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A DESIGN APPROACH BASED ON A CORRELATIVE RELATIONSHIP BETWEEN MAINTAINABILITY AND FUNCTIONAL CONSTRUCTION

PODEJŚCIE PROJEKTOWE OPARTE NA KORELACYJNYM ZWIĄZKU MIĘDZY KONSERWOWALNOŚCIĄ A FUNKCJONALNĄ BUDOWĄ PRODUKTU

As an important quality characteristic, maintainability is the ability of a product to be repaired efficiently and economically. Because it is mainly determined at the design stage, maintainability is mostly affected by the construction of a product. Traditional product design methods put more focus on design for function and production, neglecting design for maintainability, which causes a gap between functional construction design and maintainability design. The delay of maintainability design results in huge costs for design changes and even irrevocable design flaws. Because of the weak relationship between functional construction and maintainability in product design, the influence of maintainability design on the product is limited. To resolve this problem, this paper proposes a design approach considering the relationship between maintainability and functional construction. First, maintainability design factors (MDFs) and functional construction design factors (FCDFs) are defined and classified. Second, based on topology graphic theory, a correlative relationship model is constructed by graphically combining the MDFs and FCDFs into a network diagram. Third, to determine primary design factors, a quantization matrix is developed to perform importance evaluation of the correlative relationship. Finally, a practical case is studied by implementing the proposed approach for the lubrication system of an armoured vehicle. The results validate the effectiveness and feasibility of the approach.

***Keywords**: maintainability design, correlative relationship, functional construction design factors, maintainability design factors.*

Konserwowalność to ważna charakterystyka jakościowa, którą można zdefiniować jako możliwość wydajnej i ekonomicznej naprawy produktu. Ponieważ o konserwowalności produktu decydują głównie wybory dokonane na etapie projektowania, największy wpływ na nią ma budowa produktu. Tradycyjne metody projektowania produktów kładą większy nacisk na projektowanie funkcji i produkcji, zaniedbując projektowanie pod kątem łatwości konserwacji, co powoduje powstanie luki między projektowaniem funkcjonalnej budowy produktu a projektowaniem jego konserwowalności. Opóźnienie etapu projektowania konserwowalności generuje ogromne koszty związane z koniecznością zmian projektu i może nawet prowadzić do nieodwracalnych wad projektowych. Ze względu na słabą zależność między budową funkcjonalną a konserwowalnością w projektowaniu produktu, wpływ projektowania konserwowalności na produkt jest ograniczony. Aby rozwiązać ten problem, w niniejszej pracy zaproponowano podejście projektowe uwzględniające związek między konserwowalnością a budową funkcjonalną wyrobu. Po pierwsze, zdefiniowano i sklasyfikowano czynniki konstrukcyjne (projektowe) dotyczące konserwowalności (MDF) oraz czynniki konstrukcyjne związane z budową funkcjonalną produktu (FCDF). Po drugie, w oparciu o teorię graficznej reprezentacji topologii, zbudowano model zależności korelacyjnych między MDF i FCDF w postaci diagramu sieciowego. Po trzecie, w celu określenia podstawowych czynników konstrukcyjnych, opracowano macierz kwantyzacji, pozwalającą na ocenę ważności relacji korelacyjnych. Wreszcie, przeanalizowano przypadek układu smarowania pojazdu opancerzonego jako przykład zastosowania proponowanego podejścia w praktyce. Wyniki potwierdzają skuteczność omawianego podejścia oraz możliwość jego praktycznego wykorzystania.

***Słowa kluczowe**: projektowanie konserwowalności, związek korelacyjny, czynniki konstrukcyjne dotyczące funkcjonalnej budowy, czynniki konstrukcyjne dotyczące konserwowalności.*

1. Introduction

The quality level determines to a great extent if a product can achieve performance continuously and effectively. Maintainability is an important product quality characteristic that reflects the ability for fast, easy and economical maintenance of a product [12, 20]. Therefore, it is crucial to improve product maintainability, which helps increase the quality level of a product. To achieve this purpose, maintainability design is an effective and feasible way. Recently, a large body of literature has been published on maintainability design.

Repair time is an important quantitative design factor. Several papers have proposed improving maintainability design by the rational planning of repair time. D Khandelwal et al. presented an optimal maintainability strategy for machines by switching the maintainability time and the end time using the optimal periodic control theory [14]. T Dohia et al. proposed a new graphical method to estimate optimal repair-time limits with incomplete repair and discounting [9]. D Zhou et al. proposed an improved method of maintainability allocation based on time characteristic [29]. Y Yin et al. emphasized that arrangement of maintainability times by means of CON and SLK time allocation methods optimizes maintainability frequency and location of maintainability operations [27]. Reasonable allocation for repair time can improve maintainability design and avoid waste. However, these methods mainly concentrate on quantitative aspects, rather than the entire maintainability design.

Maintenance strategy optimization is also a research focus. Zhen, F et al. proposed a modelling method for maintenance design of product level reuse using the approach of house of quality [28]. Liu, W. and Y.U. Shui-Jun established a computer technology-based decision support system to make maintenance decisions quickly and effectively [16]. QS Jia used a simple value function representation for engine maintenance strategy optimization [13]. Peng, W. et al. developed a preventive maintenance decision model for series-parallel systems subject to reliability [21]. A Saxena et al. used a hybrid reasoning architecture based on knowledge of vehicle maintenance to solve vehicle maintenance problems [22]. Bohlin, M., et al. used condition monitoring and dynamic planning to reduce vehicle maintenance [4]. Deloux, E. constructed a specific maintenance policy, which combines a classical condition-based maintenance policy for the system state with a condition monitoring method to track environmental changes [8]. D Mazurkiewicz described the most popular diagnostic systems used in the maintenance of internal transport conveyor systems [19]. Baidya, R. et al. presented strategic maintenance options using the benefits of combined quality function deployment, analysis of hierarchical processes and scepticism technical selection [2]. Maintenance strategy optimization can effectively improve the utilization of maintenance manpower and reduce maintenance time. Research on maintenance strategy is an optimization of maintenance processes, rather than optimization of the product itself.

Several researchers considered maintainability evaluation. Chang, L., et al. performed reliability and maintainability analysis of vehicle anti-tank missiles [5]. Lu, Z. et al. presented maintainability fuzzy evaluation by virtual simulation for aircraft systems [17]. Senivongse T. and A. Puapolthep presented a maintainability assessment model for determining whether a service-oriented system is maintainable by using several metrics [23]. Guo, L performed research on equipment maintainability forecast methods based on support vector machine [11]. Ertas, et al. proposed a diagnostic approach to quantify the maintainability of a commercial off-the-shelf based system by analysing the complexity of the deployment of the system components [10]. Maintainability evaluation is an effective way to analyse the maintainability of a product and feedback suggestions on design changes. However, compared with active design of function and construction, it is a passive feedback design and requires time to complete several design loops.

However, repair time plan, maintenance strategy optimization and maintainability evaluation mainly concern more about later stage of product design. It results in the maintainability design lags to the product design. Thus, the effection of maintainability design requirements to product design is limited.

To resolve the lag issue, more scholars and experts put concerns on optimization of traditional maintainability and product design. Yau, S.S. and J.S. Collofello discussed several factors affecting the software maintainability process and important software quality attributes [26]. Ali, A. et al. presented optimized maintainability design using simulation to analyse the capability of auto part manufacturing production systems[1]. Barabadi, A. et al. used point process models to analyse maintainability of equipment solving the lack of on-site maintainability data [3]. These optimization methods are helpful to maintainability design in early stage. However, these methods are not ideal and comprehensive maintainability design, which cannot significantly improve product maintainability.

To comprehensively design maintainability in early stage, it should be combined with product design. Concurrent engineering, emphasising on maintainability design and traditional functional construction design in parallel, is proposed and developed[24]. D Zhou et al have proposed the use of digital prototyping and virtual environment to achieve parallel engineering[30]. H Zhou et al put forward the view that the maintainability model is integrated into the design process[31]. These methods proposed new insights that maintainability and product functional construction are parallel design.

To consider maintainability design in detail, several studies examine the relationship of maintainability design factors (MDFs). Li, Q. et al. analysed the relationship between maintainability qualitative factors [15]. Luo, X. et al. described the priority of maintainability qualitative factors [18]. Da, X.U. et al. studied qualitative index systems of equipment maintainability [7]. Maintainability and functional construction are closely linked. Yang, Y. presented maintainability-based facility layout optimum design of ship cabins [25]. Although maintainability design factors and their relationships are considered, little of the relationship between maintainability and functional construction is analysed.

Much of the current research on improving product maintainability is related to improvement of some special aspect. In the current approach to product design, function and construction are designed first. Next, maintainability design is considered, which means that maintainability design lags behind function and construction design. This lag results in the requirements of maintainability design having little effect on product design and limiting the improvement of product maintainability. Because product maintainability is mostly determined at the design stage, the cost is high to correct the design, even leading to irrevocable defects if not enough attention is paid to the influence of maintainability design at the initial design stage [6]. Product maintainability focuses on design factors related to function and construction, such as layout and visibility, which indicates that the design of function and construction has a significant effect on maintainability design. Therefore, it is crucial to integrate maintainability, function and construction design at the design stage.

To correlate maintainability and functional construction design, this paper presents a design approach for maintainability and functional construction using three steps: definition and classification, modelling relationship and importance evaluation. The main contributions of this paper is to propose a concurrent design method, which combines maintainability design and product functional construction design through considering the relationship between two types of design factors. Because the design factors contain quantitative and qualitative aspects of maintainability, the approach can comprehensively design maintainability in the early product stage. In addition, modelling the relationship between maintainability design factors and functional construction design factors, the maintainability requirements can affect the functional construction design of products. Finally, to validate the proposed approach, it is applied to the practical case of the lubrication system of an armoured vehicle.

2. Methodology

To bridge the gap between maintainability design and functional construction design, a design approach is proposed; its framework is shown in *Fig. 1*. The approach consists of three parts: Definition and classification of MDFs and functional construction factors (FCDFs), modelling the relationship between MDFs and FCDFs, and importance evaluation of the relationship. First, MDFs and FCDFs are defined and classified into system-level and unit-level. Second, based on topology graphic theory, a correlative relationship model is constructed by combining MDFs and FCDFs into a network diagram. Third, the importance of the correlative relationship is evaluated by a quantization matrix (QM).

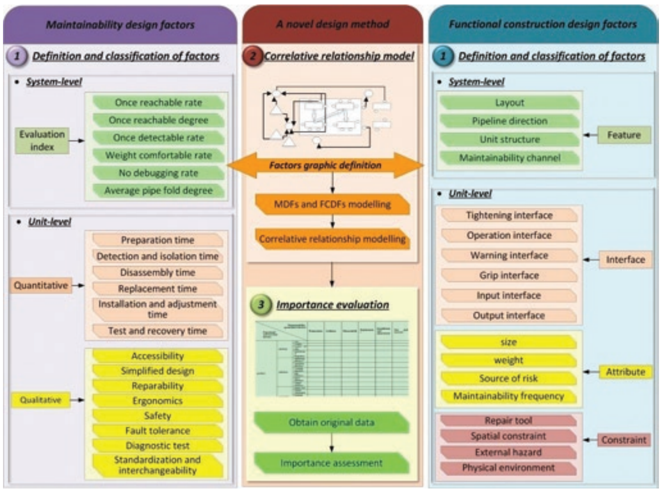


Fig. 1. Framework of the proposed methodology

2.1. Definition and classification of factors

To express product design concepts, design factors are defined and classified into maintainability design factors (MDFs)and functional construction design factors (FCDFs).

2.1.1. Maintainability Design Factors

Different design levels lead to different design considerations. System and unit are two design levels. At the system level, it is more important to consider the overall design of the system, while at the unit level, detailed design factors require more attention. MDFs are divided into two types, system level and unit level.

1) System level

As shown in Table 1, for product system maintainability, six design factors are defined as a system maintainability evaluation index, which are reachability ratio, degree of accessibility, detectable rate, weight comfort rate, free debugging rate and average pipe fold separately.

2) Unit level

Table 1. Definition of system level MDFs

Factors	Definition
Once reachable rate	It refers to the ratio of the number of units, which can be accessed and repaired without taking apart other units (excluding the normally installed cover or door, etc.) by the total number of units in the system.
Once reachable degree	It refers to the power of 1/2 of the product of the value, which is the failure rate of once reachable unit by the total failure rate of the system, and ORR.
Once detectable rate	It refers to the rate of the number of units, which can be monitored and diagnosed without taking apart other units (excluding the normally installed cover or door, etc.) by the total number of units in the system.
Weight comfortable rate	It refers to the rate of the number of units, which do not exceed 16 kg by the total number of units in the system.
No debugging rate	It refers to the rate of the number of units, which do not require debugging after maintenance by the total number of units in the system.
Average pipe fold degree	It refers to the average value of pipe folds in the system. When bending degree is greater than 90°, it is not a fold. When bending degree is less than 90°, it is counted as two folds.

Table 2. Definition of maintainability quantitative factors

Factors	Definition
Preparation time	Time for products to be repaired or maintenance tools to reach a repairable state, not including logistical delays.
Detection and isolation time	Time for fault identification, fault location, determination of fault cause and fault isolation.
Disassembly time	Time for product disassembly.
Replacement time	Time to restore the ability of a faulty product to perform a specified function.
Installation and adjustment time	Time of product installation and adjustment.
Test and recovery time	Time for checking whether a product can perform the specified function after maintenance.

Table 3. Definition of maintainability qualitative factors

Factors	Definition
Accessibility	Accessibility is the degree of difficulty in approaching different components of a product.
Simplified design	Simplified design refers to the simplification of functional construction and maintenance process.
Reparability	Reparability refers to the degree of difficulty in repairing expensive parts and battlefield parts.
Ergonomics	Ergonomics is the study of the relationship of human factors and product maintenance, and how to improve maintenance efficiency, quality and reduce human fatigue.
Maintenance safety	Maintenance safety refers to a design feature, which avoids casualties or damage to products when implementing maintenance.
Errors prevention	Error prevention means to take appropriate measures to avoid or prevent maintenance operation error at the design stage.
Diagnostic test	Diagnostic test means measures or activities taken to find fault cause and location guarantee the performance, characteristics, applicability of a product or system.
Standardization and interchangeability	Standardization is a design feature limiting viable changes to the minimum range under conditions that requirements are met. Interchangeability is a design feature that products can be physically and functionally interchangeable.

According to the traditional maintainability design and analysis method, design factors at the unit-level are divided into two types, quantitative factors and qualitative factors.

Based on maintainability design requirements, the quantitative and qualitative factors are defined and shown separately as Table 2 and Table 3. Quantitative factors are preparation time, detection and isolation time, disassembly time, replacement time, installation and adjustment time, and test and recovery time. Qualitative factors are accessibility, simplified design, reparability, ergonomics, maintenance safety, error prevention, diagnostic test, and standardization and interchangeability.

2.1.2. Functional Construction Design Factors

By analysing the maintenance process, maintenance programme and design process of maintainability, this paper summarizes various design factors of function and construction influencing maintainability. These factors are also divided into system and unit level. There are four design factors at the system level, which are layout, pipeline direction, unit structure and maintenance channel. There are three classes of design factors at the unit level interface class, attribute class and constraint class. More detailed definition and classifications are shown in Table 4.

2.2. Correlative relationship model

To solve the problem of the complex relationship of maintainability and functional construction, a correlative relationship model is built based on topology graphic theory to define the influence relationship.

Topology requires that the geometry or space after a continuous change remains unchanged. Topology takes into account only positional relationships between objects regardless of their shape and size. Topology is a branch of geometry, but it is different from plane geometry and three-dimensional geometry. Plane geometry and three-dimensional geometry are concerned with the positional relationships between points, lines, and planes, and their measurement properties. The length, size, area and volume are irrelevant to topology, which only focuses on the relationship between objects. High system reliability, relative ease to expand and each node linked with multi-points are the advantages of network topology. Considering that modelling method is designed to express relationships, not specific product size and weight, this paper uses network topology as the model basis.

Before model construction, to clearly define the meaning of graphic units and structure the model, elements in the model are defined as shown in Table 5.

To construct the relationship model, there are four steps, as shown in *Fig. 2*: (1) product structure modelling (2) FCDFs modelling (3) MDFs modelling (4) correlative relationship modelling.

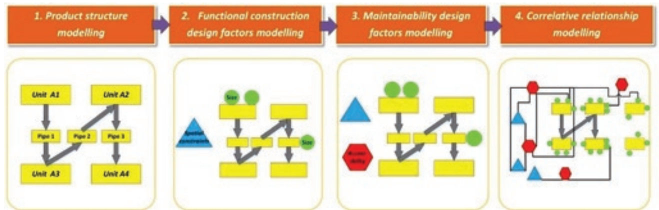


Fig. 2. Framework of modelling the relationship of MDFS and FCDFs

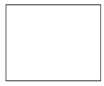
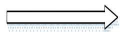
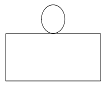
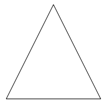
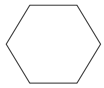
1) Product structure modelling

The first step of modelling the relationship is to analyse the product structure and the exchange of material, energy and information between units. As shown in the first phase of Fig. 2, a product system, which contains four product units and three pipes, and the interaction of the units are described. In the system, four units and three pipes are defined as product units and expressed by solid line rectangles. Each product unit is defined as a line replaceable unit, which indicates the

Table 4. Definition of FCDFs

FCDFs		Specific functional structural factors	Definition
System level	System feature class	Layout	Spatial relationship of product parts in the system.
		Pipeline direction	Line direction of transmission of material, energy and information.
		Unit structure	Types of units making up a system.
		Maintenance channel	A set of paths to pass in the maintenance process.
Unit level	Interface class	Tightening interface	A fixed way of tightening two or more parts to be an entirety.
		Operating interface	Operating port between the user and the device which is convenient for users, detecting electronic and machinery devices.
		Warning interface	Display devices, including warnings, reminders, logos and cautions, used for environmental, safety, operational and technical states, etc.
		Grip interface	Parts, including handles, spreaders and pedals, used for equipment moving and personnel climbing in maintenance process.
		Input interface	Ports used for passing external material, energy and information to the internal system or unit.
		Output interface	Ports used for passing internal material, energy and information to the external system or unit.
	Attribute class	Size	Shape data of the unit or system.
		Weight	Physical quality of the unit or system.
		Source of risk	Features of potential harm to personnel and equipment in the unit.
		Maintenance frequency	Number of repairs over a period of time.
	Constraint class	Repair tool	A set of tools used for maintenance process.
		Spatial constraint	A set of space constraints for maintenance operations in maintenance process.
		External hazard feature	Features of potential harm to personal, devices in the unit or system.
		Space and physical environment	Physical or non-entity environment of the facilities.

Table 5. Definition of model elements

Name	Specific meaning	Graphic definition	Legend
Product unit	Units making up the system	Solid line rectangle	
Virtual unit	External unit associated with the system	Dashed line rectangle	
System level	An entity to complete a function		
Physical relationship	Material and energy flow between units	Double line arrows	
FCDF	System-level and unit level design factors (not included in constraint class)	Solid line circle attached to a rectangle	
	Design factors of constraint class	Solid line triangle	
MDF	System-level and unit level	Solid line hexagon	
Correlative relationship	Associated impact between factors	Solid line	

unit can be replaced when a failure occurs, rather than repairing it after disassembling the whole product system. From the figure, the flow direction of material, energy and information is from unit A1 to unit A4.

2) Functional Construction Design Factors modelling

Nodes are widely used in different fields. In network topography theory a node is the end of any branch in the network or the common node linking two or more branches in a system, representing attributes, design features and interfaces of a product or system. Usually, the node is attached to the edge of a unit or system, showing a subordinate relationship. Nodes can be added according to need and there is no quantitative requirement.

In this model, FCDFs are defined as nodes and represented by solid line circles attached to the target product unit. Because there are many internal and external constraints in maintenance operations, design factors of the constraint class in the model are represented by solid line triangles. As shown in the second phase of *Fig. 2*, the circle marked with size attached to the rectangle indicates the size design factor of that product unit.

3) Maintainability Design Factors modelling

MDFs are modelled and defined as solid line hexagons, which surround the product units to construct a relationship. As shown in the third phase of *Fig. 2*, an MDF, accessibility, is constructed in the model and surrounds the product units.

4) Correlative relationship modelling

The final step to build the model is to construct correlative relationships between MDFs and FCDFs. The relationship is defined and represented by a solid line. Theoretically, if there is a relationship between an MDF and an FCDF, a solid line would connect the two factors. However, a system contains many product units, which means that the model is usually very large and complex, resulting in intricate lines and nodes. Therefore, to make the model more practical and easier to understand, the system usually selects strong relationships and uses nodes in the model. Because the construction of relationships depends on the deep understanding of product design, it is the most important step. As shown in the fourth phase of *Fig. 2*, the relationship is constructed, and the model is completed.

2.3. Importance evaluation

After constructing the model, the relationship between maintainability and functionality can be graphically expressed. To describe more accurately the strength of the relationship and provide effective data to guide design and improve maintainability, an importance evaluation method is developed based on a QM and described as follows.

1) Collection of original data

To obtain original data of the relationship, three data tables are designed and shown as Table 6, Table 7 andTable 8. To quantify the basic relationships, the three tables are filled by experts and designers according to the scoring rule, which uses a scoring method of 9 points. In this rule, 1, 3, 5, 7, 9 points indicate little correlation, a certain correlation, a strong correlation, stronger correlation, the strongest correlation, and 2, 4, 6, 8 are the scaling values of the intermediate states between the two adjacent numerical judgements.

2) Importance evaluation

Step 1: Construct a QM. The collected data from the tables can be abstracted into a QM, keeping the original data position unchanged. a_{ij} in the matrix is the collected data from the tables and represents the strength of relationships between FCDFs and MDSs:

$$QM = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & \ddots & \cdots & \vdots \\ \vdots & \cdots & \ddots & \vdots \\ a_{m1} & \cdots & \cdots & a_{mn} \end{bmatrix} = \begin{bmatrix} F_1 \\ F_2 \\ \vdots \\ F_m \end{bmatrix} = \begin{bmatrix} M_1 & M_2 & \cdots & M_n \end{bmatrix}, a_{ij} > 0 (i = 1, 2 \ldots m; j = 1, 2 \ldots n) \tag{1}$$

Step 2: Obtain the importance degree of every FCDF to MDF.

In this approach, assuming that the weight of each factor is equal, thus the average value is used to evaluate importance. The importance degree matrix of every FCDF to MDF (IDM_1) can be calculated by equations (2) and (3):

$$f_i = average(F_i) / 9, f_i > 0 (i = 1, 2 \ldots m) \tag{2}$$

$$IDM_1 = \begin{bmatrix} f_1 & f_2 & \cdots & f_m \end{bmatrix} \tag{3}$$

The value of f_i is between 0 and 1, reflecting the importance degree of every FCDF to MDF. If the value is larger, the importance degree is larger.

Step 3: Obtain the importance degree of every MDF to FCDF.

In this approach, assuming that the weight of each factor is equal, thus the average value is used to evaluate importance. The importance degree matrix of every MDF to FCDF (IDM_2) can be calculated by equations (4) and (5):

$$m_i = average(M_i)/9, m_i > 0 (i = 1,2 \dots n) \tag{4}$$

$$IDM_2 = \begin{bmatrix} m_1 & m_2 & \cdots & m_m \end{bmatrix} \tag{5}$$

The value of m_i is between 0-1, reflecting the importance degree of every MDF to FCDF. If the value is larger, the importance degree is larger.

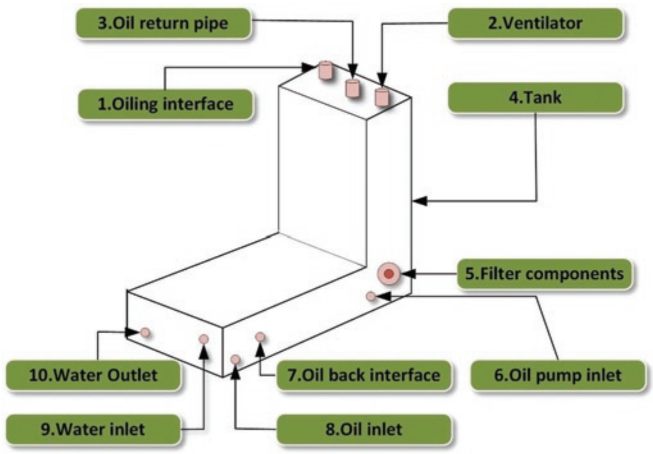


Fig. 4. Simple structure of an oil tank

3. Case Study

Because it is army equipment, an armoured vehicle requires efficient and easy repair to restore combat capacity as soon as possible when a failure occurs. This results in high demand for the maintainability of armoured vehicles. However, due to complexity of armoured vehicles in function and construction, maintainability design usually lags behind function and construction design and affects little of the design. As a result, difficulty in maintenance of armoured vehicles bothers soldiers and reduces the availability of vehicles, as shown in Fig. 3.

To validate the proposed approach, a practical case of an armoured vehicle's lubrication system is studied. As a typical system of an armoured vehicle, the lubrication system consists of mechanical and electric units, and has many typical maintenance problems.

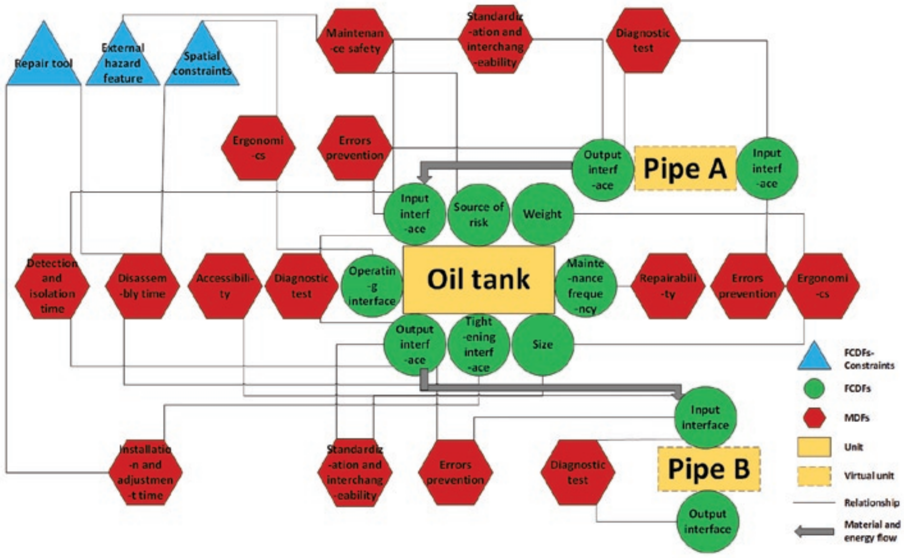


Fig. 5. Correlative relationship model of the oil tank

Fig. 3. Maintenance activities of armoured vehicles

3.1. Modelling relationship

Relationships of the two levels are analysed. At the unit level, the oil tank is selected as the study object. The entire lubrication system is selected as the study object at the system level. By analysing the traditional design process, maintenance problems and maintenance procedures in use, the relationship models of the oil tank and the system are built following the modelling approach described in section 2.2 and shown as Fig. 5 and Fig. 7.

At the unit level, the simple structure of the oil tank is shown as Fig. 4. Materials, such as water, oil and gas, are input from the input pipe A to the oil tank and subsequently output through the output pipe B. The input pipe A and output pipe B represent the oil pipe, water pipe and ventilator. Therefore, these pipes are regarded as external product units and represented by virtual units. The model is built and shown in Fig. 5. The main FCDFs of the oil tank related to the MDFs are the input interface, source of risk, weight, maintainability frequency, size, tightening interface, output interface, operating interface, repair tools, external hazard features and spatial constraints. Main MDFs and relationships with FCDFs are modelled in the figure. By constructing the model, the relationships are modelled and clear.

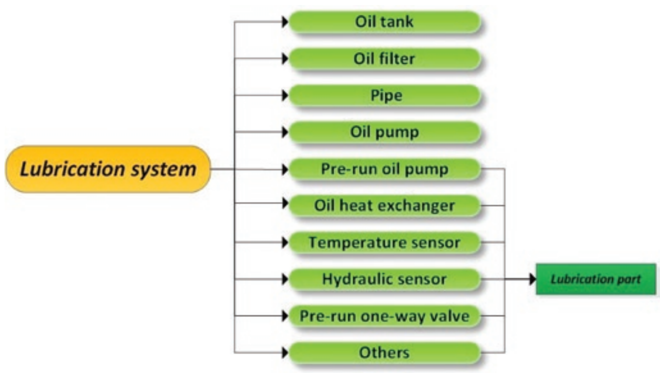


Fig. 6. Unit structure of a lubrication system

At the system level, the unit structure of the system is shown in *Fig. 6*. Units of a lubrication system include an oil tank, oil filter, pipe, oil pump, pre-run oil pump, oil heat exchanger, temperature sensor,

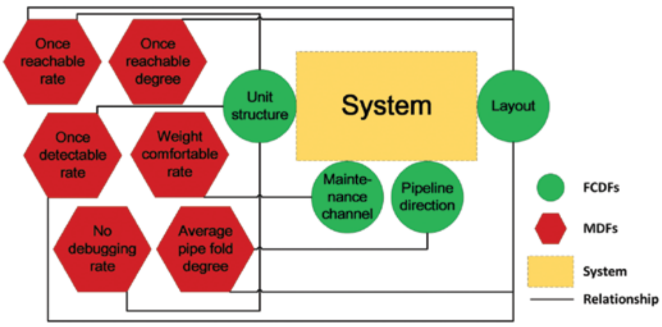


Fig. 7. Correlative relationship model of the lubrication system

hydraulic sensor, pre-run one-way valve and others. The model is built and shown as Fig. 7. The main FCDFs and MDFs of the system are four system level features and six system level evaluation indexes.

3.2. Evaluating importance

By modelling the relationship of MDFs and FCDFs at system and unit levels, the relationships are expressed graphically and clearly. To evaluate the importance of factors, three tables are provided to collect original scoring data shown as Table 6, Table 7 and Table 8. According to the approach, the three tables are filled by more than 20 experts and designers. Each sample obtained from the experts and designers is independent. Therefore, the average value of these data samples is obtained to construct the QM and shown as the Table 6, Table 7 and Table 8. The results in Table 6 and Table 7 are the importance of the relationship between MDFs and FCDFs at the unit level. The results in Table 8 are the importance of the relationships at the system level.

Three quantification matrixes are constructed and represent the importance relationships of quantitative MDFs and FCDFs at the unit level, qualitative MDFs and FCDFs at the unit level, and MDFs and FCDFs at the system level. Applying the importance evaluation method described in section 2.3 to these three matrixes, six IDMs are obtained and shown as *Fig. 8*, *Fig. 9* and *Fig. 10*.

1) Importance degree of relationship between quantitative MDFs and FCDFs at the unit level

For relationships between quantitative MDFs and FCDFs at the unit level, the evaluation results can be found in *Fig. 8*. As shown in the figure, in terms of importance degree of FCDFs to quantitative MDFs, tightening interface and repair tool are the two most important FCDFs; the corresponding importance degrees reach 0.556 and 0.5, which indicates when designing the oil tank, tightening interface and repair tool are the two most important FCDFs and warrant further investigation. For quantitative MDFs to FCDFs, disassembly time and installation and adjustment time are the two most influential quantitative MDFs; the corresponding importance degrees are both 0.484.

From engineering experience there are many maintenance problems n tightening interfaces of an oil tank, which is the oil supply device of lubrication system. Because several interfaces exist, a number of maintenance activities and time are spent in tightening interfaces on the oil tank. Therefore, tightening interface and repair tool are the two most influential factors for maintenance time. The oil tank is regarded as a line replaceable unit, most maintenance operations are disassembly, installation and adjustment. Consequently, among qualitative MDFs, disassembly time and installation and adjustment time are the two most important factors.

2) Importance degree of relationship between qualitative MDFs and FCDFs at the unit level

For relationships of qualitative MDFs and FCDFs at the unit level, the evaluation results can be found in *Fig. 9*. As shown in the figure, for qualitative MDFs, input interface and output interface are the two most important FCDFs; the importance degrees are both 0.528. For FCDFs, ergonomics is the most important qualitative MDF, and the importance degree is 0.532.

From engineering experience, input and output interfaces are important parts of regular preventive maintenance work and require frequent routine maintenance. If input and output interfaces are leaking or clogged, the lubrication system will not work normally. In the design phase, designers should focus on input and output interfaces. Ergonomics reflects the interaction between people and product, which is one of the most important factors. At the beginning of the product functional construction design, the designer should take maintenance personnel into account, providing convenient maintenance conditions, such as comfortable posture and appropriate loads for maintenance

Table 6. Unit importance of the relationship between quantitative MDFs and FCDFs

FCDFs \ Maintainability quantitative factors			Preparation time	Detection and isolation time	Disassembly time	Replacement time	Installation and adjustment time	Test and recovery time
Oil tank	Attribute class	Size	3	3	5	2	5	2
		Weight	2	3	4	3	4	3
		Source of risk	2	3	4	2	4	2
		Maintenance frequency	3	2	3	2	3	3
	Interface class	Tightening interface	4	4	8	3	8	3
		Operating interface	3	2	6	2	4	3
		Warning interface	3	2	4	2	2	4
		Grip interface	2	3	3	3	3	5
		Input interface	2	7	2	1	3	2
		Output interface	2	7	2	1	3	2
	Constraint class	Repair tool	3	3	8	2	8	3
		Spatial constraint	3	2	7	2	6	2
		External hazard feature	4	2	2	3	4	1
		Space and physical environment	5	1	3	3	4	1

Note: 1 indicates little correlation; 3 indicates a certain correlation; 5 indicates a strong correlation; 7 indicates stronger correlation; 9 indicates the strongest correlation; 2, 4, 6, 8 are the scaling values corresponding to the intermediate states between the two adjacent numerical judgements.

Table 7. Unit importance of the relationship between qualitative MDFs and FCDFs

FCDFs \ Maintainability qualitative factors			Accessibility	Ergonomics	Simplified design	Standardization and interchangeability	Errors prevention	Maintenance safety	Diagnostic test	Reparability
Oil tank	Attribute class	Size	7	8	2	2	2	2	1	2
		Weight	2	9	3	2	2	2	2	2
		Source of risk	3	3	3	3	2	8	3	3
		Maintenance frequency	4	2	2	2	1	3	2	9
	Interface class	Tightening interface	4	1	1	4	2	2	3	4
		Operating interface	2	8	1	4	3	2	2	3
		Warning interface	2	5	1	4	4	1	1	2
		Grip interface	3	4	2	3	5	2	1	4
		Input interface	2	3	4	8	7	2	8	4
		Output interface	2	3	4	8	7	2	8	4
	Constraint class	Repair tool	8	6	2	4	4	3	2	5
		Spatial constraint	6	8	4	4	3	1	3	5
		External hazard feature	2	3	1	3	3	7	2	3
		Space and physical environment	2	4	1	2	3	2	1	3

Note: 1 indicates little correlation; 3 indicates a certain correlation; 5 indicates a strong correlation; 7 indicates stronger correlation; 9 indicates the strongest correlation; 2, 4, 6, 8 are the scaling values corresponding to the intermediate states between the two adjacent numerical judgements.

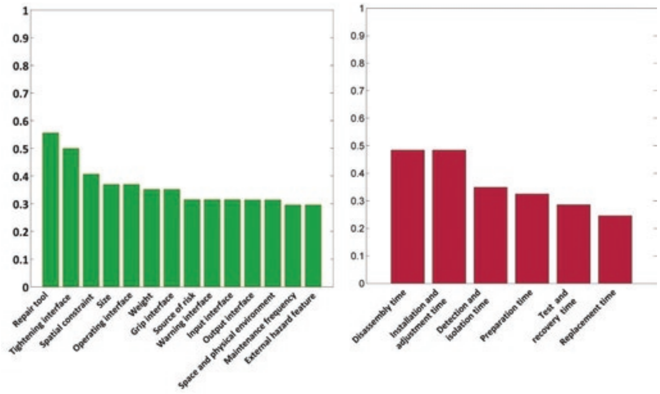


Fig. 8. Importance degree of relationship between quantitative

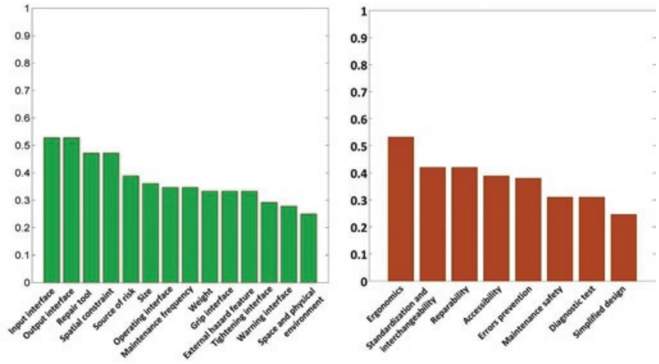


Fig. 9. Importance degree of relationships between qualitative MDFs and FCDFs at the unit level

personal. Design considerations should focus on ergonomics when designing functional structures of products at the unit level.

3) Importance degree of relationship between MDFs and FCDFs at the system level

For relationships of MDFs and FCDFs at the system level, the evaluation results are shown in *Fig. 10*. For MDFs, the importance degrees of layout, unit structure, maintenance channel, and pipe line direction are 0.704, 0.593, 0.5 and 0.426. For FCDFs, the most important MDF is average pipe fold degree where the importance degree is 0.722. Therefore, when designing products at the system level, layout and average pipe fold degree are the most important FCDF and MDF.

From engineering experience and collected data, because there are various units in the lubrication system, the layout of units impacts the maintenance space, accessibility, detectable rate and specific maintenance process. For systems, efficient layout can reduce maintenance cost. Therefore, layout is the most important FCDF considering product maintainability. Because of different types of pipes and lines in the system, the average pipe fold degree is vulnerable to product design

Table 8. System importance of the relationship between MDFs and FCDFs

FCDFs		System level MDFs: Once reachable rate	Once reachable degree	Once detectable rate	Weight comfortable rate	No debugging rate	Average pipe fold degree
Lubrication system	Layout	8	7	7	4	4	8
	Pipeline direction	2	3	3	3	3	9
	Unit structure	7	2	8	3	7	5
	Maintenance channel	5	3	3	7	5	4

Note: 1 indicates little correlation; 3 indicates a certain correlation; 5 indicates a strong correlation; 7 indicates stronger correlation; 9 indicates the strongest correlation; 2, 4, 6, 8 are the scaling values corresponding to the intermediate states between the two adjacent numerical judgements.

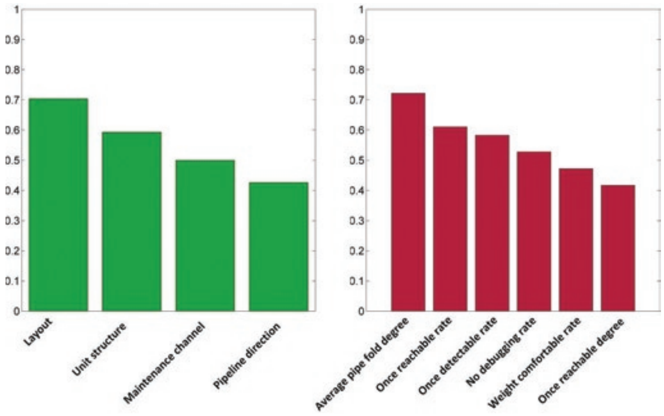


Fig. 10. Importance degree of relationship between MDFs and FCDFs at the system level

of function and construction. Practically, the factor of average pipe fold degree affects most functional construction design of products.

The results obtained by the proposed method are consistent with engineering practice, which validates the effectiveness and feasibility of the proposed method. Through this design approach, maintenance design guidance can be provided for designers early in the design stage.

4. Conclusions

To improve product quality level, maintainability should be designed and related with function and construction at the design stage. To achieve this purpose, the paper proposes a design approach based on correlative relationships between maintainability and functional construction. The primary innovations of this paper are the following: (1) design requirements and characteristics of maintainability and functional construction are defined and classified into MDFs and FCDFs at the system and unit level; (2) a relationship model of maintainability and functional construction is proposed by combining the MDFs and FCDFs based on topography theory; (3) to provide quantitative suggestions on design, an importance evaluation is developed based on a QM and the relationship model.

An engineering application is studied by applying the approach to the design of the lubrication system of an armoured vehicle. Compared with engineering experience and practical data, the results obtained by the proposed approach are useful and effective and can be useful quantitative guides for design of product maintainability and functional construction. The proposed approach overcomes the lagging problem of maintainability design and enriches the integrated design of product maintainability and functional construction.

Although integrated design of maintainability and functional construction is important, there is little peer-reviewed literature or work conducted on this issue. Therefore, the proposed approach cannot be validated by comparison to other methods. In addition, due to confidentiality of the data, details on the product in the case cannot be provided. Future efforts will be on approach improvements and extension of applications.

References

1. Ali A, Chen X, Yang Z, Lee J, and Ni J. Optimized maintenance design for manufacturing performance improvement using simulation. Winter Simulation Conference 2008; 1811-1819, https://doi.org/10.1109/WSC.2008.4736270.
2. Baidya R, Dey P K, Ghosh S K, and Petridis K. Strategic maintenance technique selection using combined quality function deployment, the analytic hierarchy process and the benefit of doubt approach. International Journal of Advanced Manufacturing Technology 2016: 1-14, https://doi.org/10.1007/s00170-016-9540-1.
3. Barabadi A, Garmabaki A H S, Yuan F, and Lu J. Maintainability analysis of equipment using point process models. in IEEE International Conference on Industrial Engineering and Engineering Management 2016: 797-801.
4. Bohlin M, Forsgren M, Holst A, Levin B, Aronsson M, and Steinert R. Reducing vehicle maintenance using condition monitoring and dynamic planning. in Iet International Conference on Railway Condition Monitoring 2008: 1-6, https://doi.org/10.1049/ic:20080329.
5. Chang L, Du E X, Zhang C L, and Tang X X. Reliability and maintainability analysis of vehicle anti-tank missile. in International Conference on Quality, Reliability, Risk, Maintenance, and Safety Engineering 2012: 1400-1402, https://doi.org/10.1109/ICQR2MSE.2012.6246483.
6. Coulibaly A, Houssin R, and Mutel B. Maintainability and safety indicators at design stage for mechanical products. Computers in Industry 2008; 59(5): 438-449, https://doi.org/10.1016/j.compind.2007.12.006.
7. Da X U, Chuang L I, Jiao Q, and Yang L I. Research on the comprehensive evaluation of equipment maintainability qualitative index based on VIKOR. Manufacturing Technology & Machine Tool 2014: 9.
8. Deloux E, Castanier B, and Berenguer C. Maintenance policy for a non-stationary deteriorating system. Annual Reliability & Maintainability Symposium 2008: 496-501, https://doi.org/10.1109/RAMS.2008.4925846.
9. Dohi T, Kaio N, and Osaki S. A new graphical method to estimate the optimal repair-time limit with incomplete repair and discounting . Computers & Mathematics with Applications 2003; 46(46): 999–1007, https://doi.org/10.1016/S0898-1221(03)90114-3.
10. Ertas, M W, Smith, Tate, W D , Lawson, T B, Baturalp. Complexity of system maintainability analysis based on the interpretive structural modeling methodology: transdisciplinary approach 2016; 25(2): 254-268.
11. Guo L. The research of equipment maintainability forecasts methods based on support vector machine. in Chinese Automation Congress 2016: 486-488.
12. Jardine A K S and Tsang A H C. Maintenance, replacement, and reliability : theory and applications. CRC Press, Taylor & Francis 2013.
13. Jia Q S. Engine maintenance policy optimization with succinct value function representation. in Asian Control Conference, 2009. Ascc 2009: 1548-1553.
14. Khandelwal D, Sharma J, and Ray L. Optimal periodic maintenance of a machine. IEEE Transactions on Automatic Control 1979; 24(3): 513-513, https://doi.org/10.1109/TAC.1979.1102068.
15. Li Q, Huang D, Wang F, Zheng Y, Li J, and Yan D. Analysis of the equipment maintainability qualitative evaluation index based on interpretive structure modeling. in International Conference on Fuzzy Systems and Knowledge Discovery 2016; 649-653.

16. Liu W and Shui-Jun Y U. Study on Decision Support System for Electronic Armament's Maintenance Structure. Computer Simulation 2006; 23(1): 5-3.
17. Lu Z, Zhou J, and Li N. Maintainability fuzzy evaluation based on maintenance task virtual simulation for aircraft system 2015; 17(4): 504-512.
18. Luo X, Yang Y, Ge Z, Wen X, and Guan F. Fuzzy grey relational analysis of design factors influencing on maintainability indices. Archive Proceedings of the Institution of Mechanical Engineers Part E Journal of Process Mechanical Engineering. Part E: Journal of Process Mechanical Engineering 2015; 229(1): 78-84, https://doi.org/10.1177/0954408914522616.
19. Mazurkiewicz D. Computer-aided maintenance and reliability management systems for conveyor belts. Eksploatacja i Niezawodnosc - Maintenance and Reliability 2014; 16(3): 377-382.
20. Nakagawa T. Maintenance Theory of Reliability. Springer London. 2005.
21. Peng W, Huang H Z, Zhang X, Liu Y, and Li Y. Reliability based optimal preventive maintenance policy of series-parallel systems. Eksploatacja i Niezawodnosc - Maintenance and Reliability 2009; 42(2): 4-7.
22. Saxena A, Wu B, and Vachtsevanos G. A hybrid reasoning architecture for fleet vehicle maintenance. Instrumentation & Measurement Magazine IEEE 2006; 9(4): 29-36, https://doi.org/10.1109/MIM.2006.1664039.
23. Senivongse T and Puapolthep A. A Maintainability Assessment Model for Service-Oriented Systems. Proceedings of the World Congress on Engineering and Computer Science 2015: 1.
24. Stjepandić J, Wognum N and Verhagen W J C. Concurrent Engineering in the 21st century. Foundations, developments and challenges. Cham [Switzerland]: Springer, 2015.
25. Yang Y. Maintainability-based facility layout optimum design of ship cabin. International Journal of Production Research 2015; 53(3): 677-694, https://doi.org/10.1080/00207543.2014.919416.
26. Yau S S and Collofello J S. Some stability measures for software maintenance. in Computer Software and Applications Conference, 1979. Proceedings. COMPSAC 79. The IEEE Computer Society's Third International 2002; 6: 545-552.
27. Yin Y, Wu W H, Cheng T C E, and Wu C C. Due-date assignment and single-machine scheduling with generalised position-dependent deteriorating jobs and deteriorating multi-maintenance activities. International Journal of Production Research 2014; 52(8): 2311-2326, https://doi.org/10.1080/00207543.2013.855833.
28. Zhen F, Univ X, and An X. Maintenance Design for Product Level Reuse Based on House of Quality. Computer Integrated Manufacturing Systems 2004; 10(4): 476-480.
29. Zhou D, Jia X, Lv C, and Li Y. Maintainability allocation method based on time characteristics for complex equipment. Eksploatacja i Niezawodnosc - Maintenance and Reliability 2013; 15(4): 441-448.
30. Zhou D, Wang M H, Guo Z Q, and Lv C. Maintenance Simulation and Maintainability Design Based on Virtual Reality. Key Engineering Materials 2011; 467: 457-461, https://doi.org/10.4028/www.scientific.net/KEM.467-469.457.
31. Zhou H, Gan M Z, Liu A Q, and Liu J M. Maintainability design of product based on concurrent engineering. Journal of Machine Design 2003; 20(9): 3-5.

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