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Design of reliability critical system using axiomatic design with FMECA

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A B S T R A C T

In product design, the initial design stage is being increasingly emphasized because it significantly influences the successive product development and production stages. However, for larger and more complex products, it is very difficult to accurately predict product reliability in the initial design stage. Various design methodologies have been proposed to resolve this issue, but maintaining reliability while exploring design alternatives is yet to be achieved. Therefore, this paper proposes a methodology for conceptual design considering reliability issues that may arise in the successive detailed design stages. The methodology integrates the independency of axiomatic design and the hierarchical structure of failure mode, effects, and criticality analysis (FMECA), which is a technique widely used to analyze product reliability. We applied the proposed methodology to a liquefied natural gas fuel gas supply system to verify its effectiveness in the reliability improvement of the design process.

1. Introduction

Product design starts with the conceptual design stage, in which major functions and components are explored and determined. Although design details are not specified, this stage significantly impacts major product characteristics such as performance, reliability, and cost since it determines the overall product framework. However, the development of creative conceptual designs is a complicated process and usually relies on the intuition or experience of a human designer (Park, 2007). Conceptual design with high reliability is particularly important in industries associated with safety-critical products. Thus, Failure mode, Effects, and Criticality Analysis (FMECA) is frequently employed to verify the conceptual design's reliability. After identifying potential risks in the conceptual design, the components and/or subsystem with inherent risk are modified or even redesigned. However, this procedure involves many iterations as well as premature design constraints as it prioritizes reliability verification over new design explorations. Numerous studies have attempted to resolve this issue.

Arcidiacono and Campatelli (2004) proposed Failure Mode and Effect tree Analysis (FMETA) to improve engine performance. FMETA conducts system analysis with Axiomatic Design (AD) and risk analysis by integrating Failure Mode and Effects Analysis (FMEA) and Fault Tree Analysis (FTA). This method is useful for checking system reliability and arranging failure modes and effects; however, it focuses on identifying the problem of the present system instead of deriving and evaluating an improved design alternative. Kulak et al. (2005) proposed a multi-attribute comparison of Information Technology Systems (ITS) based on Fuzzy AD. ITS is mainly designed for information systems with a heavy focus on the minimum information axiom of the AD theory; it is inappropriate for general product design. Heo et al. (2010) proposed an interactive design framework that integrates AD and FTA. In their framework, FTA is performed to model the reliability issue in AD. However, this framework only identifies the problem and the risks in the proposed design and does not alleviate the identified problems and risks in the product design. Most conceptual design studies are based on AD and use Triz to compensate for the defects in AD (Shirwaiker and Okudan, 2008; Shin et al., 2007; Yang and Zhang, 2000; Shin and Park, 2004; Lee and Choi, 2009; Chen and Tan, 2006). Although Triz is used as a supportive measure during the design procedure, AD and Triz share few common structures and hence they are difficult to systematically integrate.

Other studies have attempted to combine conceptual design and risk analysis to some extent, but they are mostly limited to the identification of problems in the design stage (Joseph and Childs,

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Nomenclature

FMECA	Failure Modes, Effects, and Criticality Analysis
AD	Axiomatic Design
CAs	Customer Attributes
FRs	Functional Requirements
DPs	Design Parameters
PVs	Production Variables
RPN	Risk Priority Number
S	Severity
O	Occurrence
D	Detection
LNG FGSS	Liquefied Natural Gas Fuel Gas Supply System
PSVs	Platform Supply Vessels
PFD	Process Flow Diagram
DFDE	Dual Fuel Diesel Electric
BOG	Boil-off Gas
PT	Pressure Transmitter
LT	Level Transmitter
PID	Proportional–Integral–Derivative

1999; Zigmund et al., 2005; Pickard et al., 2005; Arcidiacono, 1997, 2000; Arcidiacono and Delogu, 2001). To improve the design and reliability issues at the conceptual design stage of reliability critical products, this study proposes an efficient systematic design methodology that combines the strengths of AD and FMECA, e.g., considering multi-failure modes, to obtain a synergistic effect. For the verification purpose, a conceptual design of LNG fuel supply system is analyzed and then redesigned to improve the system reliability with the proposed methodology.

2. Axiomatic design and FMECA

2.1. Axiomatic design

AD (Suh, 1990) is a logical and systematic design methodology that allows a departure from existing processes, which are dominated by intuition and experience. AD relates functional requirements with design parameters, and designers define problems in the domain of customer attributes (CAs), functional requirements (FRs), design parameters (DPs), and production variables (PVs). CAs in the customer domain are translated into FRs in the functional domain. These are then used to determine DPs in the physical domain followed by PVs in the production domain. The design process is broken down through such interactions and the relationships between domains can be represented as matrices. In this method, evaluations are performed based on relationships represented by design matrices. The two axioms in AD are the independence axiom, which requires functional requirements to maintain independence, and the information axiom, which minimizes the information content of design (Suh, 1998; Park, 2007). The information axiom implies that the design with the least information content satisfying functional requirements is the optimal among all alternatives. However, a single configuration of the FR–DP relationship may be insufficient for designing complex systems. In this case, the FR–DP relationship is hierarchically defined by zigzagging between the functional and physical domains as shown in Fig. 1 (Suh, 1998).

Designers first define DPs that match the predetermined upper-level FRs (Line 1 in Fig. 1) followed by lower-level FRs related to FRs and DPs (Lines 2 and 3 in Fig. 1). This design process segments FRs and DPs into hierarchical upper and lower-level relationships, and lower-level conditions must be satisfied to fulfill upper-level conditions. Generally, the upper-level FR–DP relationship must satisfy the two axioms of AD for good designs to be derived at the lower level. Matrices can be used to determine mutual interferences and evaluate designs, which serve as an important basis in the assessment of conceptual designs (Park, 2007).

2.2. Failure mode, effects, and criticality analysis

Developed by a reliability engineer in the 1950s to analyze problems that may lead to failure in military systems, FMECA has been implemented in the early stages of various reliability studies (Rausand and Hoyland, 2004). To analyze the causes and influence of failure modes, FMECA defines potential failures based on extensive reviews of components and subsystems and then determines the order of eliminating them (An et al., 2010). FMECA can be easily implemented without advanced analysis techniques, but it is necessary to understand the purpose and operational boundaries of the targeted system. According to IEEE Std. 352, the basic questions to be answered by FMECA are as follows (IEEE, 1987):

1. How can each part conceivably fail?
2. What mechanisms might produce these modes of failure?
3. What could the effects be if the failures did occur?
4. Is the failure in the safe or unsafe direction?
5. How is the failure detected?
6. What inherent provisions are provided in the design to compensate for any failure?

Based on these considerations, the following steps are performed (Rausand and Hoyland, 2004).

1. Definition and delimitation of the system.
2. Definition of the main functions of the system.
3. Description of the operational modes of the system.
4. System breakdown into subsystems that can be handled effectively
5. Review of system functional diagrams and drawings to determine interrelationships between the various subsystems.
6. Preparation of a complete component list for each subsystem. Description of the operational and environmental stresses that may affect the system and its operation.

After completing the above steps, the problem definition and analysis results are recorded in the FMECA form. Each item is then assigned a Risk Priority Number (RPN) that is calculated by multiplying the failure rate, severity, and detection of each component (Abdelkader and Daoud, 1994; Seung and Kosuke, 2003).

$$\text{RPN} = \text{Severity (S)} \times \text{Occurrence (O)} \times \text{Detection (D)} \tag{1}$$

Each failure mode is classified into different levels according to the failure probability. Severity is defined according to the extent of failure, loss, and system level consequences, and the maximum value is specified among the ranks of various items. Detection refers to the ability of the system to detect potential failures and causes during various inspections conducted for system maintenance. The criteria for each item vary by system.

The rate ranking for failure, severity and detectability seems the key issues for the quantitative decision criteria of system reliability and these are system dependent factors. It is difficult to establish a database to support for generic system. In manufacturing industry, FMECA is one of the most important documents of quality control for each manufacturer. Thus, manufacturers have their own

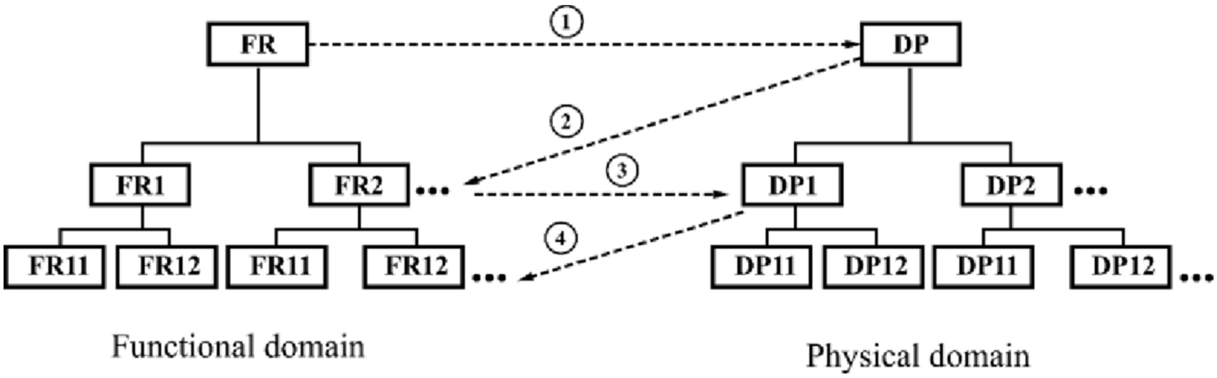

Fig. 1. Zigzagging process between domains in AD.

criterion of RPN ranking. This criterion provides an acceptable RPN: permitted limit of S, O, D combination. Most important criterion point is fatal accident and permissible number of it. To determine rankings, generally related experts co-decide the ranking reference of target system. Defined ranking is not immutable reference because it depends experts' opinions and characteristics of target system. However from the internal system point of view, it finds relatively unreliable and critical points through ranking reference. Ranking helps to eliminate the risk and critical point in design. Therefore, it should be noted that the RPN is meaningful rather than each of its components (S, O, and D) because the decision on acceptance is made by the RPN not by each of them. For example, assume that the RPN can be equal for two combinations of different S, O, and D. Then, we should make the same decision on the two combinations: accepted or rejected. the procedures of FMECA are shown in Fig. 2.

3. Design process of axiomatic design with FMECA

AD and FMECA are significantly different in terms of purpose and usage but exhibit similar hierarchical structures and characteristics when applied to design problems. AD provides an efficient design framework and focuses on allowing systematic implementation of the conceptual design, whereas FMECA analyzes overall system reliability based on failure modes and risks and offers quantitative analysis of severity levels (Rausand and Hoyland, 2004). Table 1 compares the two methodologies.

As shown in Table 1, both AD and FMECA have hierarchical structures and tend to approach systems in a similar manner. FMECA can be classified into bottom-up and top-down approaches. The bottom-up approach is usually employed in production, while the top-down approach is used to analyze the main functions before the system is complete. Fig. 3 illustrates the top-down approach, which is more suitable for assessing new system designs as possible failures are analyzed without configuration of system factors. Moreover, mutual comparisons can be facilitated with AD focusing on FRs and FMECA focusing on DPs. FMECA can also be used as a tool to compensate for the weaknesses of AD, and AD can be employed to search for solutions to problems occurring after FMECA implementation. AD allows detailed design based on a systematic and methodical approach but does not ensure reliability of the proposed conceptual design and fails to predict possible problems. While FMECA cannot proceed to the final design on its own, it enhances product reliability by analyzing the failure modes of various components and the influences of the failure modes within the system. It can also propose solutions that prevent the failure of a component from spreading to other areas. From this perspective, FMECA can support AD in producing improved designs.

The proposed design methodology aims to integrate the advantages of hierarchical representation in AD and FMECA. Designs that satisfy the independence axiom have weaker relations between DPs and smaller interference, thus resulting in a small impact on the overall system in the case of subsystem failure. This implies lower severity levels in FMECA. Under the information axiom, the best design is the one that has the simplest information and system structure, indicating that FMECA is associated with small failure rates and detection ranks. A design that satisfies both the independence axiom and information axiom will have a low RPN value, which is recommended for FMECA. Therefore, this study proposes a conceptual design method that combines the advantages of the two theories.

Based on the complementary interaction between AD and FMECA, the proposed method enables the system to have multiple failure modes. While FMECA considers only a single failure mode as it is retaining the drawback of FMECA, AD complements the defining procedure of the components relation in FMECA to consider and analyze multiple failures. Moreover, FMECA allows considering failure and reliability when using AD. Fig. 4 shows the example system for explaining multiple failure modes (Pickard et al., 2005). In single failure, the system is analyzed through the OR logic. However, from the system level in the figure, this system also has the potential to detect top event Y and failure C through AND logic. That is, we can find and evaluate these AND situations and networks using the proposed method. Moreover, the method can suggest design alternatives to avoid multiple failure modes or minimize their effect.

The failure effect contains the failure of each part, as shown in Fig. 4. The failure effect results from failure in the higher physical or functional domain of the part; however, FMECA lacks a description of the hierarchical analysis of physical parameters and functions. It is difficult to identify a connection relationship between each part. However, it can be easily expressed with the design matrix of AD.

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \end{bmatrix} = \begin{bmatrix} X & & & \\ & X & & \\ & & X & \\ & X & X & X \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \end{bmatrix} \tag{2}$$

This AD matrix not only increases design efficiency but also systematically organizes information for the multi-failure analysis mentioned above. When DP1.1 and DP1.2 are children of DP1, they are included in the physical domain of DP1 and are in charge of the functional domain of FR1. Moreover, they have an independent relationship with FR2, FR3, and FR4. For failure modes, the internal

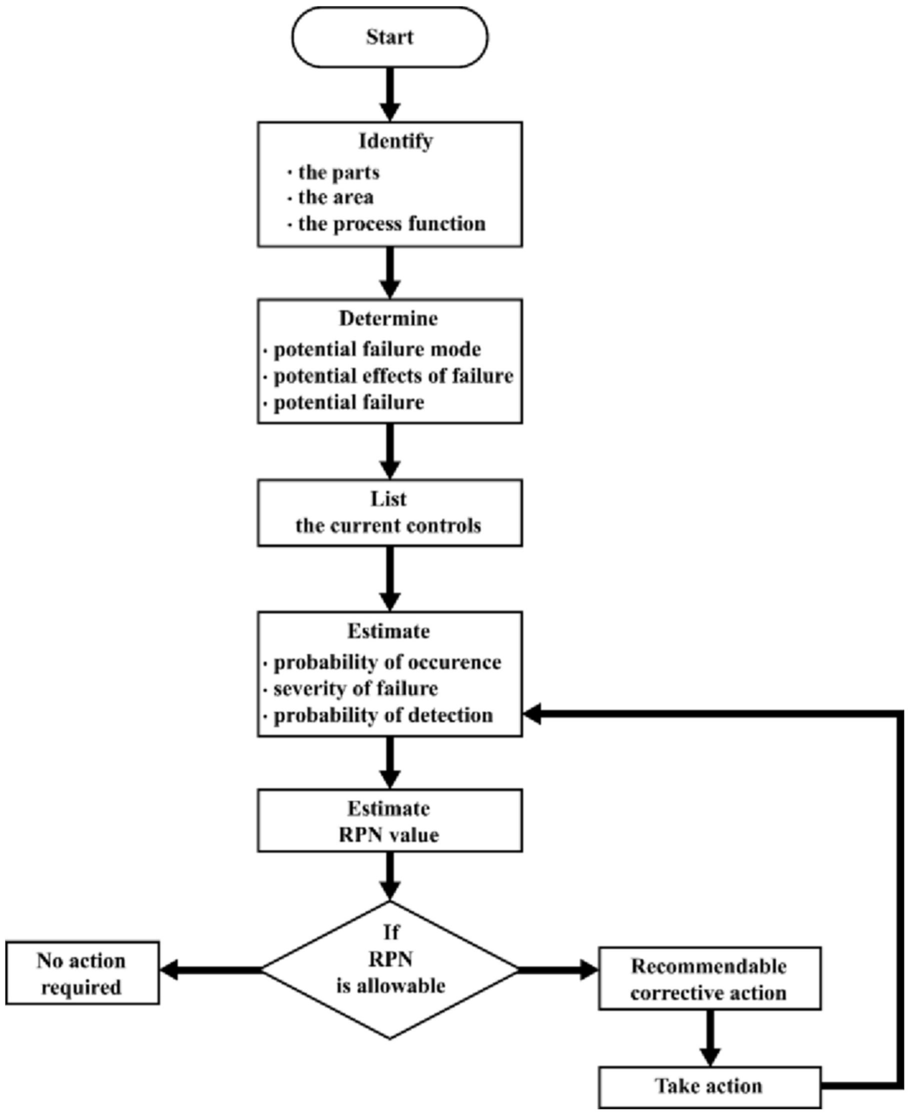

Fig. 2. FMECA process (Telsang, 2006).

Table 1
Comparison of AD and FMECA (Goo et al., 2011).

	AD	FMECA
General	Design methodology for evaluating the design using the axioms	Analyze & evaluate the causes and influences of failure modes
Purpose	Logical specification of the design	Problem Analysis (Risk)
Approach	Top-down	Top-down/Bottom-up
Analysis	Hierarchical analysis based on FRs	Hierarchical analysis based on DPs

components of DP1 can influence the functional domain of FR1. In addition, DP1 can influence the physical failure effect on internal components.

However, DP2, DP3, and DP4 are different from the above DP1 case. For example, DP3 not only influences FR3 but also FR4 with DP2 and DP4. This design has the potential to experience multiple failures. DP3 has a failure effect on the functional failure of FR3 and FR4. In particular, FR4 has a relation with DP2 and DP4. Thus, DP2, DP3, and DP4 can cause the failure of not only the independent function of each DP but also the networked system. Therefore, as mentioned above, such multiple failures can be evaluated by a combination of FMECA and AD.

The conceptual design methodology proposed in this paper can be divided into Phase I—development of the conceptual design and analysis—and Phase II, which repeats the analysis process to achieve enhanced design, as shown in Fig. 5.

3.1. Phase I

In Phase I, the conceptual design is constructed using AD and the DPs of AD are employed to compile a list of all components. AD is usually used to derive conceptual designs in the early stage of development; it is also used to evaluate or improve the design of existing systems (Park, 2007). The initial conceptual design must be

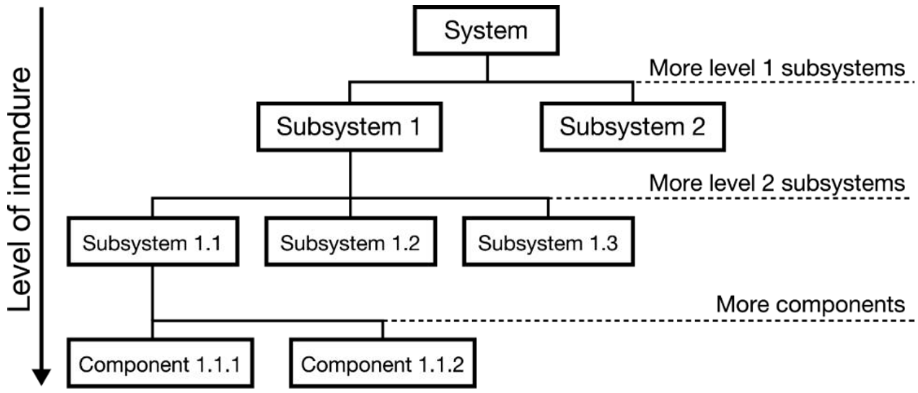

Fig. 3. Top-down tree structure.

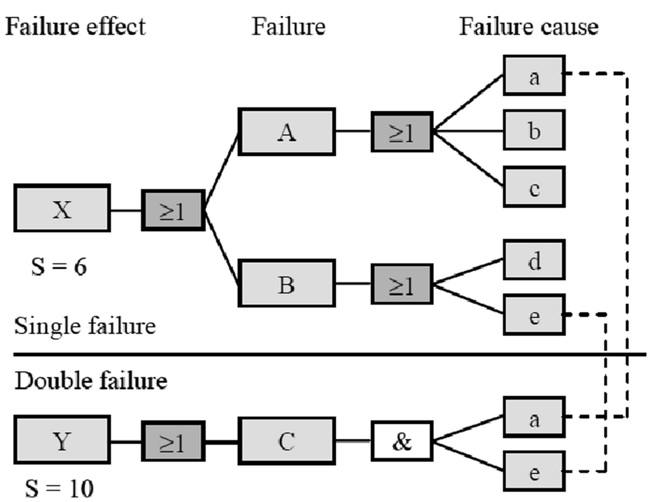

Fig. 4. Single and multiple failure networks in a failure tree (Pickard et al., 2005).

developed with caution against coupled design. The specification of AD should be conducted to a level corresponding to the design purpose while ensuring that the required DPs are clearly distinct. When evaluating and improving existing systems, after analyzing FRs of the target system, the analyzed FRs are matched to the DPs for further design analysis. Coupled design is allowed in the design matrix, but the number of FR—DP levels and their numbers should match. If this is not the case, it will be impossible to properly perform analysis using AD, thus making further evaluation and enhancement difficult. When analysis via AD is complete, DP information should be utilized to generate a list of components. The defined components must be the same as or more detailed than the defined DPs, and the specification levels should be matched as closely as possible. If the number of components is greater than the number of DPs or if classification is difficult, reimplementation of AD is recommended at a higher specification level. Phase II begins once specification is complete for all components involved in the conceptual design.

3.2. Phase II

In Phase II, FMECA is performed using the list compiled in Phase I; the analysis results are utilized to propose a new conceptual design. First, FMECA is performed on the list obtained in Phase I. The failure modes and influences of each component are analyzed and detailed information that was previously excluded in the AD matrix can be added. Comparisons are made to check for details uncovered by AD. The assessment criteria for implementing FMECA are determined by the designer to suit the target system.

When all components have been analyzed, the assessment criteria are used to assign risk priority numbers. The reliability of each component is determined quantitatively, and the designer inspects items for possible problems. While existing methods go through the design process again after detecting problems, the proposed methodology employs AD. After checking the problematic components and the related FR—DP list of the design matrix, an improved conceptual design is derived by considering RPN as the information content of AD. However, the FMECA approach is different from AD in that the overall system has to satisfy certain conditions.

The focus of this process is to reflect the FMECA analysis results in the design matrix. Components with reliability problems are identified and related DPs are designated as DPs requiring modification. If the related FRs cannot satisfy certain requirements or if they are not fully defined, all FRs of AD must be redefined. In this case, there is a high possibility of deriving new subsystems to resolve problems. If there are no problems with the related FRs, greater emphasis is placed on finding alternatives for DPs.

When a new conceptual design is derived by the above process, the listing of components as described in Phase I is repeated. Phase II ends if FMECA analysis does not find any problems and the proposed design at this point is selected as the final conceptual design. As demonstrated above, when AD is used in tandem with FMECA, a highly reliable conceptual design can be effectively obtained in the conceptual design stage. The two methodologies can be integrated if the functional requirements of the system can be clearly defined, but this can be difficult in situations lacking distinct functional requirements, e.g., component arrangement.

4. Case study

The proposed methodology was applied to the design improvement of a liquefied natural gas fuel gas supply system (LNG FGSS).

4.1. LNG FGSS

In an LNG-fueled ship, the LNG FGSS stores and delivers fuel to the engine as required. The proposed methodology attempted to identify problems and improve the design of the FGSS. Most FGSSs use heavy fuel oil or marine diesel oil as fuel, but LNG has emerged as an alternative as stricter regulations have been imposed on harmful emissions such as SOx, NOx, and particulate matter

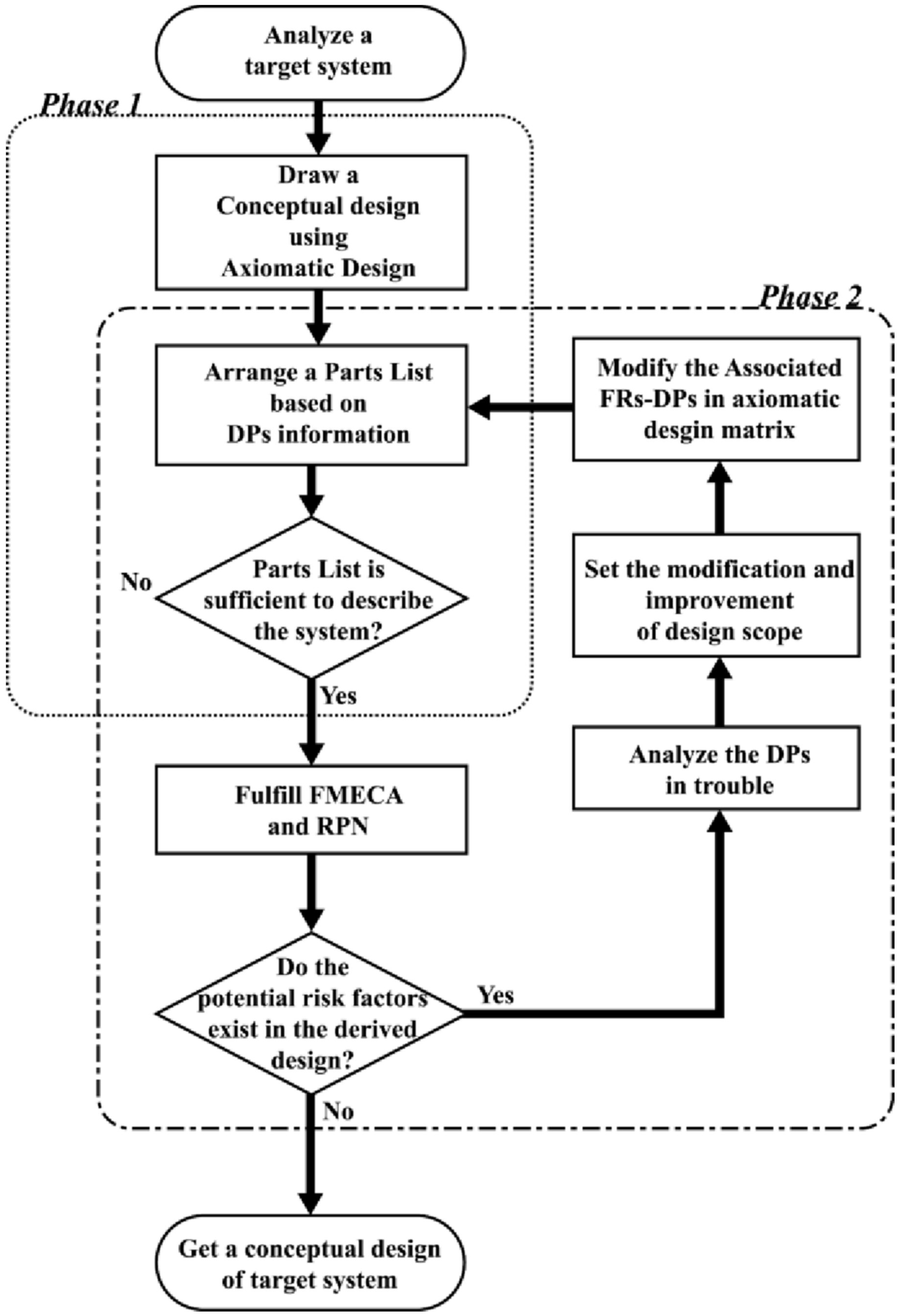

Fig. 5. Axiomatic design with FMECA process.

(Wuersig, 2014). The LNG FGSS was introduced in the early 2000s when LNG became more commonly used as fuel for ships. Some LNG carriers use BOG from the LNG cargo tank as fuel. However, this research focuses on the LNG-FGSSs for general merchant ships that do not have an LNG cargo tank (Seo et al., 2014).

Small vessels operating in near-shore areas, including platform supply vessels, car ferries, and tugs, are usually equipped with the FGSS. However, larger LNG fuel tanks are required for large LNG-fueled ships such as container ships and general cargo ships. To design a larger FGSS, the existing system must be inspected and improved.

Small vessels can operate engines with electricity generated from BOG, but it is insufficient to operate large vessels. Thus, large vessels use additional pressure devices to satisfy the pressure and flux condition of LNG. Fig. 6 shows the general structure of an LNG FGSS for large ships. LNG in the fuel tank is pumped and supplied to the vaporizer, and vaporized LNG is delivered to the engine. This process also requires a suction tank, which returns vaporized LNG to the fuel tank and prevents the vaporized gas from entering the pump. The methodology proposed in this study will be applied to inspect and improve the existing system (Seo, 2012).

4.2. Phase I

Ship owners require a new LNG FGSS for large LNG-fueled ships. We defined CAs with the LNG FGSS designer or ship owner as the

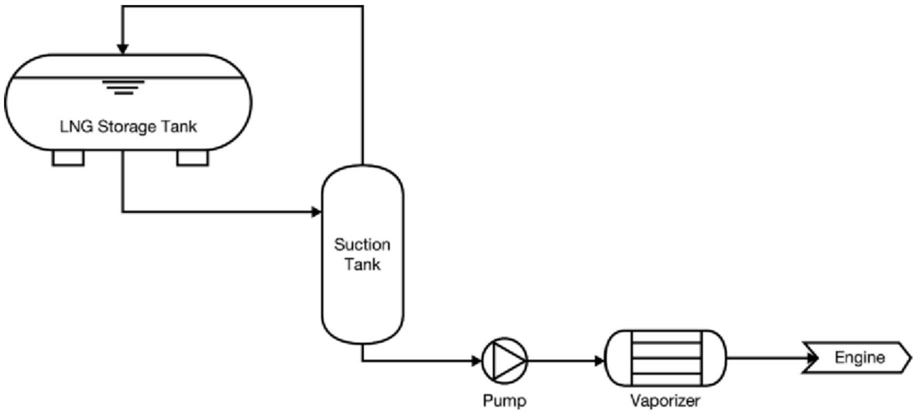

Fig. 6. Pressurized tank with cryogenic pump system.

customer.

CA1. Type of LNG fuel tank: Type C (pressurized tank)
CA2. Type of target engine: Low-pressure gas fuel engine (requiring c.a. 6 bar fuel gas)
CA3. Stable fuel supply during sailing
CA4. Applicability to large LNG-fueled ships
CA5. High system reliability during sailing and repair/maintenance

The upper-level FR and DP of the LNG FGSS are as follows. The LNG FGSS must essentially supply fuel to the low-pressure engine.

FR: Supply LNG fuel gas to the low-pressure engine
DP: LNG FGSS system for the low-pressure engine

To ensure LNG fuel supply, the key functions of FGSS were classified up to FR4. Based on the process flow diagram shown below, the DPs of the current system were identified and defined (Seo, 2012).

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \end{bmatrix} = \begin{bmatrix} X & & & \\ & X & & \\ & X & X & \\ & X & X & X \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \end{bmatrix} \tag{3}$$

The above is an analysis of the uppermost FR–DP; more detailed definitions are required to determine component labels. The above design matrix has a decoupled structure. FR2 to FR4 were found to significantly influence the key factors of the system configuration. Each of the four FRs were further broken down into lower levels and the corresponding DPs were defined. The results are given in Table 2.

Despite the decoupled design, DP2 to DP4 simultaneously influence FR4. This is because DP2 to DP4 tend to influence one another owing to the vaporization problem of LNG. To improve this design, FMECA analysis was performed on the key factors and the problematic areas were identified. New DPs were proposed after identifying problems with the related FRs.

4.3. Phase II

The failure modes and related information of components in the LNG FGSS system were classified by the system.

Beginning with the specification of the detailed components under a top-down approach, FMECA proceeds with RPN analysis using severity (S), occurrence (O), and detection (D). All ranking references are defined through a multi-disciplinary group meeting. Assessments were made for each S, O, and D item of the components in the conceptual design derived from AD, and RPN values were quantitatively calculated. Items with high RPN values were defined as high-risk design components and were identified as requiring design modifications. Analysis of S, O, and D items was performed to determine the cause of risks and to recommend modification directions. By locating DPs and related FRs in AD, the target areas for design modification were defined. Failure rate and repair information were recorded for each category. As shown in Tables 3–5, regular standards were applied for the RPN calculations.

Refer to the RPN calculation tables, RPN values range from 1 to 125. 125 means the worst design condition and it is better condition as the value approaches closer to 1. In case of LNG FGSS, we aimed that the value should not exceed 20.

The results of the FMECA analysis are summarized in Table 6. Among the five areas, higher RPNs were obtained for the pressurization system (RPN:45) and isolation valve (RPN: 30) of the monitoring system. The high RPN values indicate that the two areas have low reliability and are likely to contribute to instability of the system.

The areas requiring design modification were identified from FMECA analysis and the related FRs were examined for possible problems. If FRs are clearly defined, DPs are selected to resolve problems identified in FMECA and an improved conceptual design is derived. In this case, FMECA was performed on DPs interfering with the newly defined components and the design matrix of AD. These procedures were terminated when all components attained RPN values below standard values. Here, the standard values vary according to the system or circumstances.

In the LNG FGSS case study, the pressurization system and isolation valve revealed that DP2 to DP4 were problematic areas. Since these DPs were each related to FR2 to FR4, the identified DPs and corresponding FRs must undergo modification. As shown in Table 7, the direction of design modification is determined based on FMECA analysis.

From the above results, we can see that the existing pump system is associated with high risks, and there is little room for improvement owing to structural constraints. To resolve this problem, the design must be modified under a fundamentally different approach. The new system should be designed to decrease severity levels while connecting the existing LNG fuel tank and engine. Using the AD methodology, a new design was developed and evaluated.

The above analysis result suggests the direction and range of

Table 2
Level 2 AD of pressurized tank with cryogenic pump system.

FR1: Store LNG	DP1: LNG storage facility
FR11: Store LNG in tank FR12: Control the peak pressure FR13: Mitigate the pressure rise FR14: Monitor the internal conditions	DP11: LNG fuel tank DP12: Emergency safety device/Vent valve DP13: Insulation & spray system DP14: Measuring devices (Pressure, temperature, and level sensor)
FR2: Supply LNG to the engine	DP2: Fuel conditioning equipment
FR21: Pressurize LNG FR22: Control temperature of LNG	DP21: Cryogenic pump DP22: Cooler or heater
FR3: Vaporize LNG	DP3: Vaporization system
FR31: Vaporize LNG FR32: Supply LNG fuel gas to the engine	DP31: Vaporizer DP32: LNG fuel gas supply valve
FR4: Maintain operability	DP4: Operational functioning system
FR41: Block boil-off-gas (BOG) to the cryogenic pump FR42: Make provision for emergency FR43: Control devices automatically FR44: Detect gas leakage FR45: Alarm the state	DP41: Suction tank between LNG fuel tank and cryogenic pump DP42: Redundancy (pump, vaporizer) DP43: Automation device & control program DP44: Gas detecting sensor DP45: Alarm system, Isolation valve

Table 3
Failure rate ranking.

Rank	Occurrence period
5	less than 1 month
4	1 month to 1 year
3	1–10 years
2	10–100 years
1	100–1000 years

Table 4
Severity ranking.

Rank	Safety	Loss (1000 $)	Lost time (h)
5	Multiple fatalities	>100	Non-repairable onboard
4	Single fatality	50–100	Non-repairable onboard
3	Major injury	25–50	3–6
2	Minor injury to personnel	12–25	1–3
1	No injury to personnel	<12	<1

Table 5
Detectability ranking.

Rank	Detection probability	Detectability (%)
5	Very low probability	<10
4	Low probability	10–50
3	Moderate probability	50–80
2	High probability	80–95
1	Very high probability	>95

concept design modification. In this case, the main problem parts were DP2 and DP4. Thus, we thoroughly examined these for relevant FR2, FR3, and FR4. Consequently, we decided to change DP2, DP3, and DP4 in the LNG FGSS to satisfy the existing FRs because relevant FRs include the essential functions of the system. Three alternatives were (1) performance upgrade of the existing DPs, (2) adding DPs for solving problems, and (3) suggesting new DPs instead of the existing DPs to improve the concept design.

Performance upgrade of the existing DPs may be the simplest way to solve the problem. It just requires higher performance ratings of the DPs without changing the AD matrix. However, this may lead to a significant increase in product cost. However, owing to the risk of the pump system, we could not effectively solve the problem with alternatives (1) and (2). Thus, new DPs have been devised to replace the existing DPs.

The new DPs are designed to not only replace the function of the pump system but also resolve the fundamental problem of the risk source. In particular, it aims to reduce the failure rate and system load when the system is down and/or malfunctions. We can reduce risks in the system by alleviating the evaporation and maintainability problems. We plan to improve the design using the new DPs that.

1. Perform the same task as the pump system.
2. Remove gas or ensure the system operation is affected by gas.
3. Possess a failure mode response system.
4. Immediately repair upon failure.

Various options have been proposed but an approach with a pump-based system is excluded because of the severity-level problem. Improvement direction is that BOG cannot affect operability. Thus, replacement of the pump system should suppress BOG or utilize it as part of the fuel supply. Moreover, an additional device should be considered to immediately detect failure modes. To satisfy maintenance and operability standards, the main—auxiliary—control system has been considered instead of two main systems. In the design improvement process, we introduced an improved design of a pump-free system (Fig. 7) that includes pressurization of BOG, two fuel supply devices organically linked, and a control system to immediately detect failure modes. The new system functions as a gas pressurization and supply system but is different from the ordinary gas pump system.

The pump-free system comprises two booster tanks instead of a suction tank and a pump and is designed to supply the vaporizer with LNG (Seo, 2012). While the original system used a suction tank to resolve the vaporization problem, the new system supplies LNG using vaporization at each booster tank. The booster tanks heat up the tank to vaporize LNG, and the increased pressure within the tank facilitates LNG supply to the system. In this system, a previously heated tank has to be filled again with LNG. During this time, the system ensures stable fuel supply by using the other booster tank to supply LNG. The proposed system consists of two boosters, each of which is equipped only with a mini-vaporizer and

Table 6
FMECA of pressurized tank with cryogenic pump system.

Description of item				Description of failure			Effect of failure	Failure rate ranking (1–5)	Severity ranking (1–5)	Detectability ranking (1–5)	RPN
Ref. No.	Main item description	Function	Operation mode	Failure mode	Failure cause or mechanism	Detection of failure	On the system function				
C-1	Vacuum pump	Maintaining vacuum within the chamber, Insulation of the fuel tank	Normal	Overpressure	Heat penetration into the fuel tank	Pressure enhancement	To vent the excessive boil-off gas	3	3	1	9
T-1	Suction tank	Block BOG to the cryogenic pump by separating gas and liquid	Normal	Leak	Crack induced by external force, corrosion	Pump degradation	To cause mechanical damage to the cryogenic pump	2	3	2	12
P-1	Impeller	Compressing the LNG, transport LNG to the vaporizer, engine	Normal	Performance degradation, impeller damage	BOG generation around the impeller	Pressure reduction, human perception	To stop the entire system	3	5	3	45
P-2	Seal, Gasket			Leak/Rupture	Corrosion, overpressure	Gas detection, human perception					
P-3	Diffuser casing				External force, corrosion						
V-1	Glycol heat exchanger	Evaporating pressurized LNG, heat exchange between steam and glycol (heating medium)	Normal	Leak/over-temperature	Lack of glycol, corrosion	Pressure reduction, high temperature	To stop the entire system	2	4	2	16
I-1	Isolation valve	Inventory segmentation, protecting from accident	Emergency	Not on control	Power failure, connection out	Status of display, human perception	To be exposed to a severe accident such as fire, explosion	2	5	3	30

Table 7
Evaluation of the design.

	Problem	Improvement direction
P.1~3	High failure rate and severity The entire system may be stopped when failure occurs and it causes significant cost & time losses	Design changes to reduce the failure rate and system load when failure occurs Reduce cost & time losses when failure occurs
I.1	It is difficult to find failure mode. The entire system may be stopped when failure occurs	Design changes to reduce the failure rate and system load when failure occurs

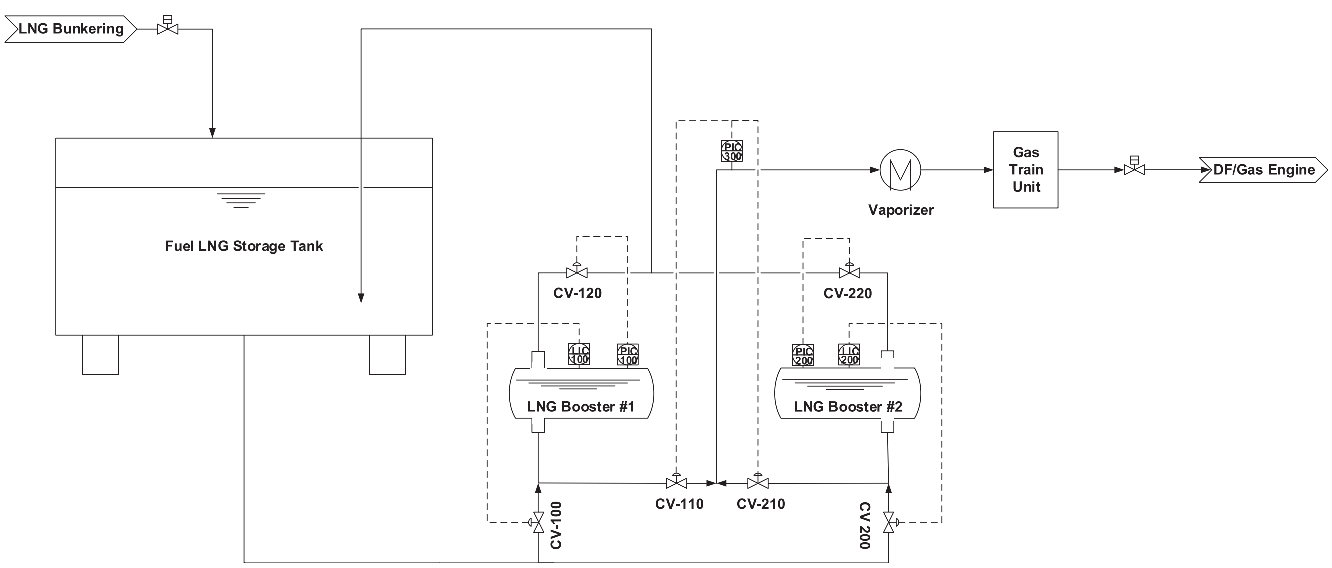

Fig. 7. Pump-free system.

regulating valves. The two boosters work in an alternative way to guarantee continuous export of the low-temperature liquid. The mini-vaporizer of the first booster increases the internal pressure and continuously exports the pressurized liquid while the other booster is filled with the low-temperature liquid, waiting for its turn to export the contained liquid. It is illustrated in Table 8. Detailed design was performed after a review of the uppermost level FRs. DP2 and DP4 were modified, thus lowering the risk of

Table 8
FMECA of pressurized tank with a cryogenic pump and pump-free system.

Item	Level 1	Level 2	Category (Ref. No.)	Failure rate (Per 10^6 h)	Failure rate (Per 1 year)	Repair time (h)	Note
Pressurization system I (Original)	Cryogenic pump	Impeller	P-1	86.51	0.02	Non-repairable onboard	Pump, Centrifugal
		Seal, gasket	P-2				
		Diffuser casing	P-3				
		Electric motor	P-4				
Pressurization system II (Improved)	Heating type pressurizing unit	Vessel	PP-1	24.47	0.21	8.5	–
		Electric heater	PP-2	16.81	0.15	24	–
		Control valve	PP-3	2.35	0.02	–	–

Table 9
FMECA of heat booster tanks in pump-free system.

Item				Failure			Effect of failure	Failure rate ranking (1–5)	Severity ranking (1–5)	Detectability ranking (1–5)	RPN
Ref. No.	Main item description	Function	Operation mode	Failure mode	Failure cause or mechanism	Detection of failure	On the system function				
PP-1	Pressurized tank	Compressing LNG, transport LNG to the vaporizer, engine	Normal	Leak	External force, corrosion	Pressure reduction, human perception	To stop the entire system	3	3	2	18
PP-2	Electric heater			Not on control	Power failure, connection out	Pressure reduction, human perception		3	3	2	18
PP-3	Control valve			Not on control	Power failure, connection out	Status of display, human perception		2	3	2	12

vaporized LNG entering the pump. The resulting decoupled detailed design is shown below.

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \end{bmatrix} = \begin{bmatrix} X & & & \\ & X & & \\ & & X & \\ & X & X & X \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \end{bmatrix} \tag{4}$$

In the above matrix, there is no relationship between FR1 and DP4 because DP4 covers the operability of the boosting tanks. It controls the valve and does not cover the overall system. Thus, main tank failure or leakage within the hull would lead to system shutdown and loss of fuel supply. It is only a problem between FR1 and DP1 relations. FMECA analysis was performed on the improved design. From Table 8, we can see that improvements were made in failure rate and repair. In particular, repair-related items are improved significantly. Therefore additional spare booster banks can be installed to enhance system stability. Because of these features, result of design reduces severity levels, as in Table 9.

Potential risk assessment using FMECA led to a notable decrease in the risk associated with the pump. The modified design is also more economical, although this effect is not prominently visible above.

5. Conclusions

This study proposed a novel methodology to derive conceptual designs for improved design reliability in the shipbuilding industry and other large, complex industries associated with safety-critical products. The methodology succeeded in developing highly reliable conceptual designs by adequately combining AD and FMECA at the initial design stage.

FMECA is a systematic procedure for identifying the failure modes in the initial design stage. Thus, it can predefine risk factors of the conceptual design and reduce potential risks and AD can be utilized to prevent the propagation of the risk factors to other design parameters. It means that there should be optimum system reliability that minimizes the sum of the initial cost and the operating cost (i.e., the lifecycle cost). Therefore, it provides various selections of conceptual design. The designer can choose or induce the design that has initial and operation cost benefits.

The reliability of the conceptual design methodology was evaluated and improved through application to the design improvement of LNG FGSS. The case study verified the applicability and effectiveness of the proposed methodology.

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