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Applications of Axiomatic Design in Developing Nuclear Systems

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1. Introduction

The first step of designing nuclear systems starts with the identification of the top-level requirements given by stakeholders and regulatory authorities. A detailed design of structure, system and component then follows. Design is divided into two processes: 'synthesis' and 'analysis.' While synthesis is the process of decision-making on parameters, analysis is the process of optimizing the parameters selected. It is known from experience that the mistakes made in the synthesis process, particularly of a conceptual stage, are never completely corrected in the analysis process, which is more serious in designing complex safety critical systems such as nuclear power plants [1]. It should be also noted that we normally believe that synthesis is only driven by engineers' heuristic knowledge. This paper proposes the applications of Axiomatic Design (AD), which is a design management tool as slightly opposed to this conventional view. I hypothesize that the design management using design axioms reduces uncertainty and subjectivity particularly at a conceptual phase so that a safer nuclear system can be developed while reducing cost in view of the system's entire life cycle. I will describe the notion of AD and introduce a few case studies.

2. Application of Axiomatic Design

In engineering education, 'systematic design' is a quite traditional topic. 'Systematic' is interpreted as 'minimizing' uncertainty and subjectivity in choosing design parameters so that a system can meet higher performance and/or safety requirements while reducing cost. The representative methodologies are AD [2], Decision-based Design [3], Information-based Design [4], Design for Six Sigma [5], and TRIZ [6]. Recently the requirements engineering was applied to the NSSS design [7]. Even though the details are different from each other, their generals could be summarized into four items; (1) mapping customers' requirements with engineers' terminologies, (2) the direction or rules of better design, (3) the method of evaluating system's ideality, and (4) the feedback of the evaluation results.

2.1 Design Management Using Axiomatic Design

AD is a kind of design management tools. It facilitates synthesis and analysis process by organizing functional requirements at each design phase in a traceable way. AD classifies the entire design process into four domains; (1) Customer Attribute (CA), (2) Functional Requirement (FR), (3) Design Parameter (DP) domain, and (4) Process Variable (PV). The four domains enable us to manage the entire system design even including operation and maintenance. The synthesis process in the AD framework is achieved by a zigzagging decomposition between the FR domain ("what we want to achieve") and the DP domain ("how we achieve it"), and supervised by two axioms:

- The independence axiom: maintain the independence of FRs
- The information axiom: minimize the information content of a design

The AD hypothesizes the interaction between the FR and DP domain determines qualitative goodness of design, which is indicated by the independence axiom. The information axiom provides the quantitative method for evaluating system's ideality. The information content is a quantity measuring how difficult a top FR is achieved.

The study evaluating the design process of Emergency Core Cooling System (ECCS) provides how AD helps to explain the different responsibility of the design principles such as independence or redundancy [8]. Figure 1 show the DM of the ECCS in OPR1000 and APR1400. This case study shows that two design axioms can provide the priority and the direction for deploying design principles.

2.2 Axiomatic Design Combined with Fault Tree

While AD plays a role in the level of design strategy, a lot of analysis tactics can be applied for a specific purpose [9]. A FR-DP tree and a Design Matrix (DM), that is the schematic tools which the AD framework offers, facilitate applying the independence axiom. Though the calculation of the information content is theoretically feasible, an enormous number of variables affecting the information content make it practically impossible. I suggested the information content could be approximated to the failure rate or probability determined by Fault Tree Analysis (FTA) for the applications of designing nuclear systems. I developed the methodology of converting a FR-DP tree into a fault tree on the basis of their complementarity [10]. We have therefore the following benefits given by the proposed design management. The synthesis process driven by

AD involves a lot of available information so that we can carry out the FTA with less amount of effort. In the mean while, we should be able to get the same amount of insight from the FTA converted from AD. The fault tree during the synthesis process allows a better chance to find out design vulnerabilities by observing a system from the viewpoint of failure domain. The survey on failure domain may be useful to complete missed sets of FRs and DPs. Figure 2 illustrates the entire design process based on AD.

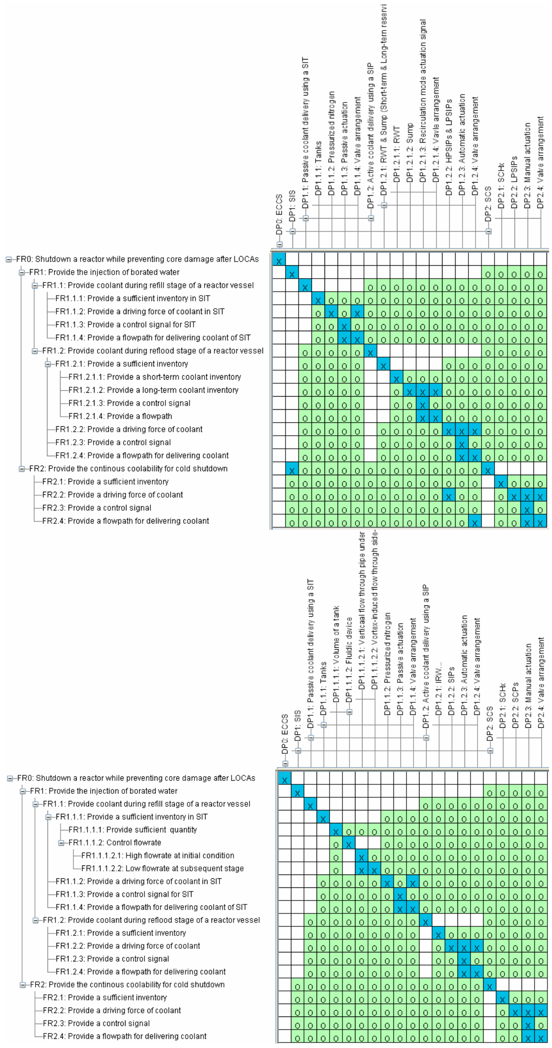

Figure 1. Design matrix of the ECCS in OPR1000 (Upper) and APR1400 (Lower).

For demonstrating the use of FTA as one of the design tactics, I illustrated design process of Containment Heat Removal System [10]. This study step-by-step explains the entire design process on the basis of the proposed synthesis strategy. These case studies tried to integrate synthesis and analysis process to meet a top FR in an effective solution, while spending less design resource.

3. Conclusion

Currently the need and interests of the configuration management is increasing rapidly in nuclear industry [7]. This paper dealt with how we manage the design process using AD, which might be more useful as the framework of creating new nuclear systems. From the experience of applying AD to the design process of nuclear systems, we expect that AD could be a candidate of such configuration management tools.

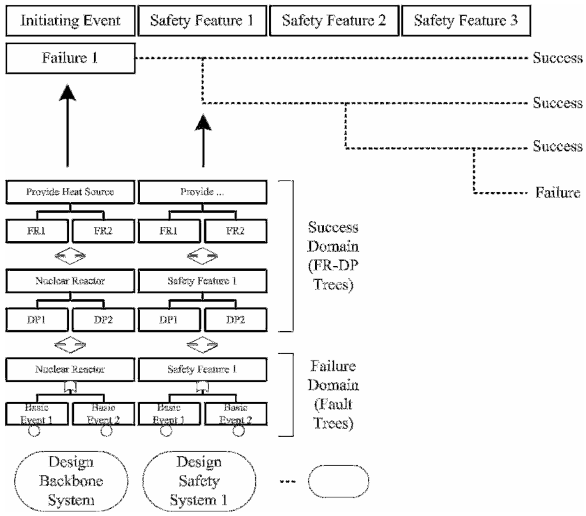

Figure 2. Illustration of the design management supervised by AD.

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