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ORIGINAL ARTICLE

A collaborative machine tool maintenance planning system based on content management technologies

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Abstract From product maintenance and service point of view, high-value sophisticated computer numerical control (CNC) machine tools in modern manufacturing factories play important roles: they are manufacturing equipment, and on the other hand, they are also products supplied by equipment manufacturers. There is a trend that manufacturers are extending their responsibilities to the products use phase to meet customers' requirements for lifetime support and service. To ensure the effective performance and efficient maintenance of high-value machine tools, information and knowledge from their lifecycle should be collected and reused. However, in the research area of product service systems and related computerised maintenance systems, there is a lack of research work on how to integrate knowledge from different stakeholders into the maintenance and service planning process, which is important for modern digital manufacturing systems to reduce machine tools' downtime and improve their working performance. This project proposed a collaborative maintenance planning framework to connect different stakeholders and integrate their knowledge into the maintenance and service process. The potential of advanced content management systems (CMSs), which are widely used non-engineering sectors such as finance, business, publishing and government organisations, has been explored and tested for applications in the manufacturing engineering domain. The research realised that CMSs have several advantages compared with traditional engineering information systems, especially in managing dynamic and unstructured knowledge. A prototype maintenance and service planning system has been developed and evaluated using a real CNC machine tool.

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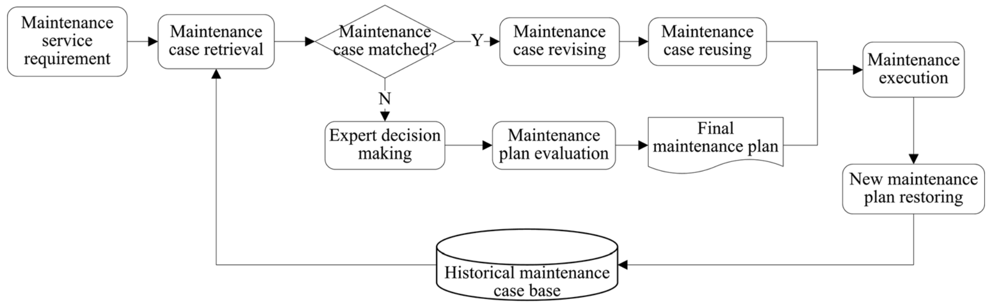
1 Introduction

Industrial maintenance plays important role in keeping or renovating manufacturing equipment to its designed functionality based on the requirements of customers or society [1]. Maintenance tasks include maintenance planning, repairing, calibrating and testing, as well as internal and external collaboration between stakeholders [2]. There are two types of maintenance, i.e. scheduled and unscheduled maintenance. Scheduled maintenance is planned according to machine tool manufacturers' maintenance manuals and current machine tools' production plan. Unscheduled maintenance includes corrective maintenance and predictive maintenance. Corrective maintenance is required when machine tools break down suddenly, and then how to take maintenance actions is planned. Predictive maintenance includes predicting when a machine tool is going to fail and planning maintenance actions in advance with respect to current production situation. When deciding maintenance actions, engineers need to check previous information and knowledge to see if there are similar cases to refer to. Figure 1 illustrates a case-based maintenance planning process, which shows that when maintenance service is required, previous maintenance cases are firstly retrieved to

Fig. 1 A case-based maintenance planning process



see if there are similar cases. If yes, then the retrieved maintenance case needs to be revised to reflect current situation and then a new maintenance plan is generated. Otherwise, a complete new plan needs to be decided by experts. After maintenance execution, the new maintenance plan is stored in the historical maintenance case base which can be reused for future maintenance planning.

Maintenance and service providers are facing the challenges of managing ever-increasing information (with associated knowledge) and complexity in products, systems and processes. Whether and how to manage, share and reuse lessons learnt from previous experiences effectively would affect the effectiveness and efficiency of new maintenance operations. With the development of intelligent manufacturing technologies in Industry 4.0, information systems should reflect and represent real-life production environment which is dynamic with changes in both machine tool conditions and individual parts and assemblies being manufactured. One of the most noticeable research advances in intelligent manufacturing was reported by Li et al. [3, 4]. In their innovative tensor-based tool path generation method, one surface of a complex part may be divided into different subsurfaces for different optimisation targets to achieve global optimised machining. There is a need for information models of real-life dynamic information to support manufacturing systems and equipment maintenance to be integrated with the dynamic product model and machine tool monitoring data.

In the maintenance and service aspect, it has been reported by engineers and managers in industry that learning from previous best practice, methods and tools used and mistakes made is very important [5]. However, currently, there are difficulties in capturing, recording and reusing such valuable knowledge. The investigation and literature survey reported by Essop et al. [5] with respect to knowledge management and lessons learnt during a product's lifecycle were conducted from late 2013 to early 2014 in a leading manufacturing company in the UK. The investigation results have shown that with complex information sharing network globally and across the supply chain, the efficiency and robust of knowledge sharing becomes a challenge. Colleagues "cannot identify what is known within their organizations" [5], and thus, the previous knowledge such as best practises and expertise cannot be easily retrieved and reused. Thus, due to the importance and the difficulty of managing and reusing previous knowledge, it is necessary to develop new tools to improve current situation.

There are already a lot of data and information management systems related to maintenance, such as e-maintenance systems [6], product data management (PDM) systems [7], product lifecycle management (PLM) systems [8] and customer relationship management (CRM) systems [9]. However, the collected data in the systems are not fully utilised to guide following maintenance actions [10]. Besides, different information storage formats may lead to misunderstanding between different systems, which may cause problems such as repeatedly ordering wrong spare parts [2]. Furthermore, information in existing systems is sometimes not up-to-date, e.g. the scheduled maintenance procedures are not updated when equipment is changed. Voice from customers about equipment reliability are gathered but cannot be fed back to the original equipment manufacturers (OEMs), which cannot be used for the improvement of new product development. Moreover, poor communication because of distrust between different stakeholders affects effective collaboration. For example, the scheduling of supporting resources is delayed because of planning information not being shared timely. Most importantly, although lessons learnt are identified and stored in some systems in certain formats, it is often left behind and hard to be retrieved and reused.

Hence, new technologies and tools to be developed should have the ability to resolve the problems in knowledge representation, updating, communication and retrieval. The effects of reusing lessons learnt not only rely on the representation format of knowledge but also relate to a series of organisational networked elements such as individual learning, culture, social, technology, process and infrastructure [11]. Process-based and social-based methods are two of the many methods used to disseminate lessons learnt. Process-based methods allow explicit knowledge to be reflected in organisations' policies, processes and procedures, while social-based methodologies are used for tacit knowledge that is transferred from one person to another [11]. Human factors have impact on the success of the lessons learnt process. Communication is regarded as the most efficient way to enhance learning and reusing knowledge, while most technologies for communicating such as blogs, e-mails or video conferencing are usually separated from projects where the knowledge comes from and the same as technologies for project management with communication tools.

CMSs are being taken as one of the most important information and communication technology (ICT) tools in managing organisation information and knowledge, especially unstructured information and knowledge, in business, media, financial and social applications [12]. Thus, it can potentially solve the above mentioned problems. However, few applications are in managing engineering knowledge for the manufacturing industry. Due to the capability, flexibility and extendibility of CMS, this research aims to implement CMS in a machine tool maintenance knowledge management system, so as to enhance the collaboration between different stakeholders in different organisations, and to improve the efficiency of maintenance planning and scheduling. The objectives of this research are as below:

- Develop a knowledge sharing, learning and reuse framework for machine tool maintenance and service;
- Propose a knowledge mapping methodology for maintenance and service knowledge reuse;
- Identify the capability and feasibility of a CMS (Drupal) for enhancing project management and communication; and
- Develop a collaborative maintenance planning system for different stakeholders distributed geographically.

2 Literature review

Product service system and lessons learnt With the development of product service system (PSS), the equipment for manufacturing systems can be taken as products of the equipment manufacturer. Apart from the benefits of selling the products by the manufacturers, their responsibilities (thus benefits) would be extended to products' whole usable life [13]. In the issues of equipment maintenance and services, information about products' (i.e. the equipment) design and manufacturing phases such as drawings, and the equipment maintenance instructions provided by the manufacturers, can be used in the maintenance decisions making as a starting point. From this point, the equipment, such as computer numerical control (CNC) machine tools, is not only the manufacturing assets in the plant but also the products to be maintained and serviced. The maintenance information and knowledge will not only be used to improve manufacturing performance for the manufacturing company but also be fed back to the equipment manufacturers to improve the reliability and quality in the future. PSS provide services (maintenance included) from the viewpoint of product lifecycle management. PSS enables collaboration between different stakeholders involved in the service process, so as to reduce impact on environment and achieve sustainability [14]. The advantage of this concept will be taken in the design of the proposed framework in this research. Based on the advantages of PSS, stakeholders from the product lifecycle involved in the maintenance actions can collaborate within the same platform. This research combined them together to generate a collaborative maintenance management system with knowledge management capability. However, PSS is still in the development stage far from being mature industrial system due to many unsolved issues such as PSS design methodologies [15], value distribution and network connecstions [16].

Knowledge dissemination and application process What is learnt from past experiences is also called lessons learnt [17]. Information of previous service experiences is reviewed and lessons are obtained, and then lessons are stored in a database system. The experience feedback is a process of "capitalization, processing and exploitation of knowledge" derived from events, both positive and/or negative aspects [17]. The value of the lessons learnt is laid on their dissemination within teams and organisations, as well as the application to new projects, not only recording it [18]. General knowledge management processes have been proposed by previous researchers [19], which include knowledge exploitation, representation, formalisation, adaption, revision and retaining. In terms of knowledge reuse, Potes Ruiz et al. [19] proposed an experience feedback process to reuse knowledge, in which case-based reasoning (CBR) was taken as a problem solving process. Experiences are regarded as cases (including problem description and solution), and then the source case will be retrieved from the database and adapted according to the new problem, then new knowledge obtained from new problems with their solutions are retained into the database for reusing and so forth. In order to carry out this process, different knowledge techniques are implemented including knowledge formalisation, aggregation and retrieving. CBR process is a process which requires engineers to retrieve the knowledge actively and record what they have got during problem solving. For people who lack initiatives, faults still cannot be completely avoided. In respect of product service process for CNC machine tools, the following actions are needed: service request receiving, scheduled maintenance alert, fault diagnosis, service planning (resources, timing), calibration and validation. For service suppliers, their maintenance and service tasks are very heavy, which need engineers to respond quickly and effectively; thus, the right knowledge to be used at each stage is better to be pushed to the right person at the right time [20].

ICT tools for product maintenance and service knowledge management For large especially global companies, geographically distributed activities are very common. Due to CNC machine tools' particularity on its roles—product of machine tool manufacturers as well as manufacturing equipment for manufactured products—their maintenance and service require the collaboration between different stakeholders such as machine tool manufacturers, manufacturing systems, service providers and part suppliers. In order to ensure successful maintenance management, experts and maintenance executors are concerned about collaborative knowledge management because the machine tools' technical problems demand diverse analysis approaches and maintenance actions frequently and regularly [19].

As a product's condition is changing due to either the normal deterioration or the increasing product diversity and complexity requirements from customers within its lifecycle, it has to be controlled using PLM methodologies while keeping the principal of sustainability and environmental protection [21, 22]. Within PLM, the engineering systems used are primarily computer-aided design (CAD) systems to manage product design data, computer-aided engineering (CAE) systems for engineering analysis, and computer-aided manufacturing (CAM) systems to manage manufacturing related information, PDM systems to integrate all product related data and information. CRM systems are used to manage customer related information. enterprise asset management (EAM) systems are implemented to manage the health of manufacturing and business related equipment and assets [23]. In terms of product maintenance and service, there are e-maintenance systems such as computerised maintenance management systems (CMMS) [10] or fault diagnosis assistant systems (FDAS) [24] which are used for managing maintenance and diagnosis-related data and information. Industrial maintenance includes strategy making, planning (scheduled and unscheduled), calibration and testing, management of maintenance actions and internal and external collaboration between different partners [2].

These systems have certain capabilities of storing different formats of contents (such as video, audio or graphic files) to support the product development, manufacturing and maintenance process. However, these contents are badly managed: engineers have difficulties in searching for the right information when needed. Although they roughly know where the information is, they still cannot find the exact place. Lesson learnt, as important industry knowledge and has been paid much attention, even has been stored, is still not effectively used to guide the working process to avoid the same faults happening. Besides, the development of most current systems is based on certain coding languages, which take a long software development cycle. As the rapid changing requirements from customers, it has difficulties for the software vendors to response to the changes quickly.

To avoid this low efficiency phenomenon of searching and reusing knowledge, knowledge push function is developed to provide right information and knowledge to the maintenance engineers to sufficiently improve knowledge sharing and reuse. Knowledge push was also proposed by Ricadela, the chief editor of American "Information Week", when he introduced the knowledge push of Microsoft [25]. Knowledge sharing can be described as either push or pull. Knowledge pull means actively searching and implementing knowledge sources identified to support knowledge users' decision making, while knowledge push means knowledge is disseminated to the user who may need to receive it [20]. This technology has been widely implemented in the management fields such as informatics and marketing, but lack of use in engineering especially in the maintenance process fields [26]. It is a key technology that ensures the application of knowledge management. Wang et al. [27] used knowledge push service technology to make design knowledge available and, thus, to improve the efficiency of knowledge acquisition for product designers. Gagnon [28] also indicated knowledge push as one of the important knowledge dissemination methods (the other two are knowledge pull and exchange). Research has shown that knowledge push has been taken as a very important approach for knowledge dissemination and learning; however, this technology has rarely been implemented in the product maintenance field. Maintenance and service are related to complex knowledge from diagnosis to execution. Engineers spend a lot of time in searching for knowledge for their decision makings; thus, the implementation of knowledge push is expected to significantly improve the efficiency of knowledge sharing and reuse.

Content management systems CMSs together with other systems such as decision support systems, semantic networks and groupware systems are regarded as the same type of knowledge management systems [29]. They can be used to define workflows, track and manage different versions of contents, identify users and their roles and publish contents to repositories to support access, search and retrieval [20]. With the increasing complexity of organisational data (structured and unstructured), CMSs are implemented to cope with these issues. Currently, CMSs are one of the most important ICT tools in managing organisation information and knowledge with strong capability, flexibility and extendibility [12]. CMSs have been widely implemented for business, media, financial and social applications [30]. For example, Clair [12] implemented CMS to deal with issues of metadata management for libraries, in terms of the responsibility, standards, workflows and barriers. Stacciniet et al. [31] developed a collaborative distance learning platform using Open Source CMS. However, there were few attempts to implement CMS in manufacturing industry to manage product and manufacturing data (including lessons learnt and best practices) and process [32]. Knowledge is highly associated with content management, and an organisation's performances, such as productivity, quality, profitability and customers' satisfaction, are significantly impacted by effective content stewardship by using appropriate information technologies. This research implemented an Open Source CMS system (Drupal) in the product maintenance and service applications to manage information and knowledge during the process of operations. The example product used is a typical complex CNC machine tool in advanced manufacturing systems.

3 The role of CNC machine tools in product lifecycle

As illustrated in Fig. 2, a CNC machine tool is a product from the view point of machine tool manufacturers as well as manufacturing equipment in manufacturing systems used to manufacture parts for other products. Different stakeholders' profits in the product life cycle are affected by the machine tool's quality and reliability. Some of the machine tool's subsystems may go wrong, for example, the feed system is one of the most important subsystems of a CNC machine tool, which is responsible for the feeding and positioning of the cutter, and the components in the axle (in the *X*-, *Y*- or *Z*-axes) are important components that affect the function of the machine tool. The axle requires scheduled checks and calibration to ensure precision requirements are met. Sometimes, components in the axle are broken because of vibration, overheat or friction. If there are defects which can be fixed, the axle is normally sent to the machine tool manufacturers to repair or remanufacture it. Otherwise, a new axle will be bought from the manufacturers. Therefore, the maintenance and service of the axle is an activity that links to its whole product lifecycle.

Within the CNC machine tools' lifecycle, machine tool manufacturers, machine tool users, service providers and machine tool part suppliers collaborate with each other. It is the responsibility of machine tool users to operate the machine correctly and enhance productivity when the machine tool is in good condition, as well as request maintenance and service once the machine tool unexpectedly breaks down. Knowledge is needed such as how to operate machine tools safely and correctly to avoid machine tool breakdowns. Machine tool manufacturers gain profits from selling machine tools, as well as from maintenance and services (in the PSS business model); thus, how to design products with good quality and high customer satisfaction is important to them. The quality feedback from machine tool users is important for them to improve the design and manufacturing of new machines. The main role of service providers, either internal maintenance department from machine tool users, maintenance department within machine tool manufacturers, third-party service providers or any combination of the three, is to make maintenance and service plan according to service request, current production schedules as well as the machine monitored data, and to schedule maintenance tasks in line with the production schedules, as well as to execute maintenance work. Thus, the knowledge required by service providers varies because of its complexity, while machine part suppliers will support service suppliers with parts.

The aim of the collaborative maintenance and service framework is to integrate all stakeholders from the machine tool's lifecycle with the knowledge to support the maintenance activities (e.g. maintenance planning and scheduling, resource allocation and maintenance execution), as well as provide knowledge feedback from the maintenance phase to other lifecycle stages. In order to provide knowledge to different stages of maintenance and service, knowledge push capability, by making full use of lessons learnt and best practices from others, is the key. The collaboration network is taking ICT technologies as supportive tools, and the Internet as

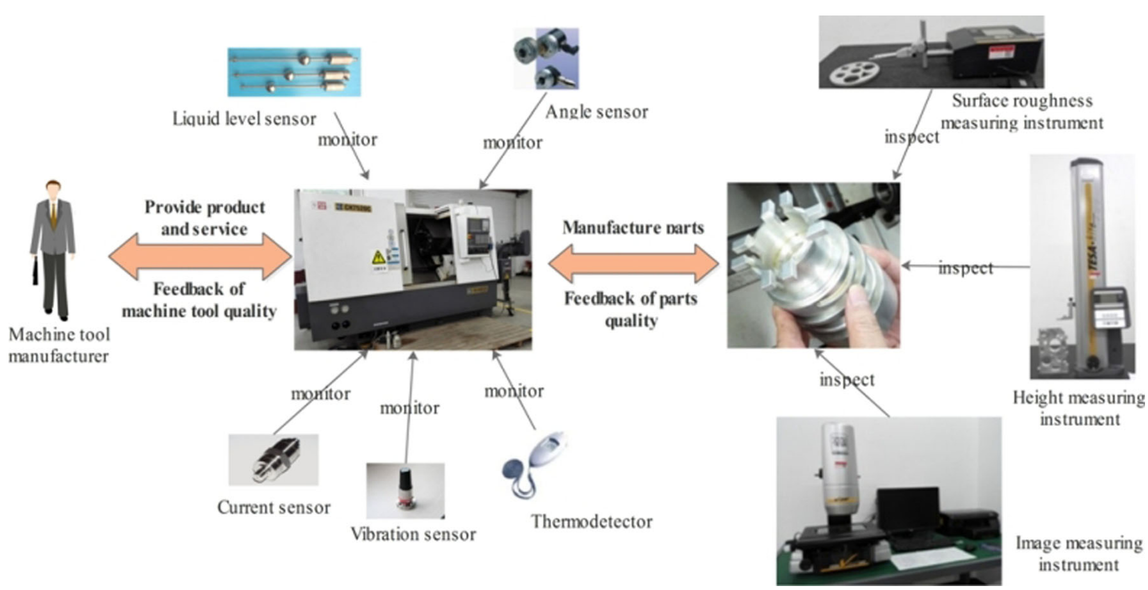


Fig. 2 The role of CNC machine tools in manufacturing systems

information dissemination approach, and provides all the stakeholders with full and real-time information, which can be achieved by integrating with their other internal management systems.

4 The knowledge management framework for machine tool maintenance and service

The collaborative maintenance and service are based on the status of machine tools, and the maintenance and service quality can be improved by using knowledge from all stakeholders in the machine tools' lifecycle. Traditional maintenance planning and fault diagnosis only use the knowledge from the machine tool users in the plant, while scheduled maintenance only relies on the maintenance manuals provided by the machine tool manufacturers. However, in reality, the maintenance schedules may vary because of the changing in the operation conditions and working environment of the machine tools. Furthermore, traditional maintenance planning only includes the prioritisation of maintenance tasks, without providing guidance of maintenance procedures—even there exists maintenance guidance, it is normally not updated.

The implemented system has knowledge push capability to provide knowledge related to each maintenance stage to engineers. As can be seen in Fig. 3, a maintenance process is divided into several stages such as receiving customers' requirements, inspection and diagnosis, scheduling and planning, resource allocation, maintenance execution, evaluation and feedback. Different stakeholders such as machine tool (MT) users, MT manufacturers, part suppliers and service providers will contribute their knowledge related to the maintenance process. For example, MT users request service by expressing their requirements such as no-fault-found, near-to-zero downtime and overall equipment efficiency (OEE), which are the inputs to the maintenance planning process. At the same time, service providers have various maintenance requirements such as maintenance rules, requirements and objectives. When making maintenance and service plan, the knowledge acquired by this stage will contain production knowledge from MT users since the machine tool's service has to be staggered with production plan. Product knowledge and maintenance recommendation knowledge from MT manufacturers are necessary since maintenance work is operated on machine tool itself; the maintenance recommendation is made based on product design parameters and is an important reference for machine maintenance scheduling. Furthermore, previous maintenance cases and related knowledge stored by service providers are important input to the new maintenance task plan to reduce duplicated work.

After the plan has been made, resource allocation acquires information of resources including engineers, spare parts, tooling and consumables, which can be supported by service providers, while the spare parts order will be sent to parts

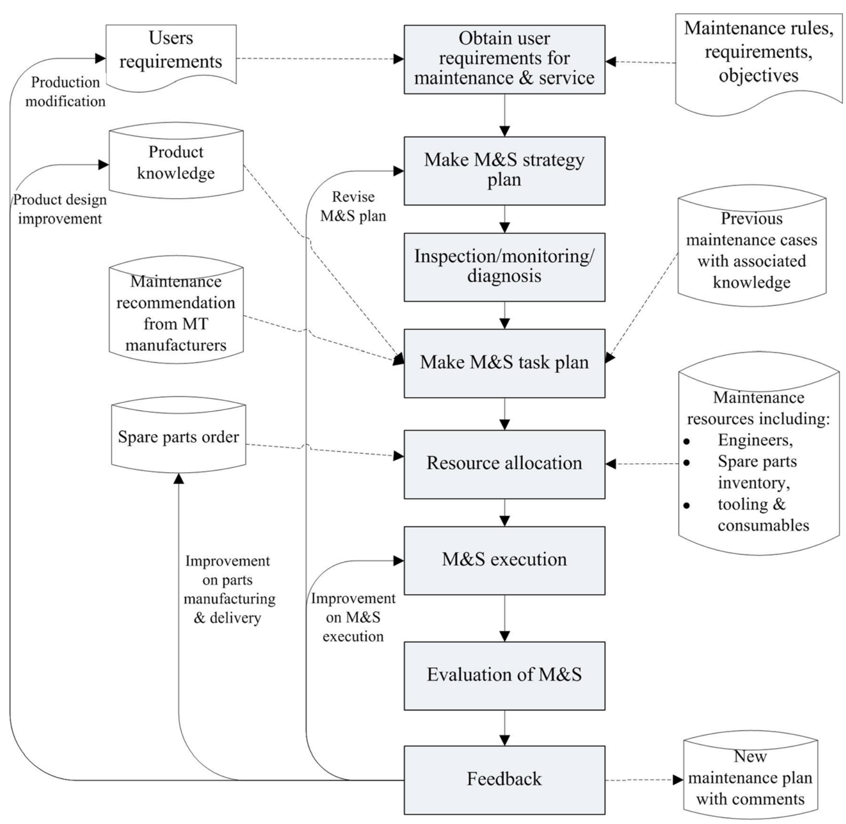


Fig. 3 The proposed framework of knowledge reuse in maintenance and service process

suppliers and the order information will be communicated in time in turn. After the maintenance has been executed and evaluated, the current maintenance case will be reviewed to generate new knowledge, restored as new maintenance plan with comments for service providers. Furthermore, the new maintenance plan can be fed back to the maintenance task planning phase to revise the original plan, resource allocation knowledge can be fed back to the execution phase to improve next resource arrangements and execution efficiency. In addition, some problems such as parts manufacturing, delivery and ordering can be learnt and fed back to parts suppliers for future improvement. If a machine tool is to be found to improve design parameters, then the information will be fed back to the machine tool manufacturers. At last, since maintenance scheduling and planning affect production directly in manufacturing systems, production plan will be modified in line with the maintenance plan so that maintenance requirements from MT users will change accordingly. Figure 3 shows a closed loop maintenance process which adopts a plan-do-check-act (PDCA) cycle.

In terms of using knowledge, each maintenance task corresponds to a maintenance task node, which is the trigger of maintenance workflow. During maintenance workflow, the context of the maintenance task will be analysed, then similar maintenance cases and related resources will be retrieved. This part of knowledge will be pushed to the maintenance task node for engineers to use. This is a dynamic and circulated process for each maintenance task node. The same knowledge retrieval and pushing activities will be executed unless maintenance tasks (including evaluation) are finished. At the same time, during the maintenance experience feedback stage, knowledge will be generated and stored into the database as new knowledge for the next reuse cycle. For example, engineers will be asked to vote if this piece of knowledge is useful. Then, with time going forth, the mostly voted knowledge/lessons learnt will become best practices to the organisation.

Case-based reasoning (CBR) is a methodology that helps progressive learning from experiences for problem solving [19]. A typical CBR can be represented as Fig. 4, which includes five basic cyclical steps:

1. Elaborate the new problem semantically as much as possible;
2. Retrieve the previous similar maintenance cases and linked knowledge from the knowledge base according to the elaborative problem description, and this knowledge will be pushed to engineers who are going to view it;
3. Reuse one similar solution of the retrieved cases, so that a solution to the new maintenance problem is proposed;
4. Revise or adapt the proposed solution considering the new problem's speciality other than the retrieved cases;

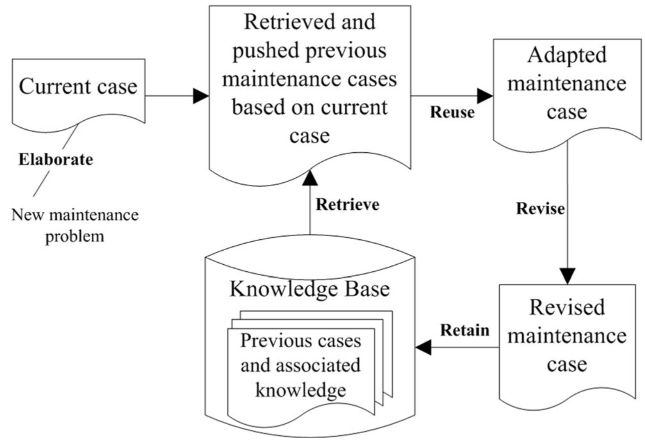


Fig. 4 A typical case-based reasoning cycle for maintenance problem solving

5. Retain the validated solution together with the new problem as another experience to the knowledge base for reusing in the future.

Usually, a case is composed of two parts: the problem and solution. It can be represented as a pair element, denoted as

$$\text{case} = (\text{prb}, \text{sol}(\text{prb}))$$

In particular, during the five steps of the CBR process, the current case can be represented as

$$\text{case}_{\text{cur}} = (\text{prb}_{\text{cur}}, \text{sol}(\text{prb}_{\text{cur}}))$$

while the retrieved previous case can be represented as

$$\text{case}_{\text{pre}} = \left(\text{prb}_{\text{pre}}, \text{sol}\left(\text{prb}_{\text{pre}}\right)\right)$$

However, one of the problems using this method is that similar cases may not get similar results, because of the different deconstruction methodology; thus, there is a need to represent the cases semantically.

The cases are a set of description of maintenance problems which are composed of the problem context, the analysis of the problem and the solution. The semantic description involves different types of maintenance and service knowledge such as product knowledge, service knowledge, resource knowledge, stakeholders' knowledge and constraint knowledge (Fig. 5). Product knowledge provides the basis for service actions, as the maintenance problems occur on certain components in the form of failure mode. It is the input into maintenance process indicating where to maintain. While maintenance and service knowledge includes service type, service cases, service plan, service workflow and lessons learnt. Resource knowledge includes the resources that support maintenance executions such as personnel, spare parts, consumables, tools and technology. Stakeholder knowledge

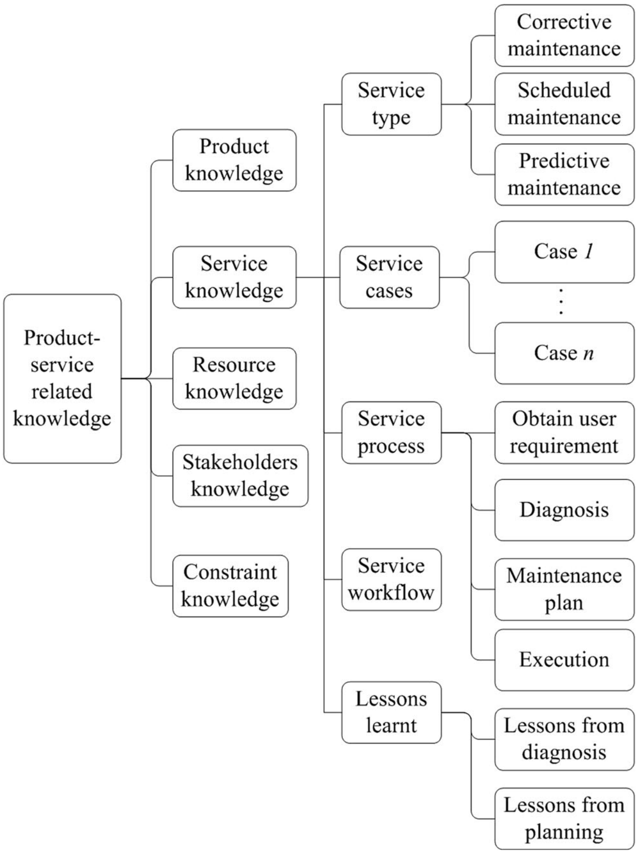


Fig. 5 An example of product-service related knowledge structure

includes the participations in the maintenance process and during the machine tools product lifecycle: the machine tool manufacturers, machine tool users, service providers and parts suppliers. At last, the constraint knowledge covers the business rules and standards, goal of machine tool's performance and management of the maintenance process.

In order to represent knowledge effectively and formally, ontology (semantic knowledge representation), as one of the most popular ways, is selected here. The term "ontology" represents domain entities and their relationships by means of *classes* and *relations*, because knowledge is contained not only in information but also in the relationships among information items [33]. Ontology allows representing the semantics of maintenance knowledge in a formal way that the computer can interpret, which enables the implementation methods of advanced computer science to manage, search and enrich the knowledge [34]. In summary, the proposed system is to improve four aspects of current maintenance management:

1. Collaboration: The proposed framework is going to integrate knowledge from all stakeholders in the machine tool product lifecycle related to the maintenance decision making to fill current gap of not using knowledge from other stakeholders;
2. Knowledge management: Content or document will be classified/structured/managed so as to solve the problem of not finding the right information when needed; latest maintenance execution procedures/steps are to be provided to users to make up for deficiencies of current maintenance management not providing maintenance procedures; then, the mostly used knowledge or lessons learnt can be seen in obvious zone in the system which can be achieved by ranking engineers' votes;
3. Process management: Process management will be enhanced in the system to be developed so that knowledge can be recommended to engineers in certain process stage to reduce engineers time to search for related knowledge; and
4. User interface: A user-friendly interface is to be designed to reduce confusion of users when using the system.

5 Implementation using content management technologies

One of the definitions of CMS is from Patel et al. [29] that a CMS is what allows you to apply management principles to contents. One of the three most widely used CMSs is Drupal (the other two are Wordpress and Joomla) [12]. Drupal can manage web contents and experiences, and is also an enterprise collaboration and social software [35].

There are five layers in Drupal that support information flow [36] (Fig. 6). The data layer is the most basic layer, where data and contents are collected. The next is the modules layer which is responsible for displaying the data and contents in different formats, such as views, calendar and panels, in which blocks and menus are examples of the formats. Besides, blocks and menus also provide links to other module functions as they can be put into a specific region on a page. In order to access and operate these modules or regions, different user roles have to be set with permissions by the user permissions

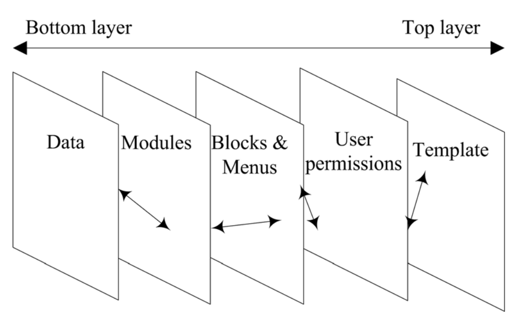


Fig. 6 Five layers of information flow in Drupal

layer. Finally, all these information will be displayed in a site template called theme in Drupal.

As introduced previously, there are three major modules to be developed: Product knowledge management, maintenance and service planning and knowledge sharing. The product knowledge to be used in maintenance planning is the product structure, assembly information, according to which maintenance plans can be made.

5.1 Knowledge of machine tools as products

In order to manage knowledge of machine tools as products, three content types are defined in Drupal: machine tool model content type, machine tool product content type and component content type, within each of them, there is a node hierarchy field, which allows them to be parent/child node of another. In this case, since one machine tool model could have several machine tool products, the machine tool model content type is the parent node of machine tool product content type. Similarly, since a machine tool product may have several components, the component content type is the child node of machine tool product content type. Table 1 shows a list of machine tool products. There are four example machine tool models inside which are CH7520C, XKA5032A, MBE1432 and MGB1432, i.e CNC lathe machining centre, CNC lifting milling machine, semi-automatic grinding machine and high-precision semi-automatic grinding machine, respectively. In the model CH7520C, there are two products CH7520C-2006-01 and CH7520C-2006-02, while there is only one product in XKA5032A machine tool model which is XKA5032A-2006-01. Similarly, both MBE1432 and MGB1432 models have one product, respectively, as well. Inside of each machine tool product, the knowledge used for maintenance are included in the machine tool product content type for service suppliers to check if needed, such as components, product description, maintenance level, location and maintenance manuals.

5.2 Corrective maintenance workflow

The service to complex engineering products has to be requested to the manufacturers by the product users and then assigned to service providers according to requirements and constraints. Then, maintenance plans and executions will be conducted by service providers. During the planning, spare parts, consumables and tools may be ordered from parts or tool suppliers. This process involves various stakeholders to complete; thus, a clear management workflow that allows them to collaborate with each other is necessary.

The workflow is controlled by Maestro module backend in Drupal, which provides a workflow engine to facilitate maintenance process in an organisation. Figure 7 shows a maintenance process from service request until maintenance solution has been given, executed and evaluated (user satisfied with the results), as well as lessons learnt is given by engineers after maintenance execution. Within this process, the assignees (engineers who execute this task) will be asked to view previous lessons learnt to aid this task to be executed successfully. Then, after users are satisfied with the results, lesson learnt creation process starts right away to record what engineers have learnt during this task, then it will be published unless managers approve it. The workflow has a start and end box to control when to start and end; here, it is started by creating a service request by the initiator (whoever initiate it, normally, it is users who operate the machine tools).

There is a series of task types in the workflow template for developers to choose, some of them are used here: Content Type Task allows the assigned user roles to create new content or edit the existing content. The If Task judges the condition and leads workflow to different branches. Interactive Content Type Task assigns a task, such as approve or submit, to a user role that is later tested by the If Task, and the interactive results will affect the workflow branches. Set Process Variable Task takes advantage of user defined process variables, which allows workflow to dynamically assign tasks based on data automatically collected during the workflow. Manual Web

Table 1 List of example machine tool products

Machine tool product number	Description	Maintenance level	Location	Model it belongs to
CH7520C-2006-01	A CNC lathe machining centre with maximum swing diameter of lathe bed 500 mm and maximum turning diameter is 280 mm, it has *C*-axis, was bought in 2006, no. 1	High	1st floor	CH7520C
CH7520C-2006-02	A CNC lathe machining centre, same parameter as above, bought in 2006, no. 2	High	1st floor	CH7520C
XKA5032A-2006-01	A CNC vertical lifting (which “50” stands for) milling machine, with table width 320 mm bought in 2006, no. 1	High	1st floor	XKA5032A
MBE1432-2007-01	A semi-automatic grinding machine with maximum grinding diameter 3200 mm. “14” stands for the type of universal cylindrical grinder. Bought in 2007	Medium	1st floor	MBE1432
MGB1432-2007-01	A semi-automatic grinding machine with high precision, maximum grinding diameter is 320 mm. “14” stands for the type of universal cylindrical grinder. Bought in 2007	Medium	1st floor	MGB1432

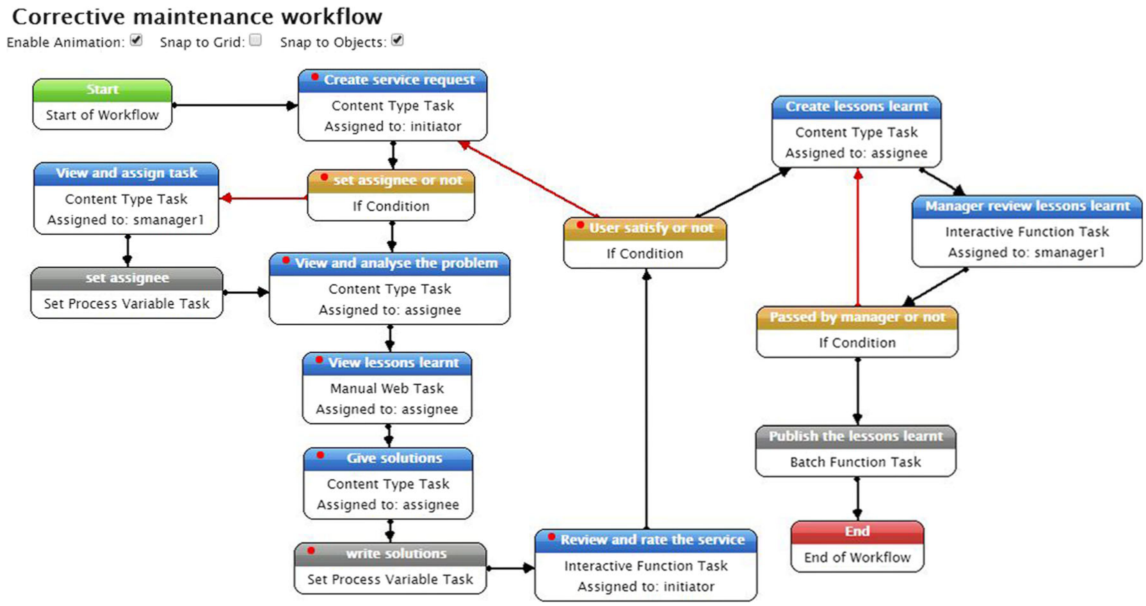


Fig. 7 The workflow control by the backend Maestro module

Task is used to provide an internal URL for engineers to view previous lessons learnt, which makes learning from previous experiences compulsory as a process stage. At last, the Batch Function Task executes function either custom code, Drupal function or other module function automatically; here, a Drupal function maestro_publishNode is used to publish lessons learnt once the manager approves the engineers lessons learnt submission. These boxes are assigned to different users who have certain roles such as initiator, managers and engineers; thus, they can execute different tasks such as request services, assign engineers, response to requests and give feedback.

5.3 Scheduled maintenance planning module

Apart from workflow management for corrective maintenance and service, the scheduled service is also taken into account. The machine tools' particularity has to be taken into account, since the machine tool, on one hand, is a product of the manufacturer and, on the other hand, is a type of machining equipment in manufacturing systems—the machine tool users; thus, the service scheduling should consider knowledge from both sides. With the Calendar Module, engineers can add schedules based on machine tools' machining scheduling and existing service schedule. After schedules being created, they can be displayed with different legends; for example, machining schedules are displayed in red, and service schedules are displayed in green. With different colours, confusion and conflicts can be avoided when creating another schedule. Different views of calendar events can also be generated such as month, week, day and year view (as seen in Fig. 8). Furthermore, either daily maintenance or 3-month maintenance, engineers need maintenance instructions to guide them to do tasks, especially new engineers need to know the steps and which component to disassembly, inspect and assembly; thus, on the system's right region, all the instructions written in book pages are displayed for users to navigate according to their requirements.

5.4 Lessons learnt and knowledge sharing module

The maintenance, repair and service for machine tools are complex processes that require high qualified and experienced engineers to accomplish. However, most of the knowledge such as working methods, working habits and what has been learnt during projects remains in the engineers head (also called tacit knowledge) which is hard to be learnt. In order to improve current practice in knowledge sharing and reuse, it is necessary to manage lessons learnt which is good for both existing and new engineers to avoid faults. Lessons learnt is the knowledge that obtained from previous experiences by engineers who execute the tasks. On one hand, some of the engineers will generalise best practices based on their own experiences. On the other hand, service team members or experts in companies who have rich experiences or are familiar with service executions will conduct period meetings to summarise lessons learnt by reviewing previous experiences. Abundant lessons learnt are generated by different people and stored in different formats such as word, excel forms or databases, and in different places such as PLM system or CAD systems. Poor management of such lessons learnt led to low efficiency to be reused.

The main purpose for managing lessons learnt is to capture tacit knowledge and previous knowledge from engineers in order to learn and reuse it more efficiently in the future. Due to the sophisticated machine tool's

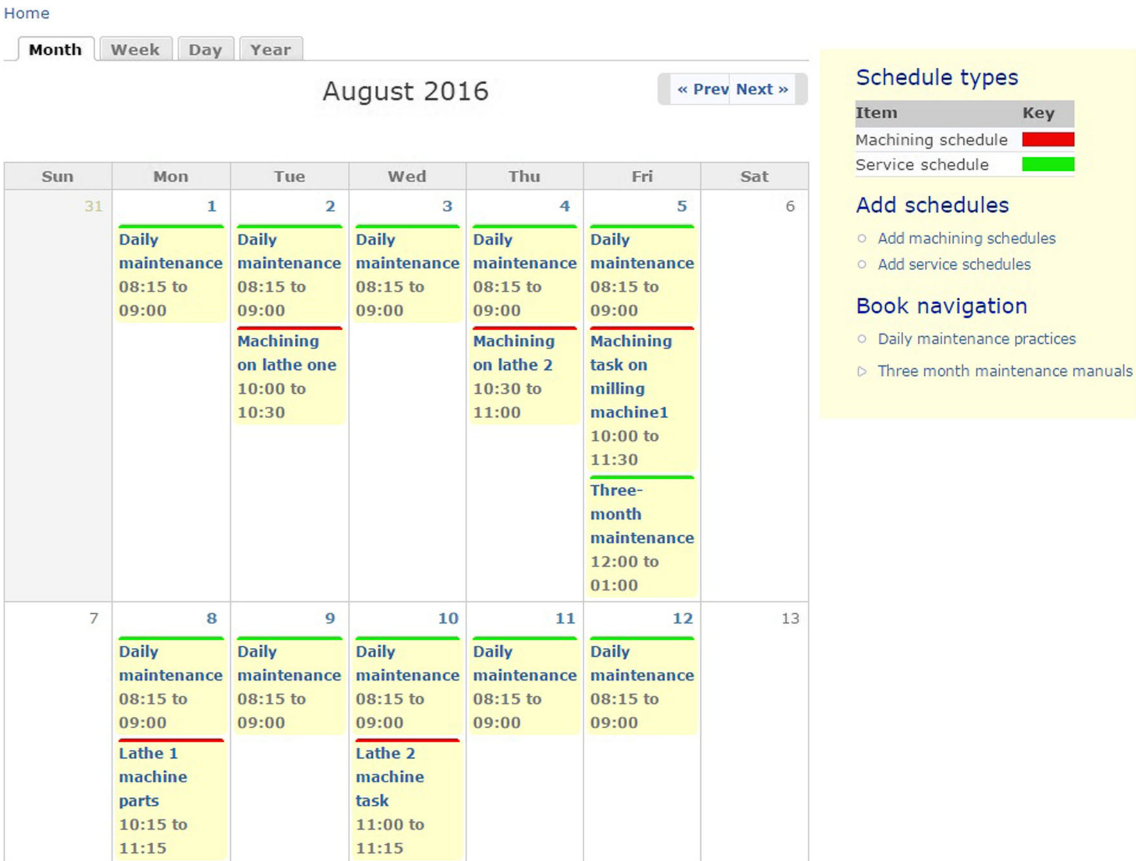


Fig. 8 Maintenance and machining schedule

product structure and complex maintenance process, to have a series of clear classification of knowledge is very useful to push-related knowledge to engineers based on their current requirements.

In Drupal, the Taxonomy Module can help to achieve the classification, and this module provides Term Reference function for content fields to refer to. Figures 9 and 10 show two kinds of taxonomies: lessons learnt and failure mode. Actually, lessons learnt are composed of not only those obtained from maintenance experiences but also those from machining operations, machine tool improvement and resources allocation, since engineers' habits in machining process affect machine's conditions and the resource supplement has impact on maintenance effectiveness and efficiency. Thus, from Fig. 9, the lessons learnt taxonomy contains maintenance operations, machining operations, machine tool improvement and resources, in which, maintenance operations includes three types:preventive maintenance (e.g. daily maintenance and scheduled maintenance), corrective maintenance and predictive maintenance (e.g. condition-based maintenance); machining operations includes daily operations, while machining improvement contains improvement on two aspects: remanufacturing and redesigning; and resources includes spare parts for machine tools, people, tooling and consumables. Lessons learnt need to be checked when diagnosing machine problems, and that is why failure mode taxonomy is necessary. The failure mode includes three aspects: electronic failure, mechanical failure and assistant system failure, and each aspect has its subcategory, for example, electronic failure includes bad line connection to the cable, component parameter drift, performance not stable, false alarm and component failure.

In order to record lessons learnt, a content type named lessons learnt is created by the Content Type Module in Drupal framework (same concept as mentioned in Sect. 5.1), it can also be regarded as a template according to which a piece of lesson learnt content can be recorded: the knowledge obtained such as "dos and don'ts" or "best practices" can be written in the body field. The classification can be achieved by referring predefined taxonomies in the reference field: "related area" and "related failure mode" in the content type; Fig. 11 is the screenshot of creating lessons learnt content in the designed system. Each time when creating a new lessons-learnt, these two types of taxonomies will be referenced and thus be linked to the specific category.

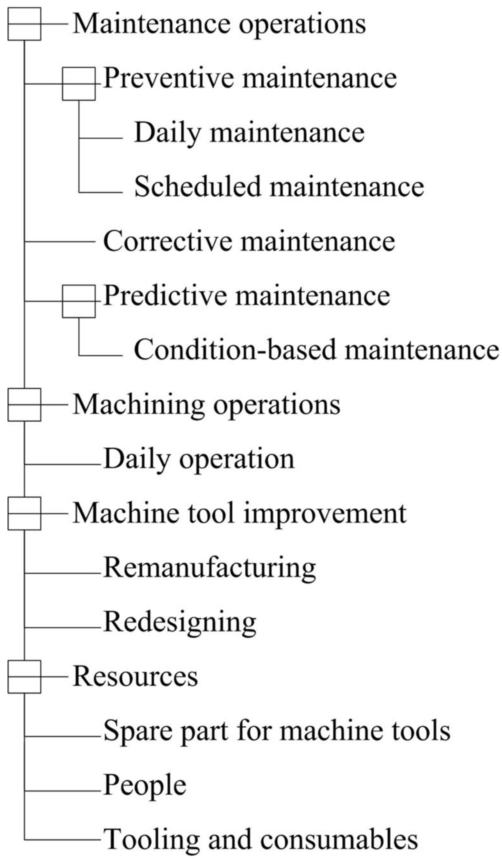


Fig. 9 The taxonomy of lessons learnt

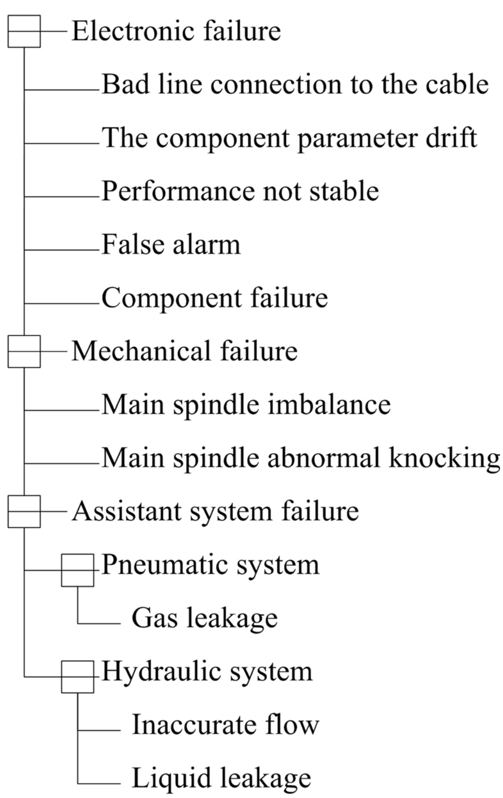


Fig. 10 The taxonomy of failure mode

6 Verification example

CH7520C, manufactured by a Chinese machine tool manufacturer, is a type of high performance CNC machining product with high power and high precision. It can achieve multiple processing such as turning, milling, drilling and tapping in a single setup. The machine tool product is designed with good operation convenience, high strength and dynamic-static stiffness, and with high protection from leakage of gas, oil and electric, as well as advanced design of the mechanical structure, coolant and safety system. It has a *C*-axis and a driving tool which can realise turning and milling compound machining. Some of its primary parameters are as follows: the maximum swing diameter of lathe bed is 500 mm, the maximum turning diameter is 280 mm, the hydraulic clamping diameters 210 (8″), the speed of main spindle ranges from 40 to 4000 r/min, the tool carrier has 12 stations, the minimum angle that the *C*-axis can control for milling is 0.001° and the lathe bed can be 45° slant. This kind of CNC machine tool product has long life during their usage, its machining stability, efficiency needs to be ensured by maintenance and service actions; thus, the efficiency and effectiveness of maintenance and service planning can help to achieve high machining performance.

Table 2 presents an example of the corrective maintenance process for a CNC machine tool type: CH7520C. Tool changer is one important component for CNC machine tool, since each step requires cutting tool to machine parts (lathe or mill). However, sometimes, the tool changer goes wrong such as tool changer cannot stop at a certain station. Due to the complex mechanical and electrical structure of CNC machine tools, the root cause for this problem is not easy to be found. Besides, the definition for the same component in database is different in different cases, since it is recorded by different maintainers. For example, tool changer is also called tool magazine. The right knowledge can be found and applied to the new case through applying the case-based reasoning method and modelling the knowledge semantically.

7 Conclusions

The main research outcomes contributing to new ideas and developments in the field of product service systems and machine tool maintenance are that, firstly, CNC machine tools are high-value manufacturing equipment, while in this project they are regarded as products to be maintained. The maintenance and service plans for the machine tools will also be considered in line with the production schedules of the manufacturing systems in which the machine tools perform manufacturing functions to make other products. The “dual” roles of the machine tools in the unique business context have not been addressed by previous researchers. Secondly, in

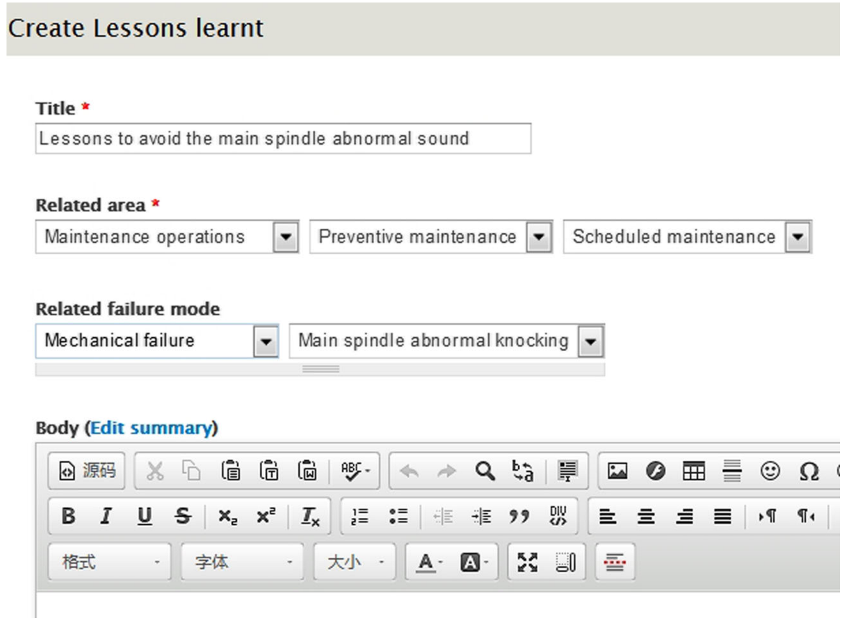


Fig. 11 The interface of creating new lessons learnt

order to solve practical knowledge management issues in industry such as knowledge representation, updating, communication and retrieval. A novel knowledge management framework that connects different stakeholders in real-life business context of machine tool maintenance has been proposed and implemented by example machine tool maintenance cases in collaboration with industry. Promising feedback has been given by engineers that the system could potentially enhance the efficiency and effectiveness of maintenance knowledge retrieval when making maintenance planning decisions. Thirdly, CMSs are widely used in domains such as business, social media and government, but rarely in engineering applications. This research proves the feasibility and advantages of using CMSs in managing engineering

Table 2 An example of corrective maintenance plan for CH7520C

Problem occurred	Analysed problem context	Retrieved relative previous cases and solution			Lessons learnt/previous knowledge	Modified chosen case
		Problem	Analysis	Solution		
Tool changer cannot stop at a certain station	Transmission is normal; Hall element is normal; vibration level is normal	The tool pot in tool magazine cannot clamp cutter	The adjusting nut looses	Rotate the adjusting nut to compress spring on both sides of tool pot to tight chuck pin.	Soft malfunction such as improper adjustment or preferences may lead to hard malfunction which is the hardware faults controlled by drive, hydro pneumatic and mechanical devices. Maintenance engineers follow the principle of "check externally before internally", "mechanical before electrical" and "enquire before acting".	Adjust the pole of magnetic steel to the right direction.
		The tool magazine cannot turn to the right place	Transmission error	Replace a new motor to adjust transmission structure.		
		The tool magazine cannot stop at one station	The pole of magnetic steel was installed oppositely	Adjust the pole of magnetic steel to the right direction.		
		The tool carrier cannot stop at one position	The magnetic steel and the Hall element are not in right height position.	Adjust the position of both magnetic steel and the Hall element.		

knowledge. The advantages of the CMS system Drupal used for system development, compared with traditional engineering information systems, are summarised below:

- It is a platform-based system that can make a new information system quickly. Users can simply configure it rather than do a lot of programming work;
- Many contributed modules can be downloaded and easily extended in functionality, and it is Open Source which allows users to make custom modules as new functions;
- More importantly, it is good at managing dynamic knowledge including lessons learnt, workflows and content publishing, which meet the requirements of machine tool maintenance planning; and
- It is easy for stakeholders to collaborate since it is a web-based system, and it is more flexible and user friendly because of the social media style.

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