 0.002 mm, which effectively prevented the deformation of the hull and the sinking of the stern rudder under the influence of gravity. Due the complexity of the surface of the stern, the reinforcement structure of compound space curved surface was designed (Fig. 14(c)).

Treatment implementation and real-time monitoring of effectiveness

During the structural intervention, several wooden frames were applied to support the stern rudder and its nearby hull to reduce the impact of the intervention process on the stern, As shown in Fig. 15(a). The 3D deformation of the stern was measured using the stereo-digital image correlation (Stereo-DIC) based on binocular vision principle with multiple camera [95–97], as shown in Fig. 15(b), which could better reproduce the true shape of the rudder and calculate the displacement at the corresponding position, with a uniform setting of horizontal to the right and vertical down as the positive direction of displacement. The deformation of the stern was continuous and uniform deformation, which means it did not have displacement mutations. The stern rudder was divided into three areas, A, B and C, and the mean value of the displacement of each area was used to represent their deformation, as shown in Fig. 15(c).

As shown in Fig. 16(a), before the installation of the reinforcing steel frame (before May 27), the mean

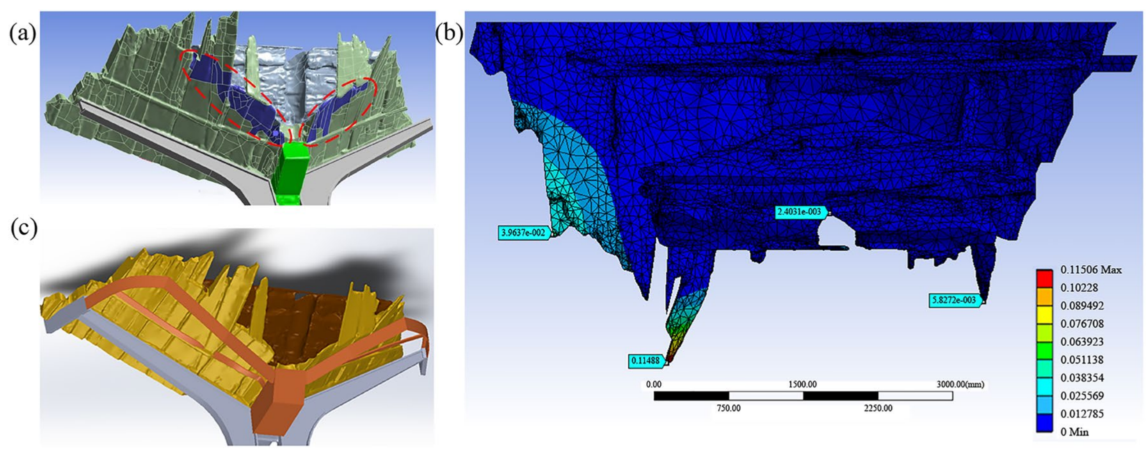

Fig. 14 **a** Area requiring reinforced. **b** Deformation with structural intervention. **c** Reinforcement scheme

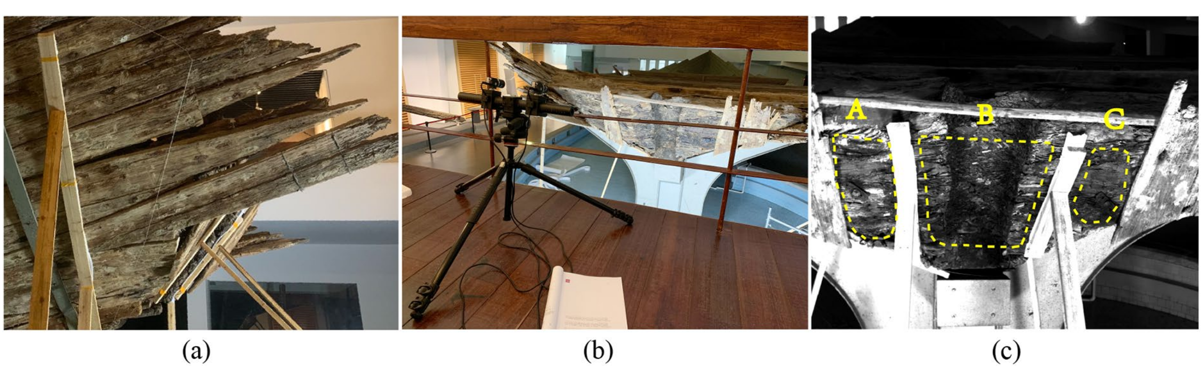

Fig. 15 **a** Wooden frame support. **b** Camera monitoring. **c** Three areas of the stern

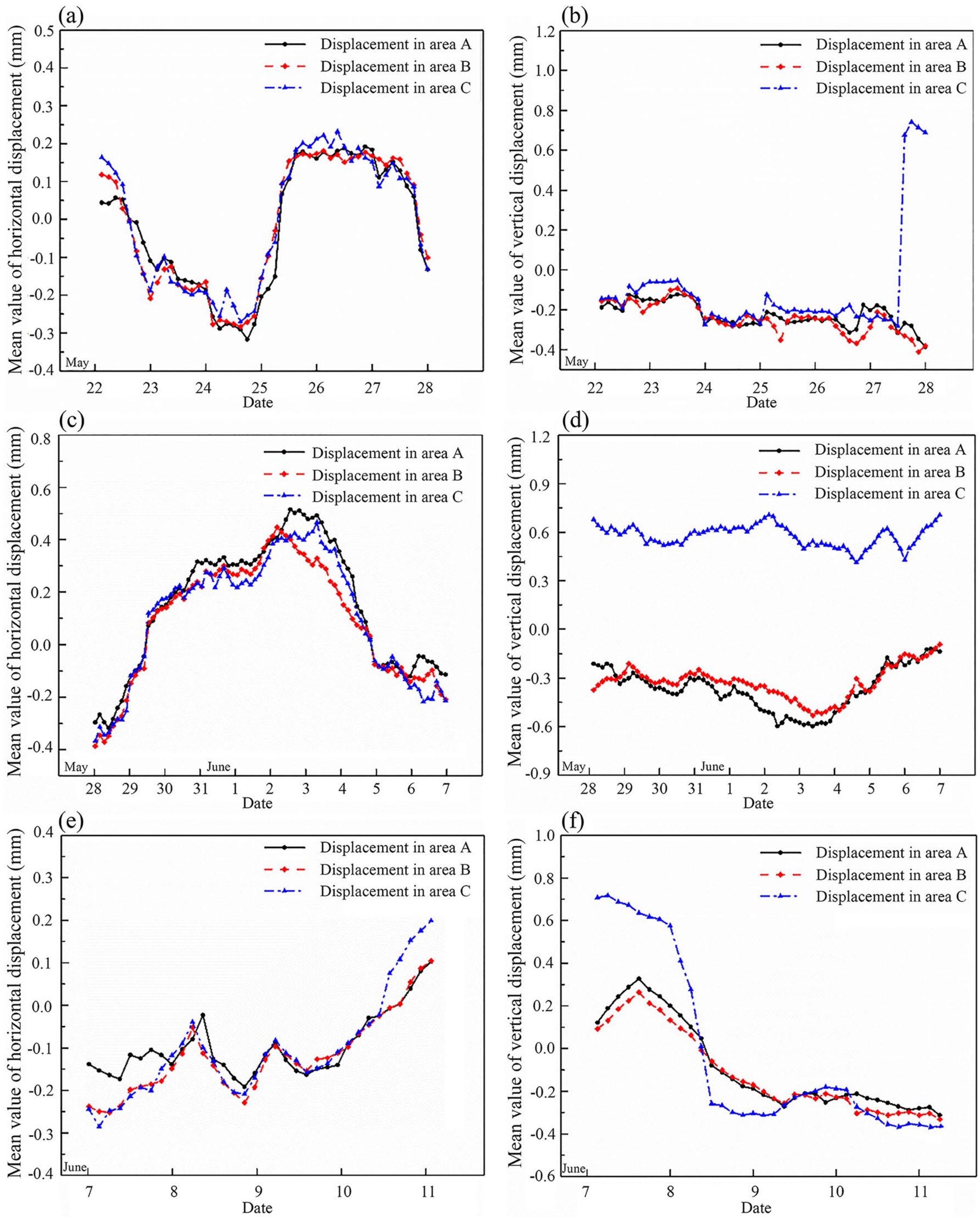

Fig. 16 The deformation displacement of the stern from 22 May to 11 June

horizontal displacement in the three areas of the stern rudder was about − 0.3 to 0.2 mm, and the mean vertical displacement was about − 0.4 to 0 mm. The small outward expansion deformation of the stern in the horizontal direction can be clearly detected, which is consistent with the predicted results of the stern digital twins. The small upward deformation in the vertical direction shows that the supporting timber frame acts as a support, and this deformation facilitates the reinforcement construction without affecting the overall structural stability.

As shown in Fig. 16(a), after the installation of the reinforcing steel frame was completed and the supporting wooden frame was removed (after May 27), the trend of the stern outward expansion was effectively suppressed. As shown in Fig. 16(b), the mean value of displacement in the vertical direction in area C changed abruptly after the installation of the reinforcement frame, and its displacement increased from about − 0.2 mm to 0.7 mm. Then, the left side of the stern was slightly raised, and the right side was relatively lowered, which caused a small clockwise rotation of the stern. This small rotation eliminated the uneven deformation on the left and right sides of the stern predicted by the digital twins, indicating that the reinforcing steel frame started to play an effective supporting role.

As can be seen in Fig. 16(c), after the installation of the reinforcing steel frame and reinforcement, the horizontal displacement to the right was produced in the three areas of the stern, indicating that the left reinforcement also played an effective supporting role, and the uneven deformation on the left and right sides of the stern was further improved, and the right side of the stern fit the reinforcing steel beam and reinforcing rib. more closely. As can be seen in Fig. 16(d), the vertical displacements in the A and B areas of the stern rudder section were about − 0.6 to 0 mm, and the vertical displacements in the C area were about 0.6 to 0.8 mm without obvious fluctuations. The raised left area and the lowered area of the stern further indicated that the uneven deformation situation of the stern was obviously improved and positive effect of the reinforcing steel frame and reinforcing rib.

As shown in Fig. 16(e), the horizontal displacements of the three areas of the stern rudder during this phase were about in the range of − 0.3–0.2 mm, and finally the three areas of the stern produced a more synchronized horizontal displacement to the right. Thus, the trend of stern outward expansion was significantly improved. As shown in Fig. 16(f), the vertical displacements in A and B were about − 0.3 to 0.3 mm, and the vertical displacements in these two areas gradually changed from downward 0.3 mm to stable upward 0.3 mm. In addition, the vertical displacements in C area were about − 0.35 to 0.7 mm, and the displacements in this area gradually changed from downward 0.7 mm to stable upward 0.35 mm. The above phenomena showed that the stern gradually fitted with the reinforcing steel frame and reinforcing rib and the force bearing points of the stern gradually increased. The overall displacement finally showed a stable upward direction compared with that before the reinforcement, which again proved that the reinforcing steel frame and reinforcing rib play an effective supporting role.

After removing the supporting timber frame, the new reinforcing steel frame and reinforcing bars played the role of support and reinforcement, and obviously improved the uneven deformation on both sides of the stern. With the gradual fitting of the stern to the reinforcing steel frame, the force bearing points and areas of the stern gradually increased, the trend of the stern outward expansion was effectively suppressed, and the structural stability of the stern was further enhanced. The monitoring data showed that the stern did not suffer obvious abnormal deformation, the rudder was finally raised by about 0.3 mm and stabilized, and the problem of sinking was also improved, which proved the rationality and effectiveness of the reinforcement scheme.

Due to the support and reinforcement of the steel frame and reinforcing bars, problems such as sinking and deformation of the stern have been significantly improved, which also could be verified in the risk assessment of the reinforced Quanzhou ship's stern. Compared to the unreinforced condition, the four criterions' values for the risk assessment of stern, including A, B, C and D, were greatly reduced. According to the actual condition of the reinforced stern, risk assessment, part of the service that is one of the five dimensional models, assigned a value of 0.35 for A, 0.1 for B, 0.15 for C and 0.1 for D, respectively. The value of Risk was 0.000525 from Eq. (1), and as shown in Fig. 11, risk of the stern was very low, which further validated the effectiveness of the reinforcement scheme.

Conclusion

This paper presents a digital twin-based method to the health management of movable wooden artifacts, which highlights the benefits of implementing the Digital Twin for preventive conservation and a detailed preventive conservation process. By combining the digital twin with real-time data provided by in situ sensors, the digital twin method strengthens the link between the digital model and the realistic model of movable wooden artifacts. This not only enables the analysis and diagnosis of existing damage, but also scenarios that can be simulated through the digital twins. The main advantages of this method compared to current methods supporting preventive conservation policies, such as 3DGIS tools, are the automation of preventive conservation process for movable wooden artifacts by predicting potential risks at an early stage, assessing the magnitude of the risks, identifying possible treatment options and evaluating their impact, monitoring the effects of treatment in real time and providing timely corrections and feedback. Thus, the application of such a method makes a big difference in interaction of information between the digital model and realistic model, which makes it possible to the time taken to obtain the necessary information for decision makers, to delay decay and limit the negative impact of deteriorating factors, to prevent or at least weaken the loss of the artifacts, and to minimize the cost of conservation work by reducing the need for treatment. In short, the method proposed in this paper allows lay managers to conserve movable wooden artifacts more efficiently and conveniently in the health management process, promoting simplicity, efficiency, systematization, and rationalization of preventive conservation.

Another important point is that the important components and process of the digital twin of the Quanzhou ship were presented in detail, specifically proposing a quantitative risk assessment method applicable to the Quanzhou ship to determine the type and priority of preventive conservation. Besides, Applying the digital twin to preventive conservation of the stern, the risk prediction and analysis of the stern, the treatment scheme and assessment, and the implementation and real-time monitoring of the treatment were completed sequentially through digital twin, which finally solved the sinking of the stern, the trend of outward expansion and the uneven deformation on both sides, proving the rationality and effectiveness of the treatment scheme and effectiveness of the digital twin in preventive conservation of movable wooden artefacts.

Abbreviation

Stereo DIC Stereo digital image correlation

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Author contributions

JZ and PW conceived this study and wrote the manuscript; PW prepared all figures; JZ and DZ gave high quality suggestions; LF, HZ, DZ and XM were involved in the project; All authors read and approved the final manuscript.

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Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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