Journal of KOSSE. (2021. 12) Vol. 17, No. 2 pp. 69-81
DOI: https://doi.org/10.14248/JKOSSE.2021.17.2.069
www.kosse.or.kr

ISSN (print) : 1738-480X
ISSN (online) : 2288-3592

# Development of a Functional Complexity Reduction Concept of MMIS for Innovative SMRs

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Abstract : The human performance issues and increased automation issues in advanced Small Modular Reactors (SMRs) are critical to numerous stakeholders in the nuclear industry, due to the undesirable implications targeting the Man Machine Interface Systems (MMIS) complexity of (Generation IV) SMRs. It is imperative that the design of future SMRs must address these problems. Nowadays, Multi Agent Systems (MAS) are used in the industrial sector to solve multiple complex problems; therefore incorporating this technology in the proposed innovative SMR (I-SMR) design will contribute greatly in the decision making process during plant operations, also reduce the number MCR operating crew and human errors. However, it is speculated that an increased level of complexity will be introduced. Prior to achieving the objectives of this research, the tools used to analyze the system for complexity reduction, are the McCabe's Cyclomatic complexity metric and the Henry-Kafura Information Flow metric. In this research, the systems engineering approach is used to guide the engineering process of complexity reduction concept of the system in its entirety.

*Key Words* : MMIS, SMR, Multi Agent Systems, Complexity Reduction, Automation

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**Received:** October 15, 2021 / **Revised**: December 9, 2021 / **Accepted**: December 17, 2021

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## 1. Introduction

Due to a variety of well-known special advantages, global interest in Small Modular Reactors (SMRs) has increased.[1] Several designs of such reactors have been developed and some yet to be deployable. These advanced reactors produce electricity of up to 300 MW(e) per module[2] and are classified as Generation IV reactors. In the nuclear industry, there are several SMR designs, and each of these reactor types has its own set of I&C needs for reactor control, monitoring, and operation. These sophisticated SMRs have advanced automation systems, which have aided in autonomous plant operations and, on the contrary, have created certain discrepancies, particularly pertaining to human performance following plant design and operations.[3],[4]

Human performance is a critical issue that numerous stakeholders are addressing due to its implications on the plant management of (SMRs) advanced reactors. These concerns [4] includes;

(i) reduced operator skills as a result of increased automated operations
(ii) difficulties understanding complicated automation
(iii) reduced situation awareness
(iv) difficulty transitioning between automatic and manual control workloads, and
(v) multi-module man-machine operational complexity
(vi) MCR monitoring and control navigation complexity.

As part of the background to this research concept, is based on an ongoing research study about an Encapsulated Nuclear Heat Source (ENHS) 125 MWth fast spectrum reactor concept that was selected by the 1999 DOE NERI program as a candidate "Generation-IV" reactor (plant). The plant is intended to offer a large tolerance to human errors, with increased automation, and is likely to get public acceptance via demonstration of excellent safety reactor.[5] Hence it is imperative to devise an innovative SMR (I-SMR) design that is speculated to support MCR operator interactions with the MMIS of these advanced reactors. However, it is ideal to speculate that introducing other innovative design features to an already existing reactor design may introduce some degree of system complexity. In view of this, the research objective is aimed at demonstrating how the proposed system design functional complexity can be reduced, also adopting other existing design features and integrating artificial intelligence technology in the man-machine interface systems (MMIS). The top level Nuscale SMR Module Protection System, which is part of the MMIS is chosen for analysis. Narrowing down the objective of this research is specifically targeting the following;

(i) Develop an innovative SMR design that illustrates less system functional complexity compared to the reference design (Nuscale SMR).
(ii) Illustrate how complexity metric tools can be used extensively to analyze and reduce system functional complexity, with the aim of exploiting for optimal

solutions.

Prior to achieving the goal of this project, attention is given to establishing a method for reducing the functional complexity of MMIS in an advanced SMR. The systems engineering approach is applied in this work to guide the engineering process of this complex system in its entirety.[6]

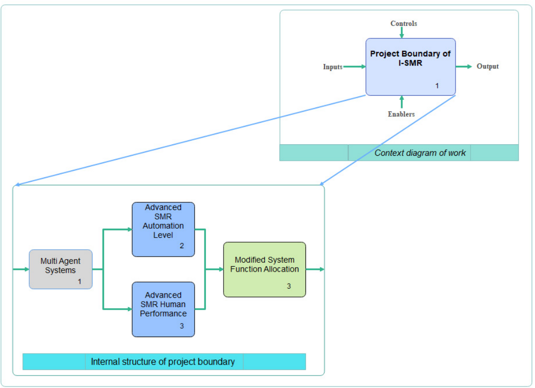
The main contributions identified in this research are:

(i) The functional complexity in the MMIS of future advanced SMRs are speculated to reduce, as the complexity metric is used to quantitative justify this concept.
(ii) Human errors during multi modular plant operations is speculated to reduce due to the operator support feature of the proposed technology introduced.
(iii) The number of MCR operating crew is speculated to reduce, as compared to Nuscale SMR MCR staffing requirement.

## 2. Systems Engineering Approach

According to INCOSE, this engineering technique covers the entire system lifecycle [7]. The ISO/IEC 15288 document is a technical standard in systems engineering produced by the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC). It specifies the procedures and lifecycle stages of a system.[8],[7] To develop a system successfully, the systems engineer must first comprehend the system of interest, including its specified boundary, intended purpose, and the synergy of components contained in the system, per the standard approach.[6]

As illustrated in Figure 1, the scope of this research is centralized on the concept of reducing the complexity of SMR's Man−Machine Interface (MMIS) design. The Nuscale SMR design is used as a reference design in this research to analyze the suggested concept development and the innovative measures chosen to be integrated. Multi Agent Systems (MAS) are introduced in the proposed architecture to allow interactive techniques of agents to make logical decisions in the plant. For its well−known collaborative learning capability of solving complex problems using a predefined set of algorithms, MAS is widely employed in industrial applications.[9],[10] The important functions (roles) assigned to man (operator) or machine (automation) were analyzed and modified by referencing available technical documentation from Nuscale SMR[11] and other applicable regulatory guides and standards[12],[13],[14],[15],[16] to generate a substantial sense of balance for the proposed design. The McCabe's Cyclomatic complexity metric[17]

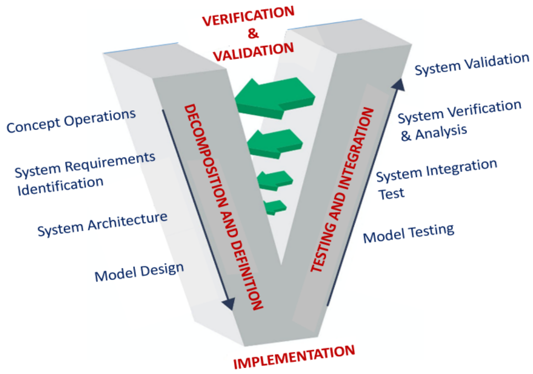


[Figure 1] IDEF0 Context diagram of work and Henry–Kafura Information Flow metric [18] are relevant metric tools for complexity analysis in this research, as recommended in NUREG/CR–6083.

As shown in Figure 1, the input, which is the concept of operations (ConOps) of advanced SMRs and its relationships with other engineering process were analyzed and modified (see Figure 3) to fit the proposed design concept. The controlling factors identified for this research were the available SMR licensing issues, Top–tier user requirements, and applicable regulatory guides. The Enablers identified were centralized on the Human Factors Engineering, Situation Awareness, and Systems Engineering. The synergy of these external entities interact within the specified boundary of this work to generate a desirable output, resulting in a reduced functional complexity of SMR Man–Machine Interface System design. Inside the boundary of this work the automation level of the reference design were analyzed, as well as the human performance issues related to such advanced SMRs were also analyzed. Moreover, a generic Multi Agent System (MAS) is adopted [19] for this research for conceptual demonstration purposes, and as a result, critical assessments and system function modifications were performed based on the recommendations provided in NUREG/CR–3331. The IDEF0 diagram aids to visualize the context diagram of work as it facilitates the desirability of this research.

### 2.1 System Development Lifecycle (V–Model)

The V–model illustrates the procedure by which the system's complexity were reduced in a step–by–step lifecycle process. Beginning with the decomposition of the problem domain into its constituent parts, as illustrated in Figure 2, then in the composition phase, possible solutions were identified and as a result the proposed system design was analyzed, tested, verified, and validated.



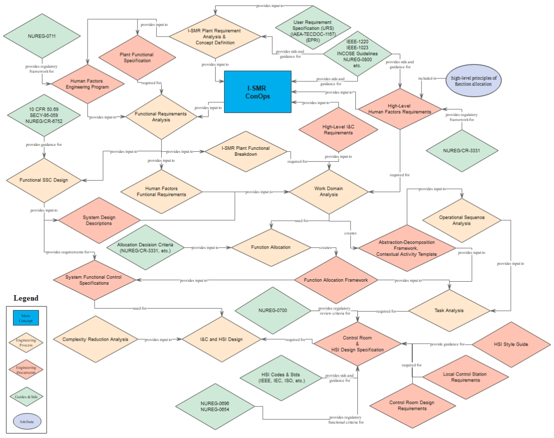
[Figure 2] Context development V–model

## 3. Concept Development

### 3.1. Concept of Operation

The framework for developing the concept of operations for the proposed innovative SMR (I–SMR) was derived from IDAHO National Laboratory's technical report.[20] The concept of operations of advanced SMRs in general, outlines in detail the characteristics of the proposed system from the viewpoint of stakeholders. Figure 3 illustrates the I–SMR’s concept of operations and its relationship with other engineering processes, this serves as input to the context of this research.

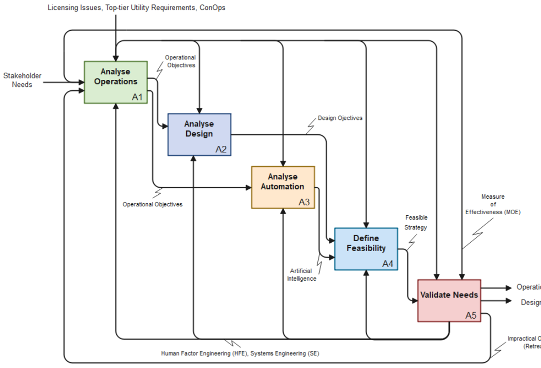
The scope of emergency conditions of the multi module plant was not analyzed in the ConOps in this research, but much emphasis is placed on the man-machine interface systems information processing and how twelve (12) power modules can be managed with a reduced number of MCR operating crews in normal operational conditions.



[Figure 3] Relationship Diagram for I-SMR ConOps and Other Engineering Processes

## 3.2. Requirement Analysis

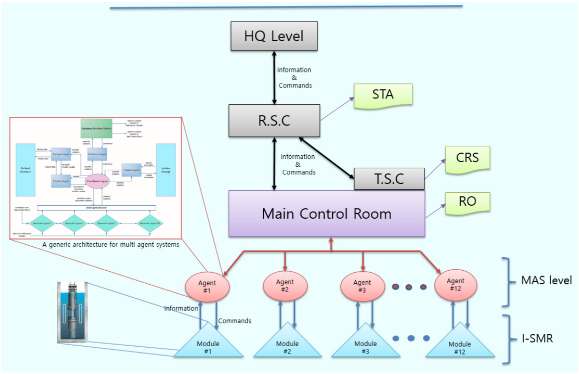
The requirement analysis aids in determining whether or not the proposed concept is desirable. In the proposed design (I-SMR), the system is expected to be operated with a reduced number of operating crew in the main control room as compared to the existing Nuscale SMR design. Also the system functional complexity of the proposed design should prove less complex using a suitable complexity metric tool. As a result, despite the fact that the plant has not yet been constructed, a reverse engineering of the Nuscale design was carried out using a detailed assessment of their publicly available technical reports. A breakdown of the requirements analyses activities done is as shown in Figure 4 using the Integrated DEfinition Function 2 model (IDEF2) diagram. Stakeholders identified in this research includes designers of Generation IV reactors, operators, regulators, users, and owners.



[Figure 4] System Requirements Identification and Analysis

## 3.3. System Architecture

Following the monitoring and control of modular reactors, many paradigms have emerged to meet the needs and challenges of plant operation and maintenance. The architecture design is an innovative adaptation of the Nuscale SMR plant, as depicted in Figure 5.



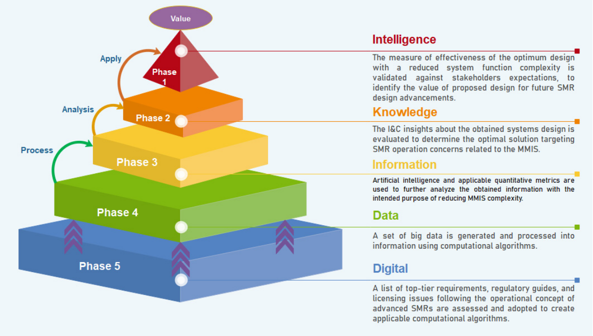
[Figure 5] I-SMR architecture development[21],[19]

The original plant design is configured for up to twelve 12 Nuscale Power Modules

(NPMs), to be monitored and controlled from a single control room. Regardless of the fact that the Nuscale plant is not yet deployed for commercial usage[21], prospects of human errors and multi-module operational complexity during plant operations is still quite skeptical following the functional complexity of the MMIS. As a result, the proposed design's advanced feature is the integration of multi-agent systems, which allows intelligent entities to execute both normal and complicated plant anticipated operational occurrences. Technical Support Centre (TSC), Regional Support Centre (RSC), and Head Quarter (HQ) responsibilities are provided in compliance with NUREG-0696 and NUREG-0711 design requirements. The Shift Technical Advisor (STA) and Control Room Supervisor (CRS) are responsible for providing technical support to the Reactor Operator (RO) located in the main control room. The bidirectional information flow of a control structure from the MCR through the MAS to the twelve modules of the plant is the focus of the proposed design structure analyzed.

### 3.4. Model Design Definition

The suggested system's model design is divided into five phases, as depicted in the pyramid in Figure 6. The innovative modular reactor from Phase 5 takes into account several related top-tier requirements, regulatory guides, and licensing issues following the concept of operations of advanced SMRs, were assessed and adopted to create applicable computational algorithms. In Phase 4, a set of big data is generated and processed into valuable information using computational algorithms. It is critical to understand that more data produced does not equal more information.[20], hence the data is refined in this phase and processed further to the next. In Phase 3, the multi agent systems introduced in the design and applicable quantitative metrics (McCabe Cyclomatic metric and Henry-Kafura Information Flow metric) are used to further analyze the obtained information, with the intended purpose of reducing MMIS complexity. The analysis of information results demonstrated the knowledge obtained in Phase 2, and in this phase the insights of I&C related to the obtained systems design is evaluated to determine the optimal solution targeting SMR functional complexity concerns related to the MMIS of the plant. The knowledge obtained is applied in Phase 1, to measure the effectiveness of the optimum design with a reduced system functional complexity which is validated against the identified stakeholders' expectations. This is necessary in order to identify the value of proposed design for future SMR design developments.



**Intelligence**

The measure of effectiveness of the optimum design with a reduced system function complexity is validated against stakeholders expectations, to identify the value of proposed design for future SMR design advancements.

**Knowledge**

The I&C insights about the obtained systems design is evaluated to determine the optimal solution targeting SMR operation concerns related to the MMIS.

**Information**

Artificial intelligence and applicable quantitative metrics are used to further analyze the obtained information with the intended purpose of reducing MMIS complexity.

**Data**

A set of big data is generated and processed into information using computational algorithms.

**Digital**

A list of top-tier requirements, regulatory guides, and licensing issues following the operational concept of advanced SMRs are assessed and adopted to create applicable computational algorithms.

[Figure 6] Model design definition diagram

## 4. Implementation

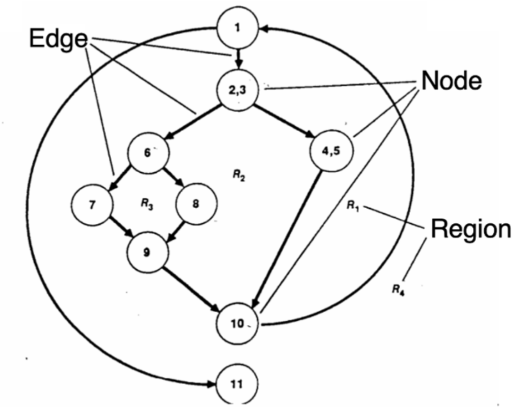
The engineering development or implementation of this work starts by using a broad based methodology proposed in NUREG/CR-3331 for determining provisional allocations based on the criteria of technical feasibility, operational requirements, and functional requirements. In the process of developing a conceptual solution to the problems identified, two complexity metrics "McCabe cyclomatic complexity and Henry-Kafura Information flow metric" were used to perform quantitative analysis on the systems of interest. McCabe's metric is best suited to check for cyclomatic complexity of the low level system control structure, while Henry-Kafura's metric is best suited to check for the degree of information flow complexity of top-level system control structures.[22] A section of the MMIS is chosen to be analyzed based on the limitation of available data from the reference design. The module protection systems were analyzed, and the proposed innovative options were altered to fit.

### 4.1. Complexity Metrics

#### 4.1.1. McCabe's Cyclomatic Complexity metrics

The cyclomatic complexity measures the complexity of control flow of a system, it takes into account the number of flow paths through a system program. The cyclomatic number v(G) of a graph G with n vertices, e edges, and p connected components is mathematically represented as:

$$v(G) = e - n + 2P \qquad \text{Equation 1}$$



[Figure 7] concept of McCabe's Cyclomatic control graph

i . The labeled circles are the nodes and denoted as "n"

ii. The connecting arrows are the "edges" and denoted as "e"

iii. The ">=2" output nodes are the predicate nodes, and are denoted as "P"

In most example calculations, a cyclomatic complexity below 4 is considered good; a cyclomatic complexity between 5 and 7 is considered medium complexity, between 8 and 10 is high complexity, and above that is extreme complexity.[17]

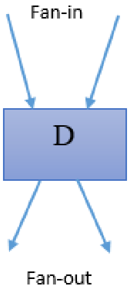
#### 4.1.2. Henry - Kafura Information Flow metrics

By evaluating the flow of data between system components or modules, information flow metrics are employed to deal with this level of complexity. This measure is provided by Henry and Kafura. As a result, it's also known as Henry and Kafura's Metric. The flow of data between system modules is measured with this metric.[23],[18] Henry-Kafura

Information flow defines the complexity of a module based on the fan–in and fan–out of information flow for the module under analyses.

ⅰ. Fan–in: number of components that can call D.
ⅱ. Fan–out: number of components that are called by D.

$$Cp(D) = [Fan-in(D) \times Fan-out(D)]^2 \quad \text{Equation 2}$$



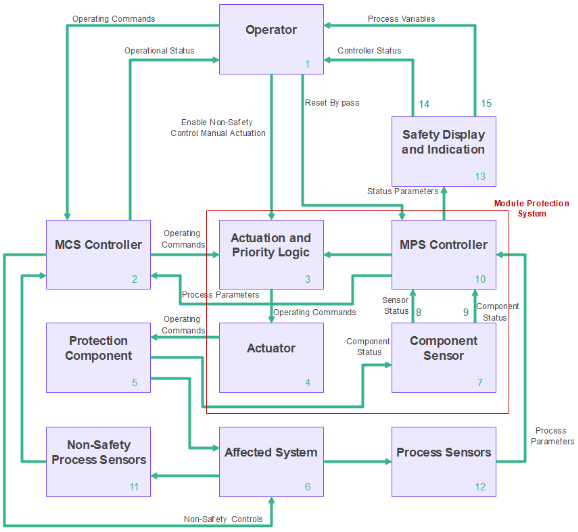
[Figure 8] Concept of Fan–in and Fan–out

Fan–in and Fan–out Metrics: Fan–in and fan–out are the metrics used to measure top level structural complexity of system modules. [22]

## 4.2. Systems Structure Analysis and Testing

### 4.2.1. Analysis of MPS High Level Control Structure

An example Module Protection System (MPS) high level control structure adopted from Nuscale SMR final safety analysis report as shown in Figure 7, was analyzed to determine where the system control function can be improved or where the interfacing safety and non– safety system components can be innovatively modified.



[Figure 9] Reference Design High Level MPS Control Structure [11]

The MPS is designed for the each plant module protection, and its prime purpose is to monitor process variables and provide automatic initiation signals during abnormal conditions, also provide protection against each unsafe Nuscale power module (NPM) during steady state and transient power operations.

### 4.2.2. Complexity Calculations

The complexity of control Structure for Figure 9 were calculated using the Henry–Kafura metric, and the following were the results obtained;

<Table 1> Information Flow Analysis for Individual Modules

| Module | Mod-1 | Mod-2 | Mod-3 | Mod-4 | Mod-5 | Mod-6 | Mod-7 | Mod-8 | Mod-9 | Mod-10 | Mod-11 | Mod-12 | Mod-13 | Mod-14 | Mod-15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fan-in (Fi) | 3 | 3 | 3 | 1 | 1 | 2 | 1 | 1 | 1 | 4 | 1 | 1 | 1 | 1 | 1 |
| Fan-out (Fo) | 3 | 3 | 1 | 1 | 2 | 2 | 2 | 1 | 1 | 3 | 1 | 1 | 2 | 1 | 1 |
| $(Fi \times Fo)^2$ | 81 | 81 | 9 | 1 | 4 | 16 | 4 | 1 | 1 | 144 | 1 | 1 | 4 | 1 | 1 |

As shown in the above table, the complexity of information flow is identified in the module protection system (Mod-10), module control system (Mod-2), and the operator (Mod-1). The Fan value of the individual module 10, is the highest and therefore subjective for further analysis as a standard approach to this metric. However the total system complexity is essential to be computed.

### i. Total System Complexity

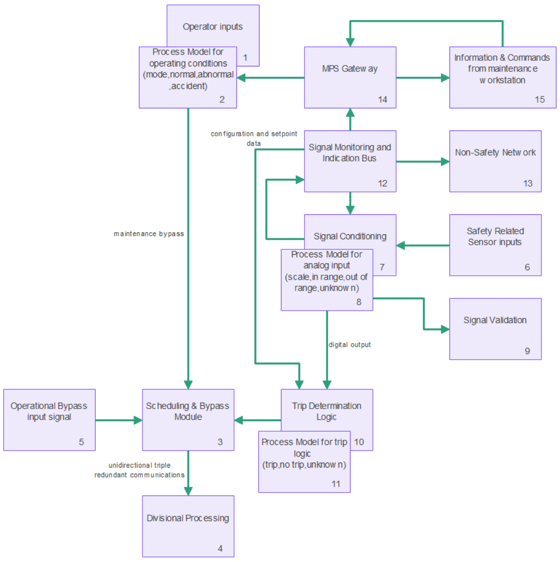
The final system sum ($C_T$) value shows the overall complexity rating and aids to compare alternative designs. The ($C_T$) is the sum of all "$(F_i \times F_o)^2$" values.

$$\text{System sum } (C_T) = 350$$

As a result of further analysis performed on module 10, the "Safety Function Module (SFM)", "Scheduling and Bypass Module (SBM)", "Scheduling and Voting Module (SVM)", "Equipment Interface Module (EIM)", were identified as sub systems integrated inside the MPS Controller but due to the limitation of open access information in this regard, only the Safety Function Module (SFM) is assessed. A low level logic structure of the SFM is analyzed using the McCabe's cyclomatic metric.

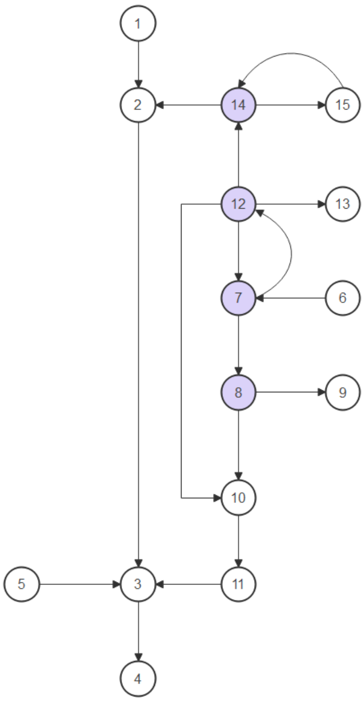
### 4.2.3. Analysis of SFM Low Level Logic Structure

The Safety Function Module according to Nuscale is designed to perform the function of signal conditioning, trip determination, and serve as a communication engine for actuation signals.



[Figure 10] Low Level Logic Structure of SFM[11]

The above SFM structure is reverted into a control graph with nodes and edges, purposely to aid the computation of cyclomatic complexity, v(G). This control graph is as shown in Figure 11.



[Figure 11] Control Graph of SFM Low Level Logic Structure

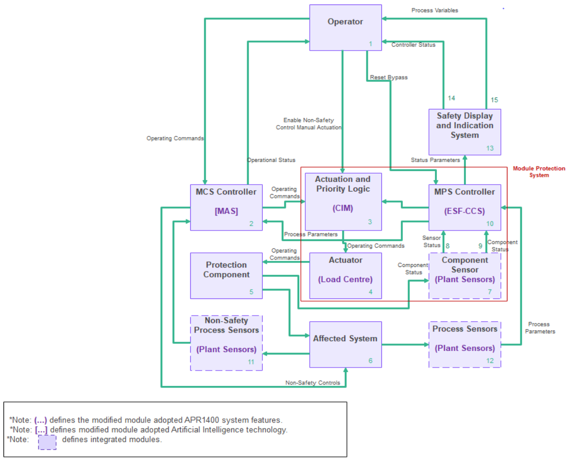
The cyclomatic complexity from the flow graph in Figure 11, can be calculated using the cyclomatic complexity equation. The v(G) is calculated using three methods;

i Method 1: $v(G) = e - n + 2(P)$ (where P is the number of connected components $= 1$)
ii Method 2: $v(G) = P + 1$ (where P is the number of predicate nodes)
iii Method 3: $v(G)$ = Number of regions

<Table 2> SFM Cyclomatic Complexity Results

| McCabe Cyclomatic Complexity Analysis | | | | |
|---|---|---|---|---|
| **Complexity** | **E** | **N** | **P** | **v(G)** |
| Method 1 | 18 | 15 | 1 | 5 |
| Method 2 | - | - | 4 | 5 |
| Method 3 | - | - | - | 5 |

The v(G) results enumerated in Table 2, implies that the cyclomatic complexity of the low level SFM is low, and therefore less prone to functional errors, likewise a low probability to software program errors. However, because the other modules are not analyzed in this work due to information limitations, we cannot speculate a low complexity for the other sub-modules. In view of this, alternate measures were adopted to reduce the system functional complexity. This is done by integrating a generic multi agent system in the innovative SMR and also adopting applicable engineered safety features of the Advanced Pressurized Water Reactor 1400 (APR1400) nuclear power plant in the I-SMR top level MPS design. The concept of system modification is as shown in Figure 12 below.

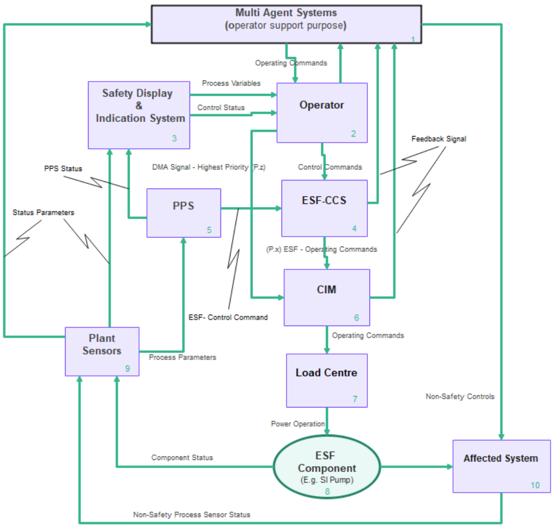


*Note: (...) defines the modified module adopted APR1400 system features.
*Note: [...] defines modified module adopted Artificial Intelligence technology.
*Note: ▨ defines integrated modules.

[Figure 12] Obtained High Level MPS Modification Diagram

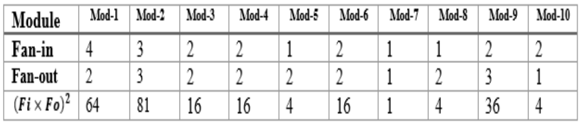
## 5. System Integration and Analysis of I-SMR

From a technology centered perspective it is known that while automation can effectively enhance operational performance of SMRs, human interactions is still essential for monitoring and top level decisions making. This research used the principles outlined in NUREG/CR-3331 to innovative devise system design options.



[Figure 13] Proposed MPS High Level Control Structure for I-SMR[11],[24] Some of the modules used in the innovative design were adopted from the Engineered Safety Features- Component Control System (ESF-CCF) schematic diagram of the Advanced Pressurized Water Reactor 1400 (APR14100). Based on the functional objective of each module in the reference design (Nuscale SMR) these adopted features were matched to fit. Based on the proposed system design as shown in Figure 13, the information flow of each module was computed and Table 3 enumerates the results.

<Table 3> Proposed MPS High Level Control Structure Information Flow results



| **Module** | Mod-1 | Mod-2 | Mod-3 | Mod-4 | Mod-5 | Mod-6 | Mod-7 | Mod-8 | Mod-9 | Mod-10 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Fan-in** | 4 | 3 | 2 | 2 | 1 | 2 | 1 | 1 | 2 | 2 |
| **Fan-out** | 2 | 3 | 2 | 2 | 2 | 2 | 1 | 2 | 3 | 1 |
| $(Fi \times Fo)^2$ | 64 | 81 | 16 | 16 | 4 | 16 | 1 | 4 | 36 | 4 |

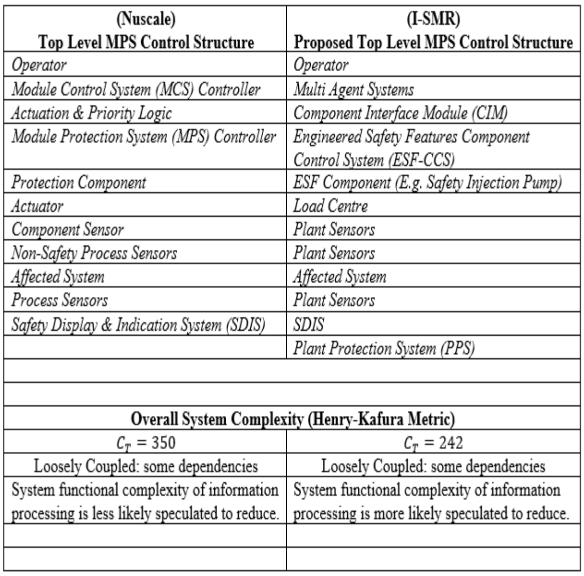
Total complexity ($C_T$) for the entire MPS control structure of I-SMR = 242

## 6. System Verification and Results Analysis

In evaluation of the results, a comparison is performed between the two designs, as Table 4 illustrates.

The above results are based on a black box testing perspective, which is also dominant in the software engineering sector for testing top level system structures. The Henry-Kafura complexity metric demonstrates a comparable test concept for quantitatively determining whether or not certain modifications will increase complexity. The results reveal that the innovative SMR's total complexity ($C_T$) is significantly lower than the Nuscale design. This is as a result of identifying modules that were tightly coupled to other modules, and devising alternate design solutions.

<Table 4> A Comparative Measure of Overall MPS Complexity



| (Nuscale)<br>Top Level MPS Control Structure | (I-SMR)<br>Proposed Top Level MPS Control Structure |
|---|---|
| *Operator* | *Operator* |
| *Module Control System (MCS) Controller* | *Multi Agent Systems* |
| *Actuation & Priority Logic* | *Component Interface Module (CIM)* |
| *Module Protection System (MPS) Controller* | *Engineered Safety Features Component Control System (ESF-CCS)* |
| *Protection Component* | *ESF Component (E.g. Safety Injection Pump)* |
| *Actuator* | *Load Centre* |
| *Component Sensor* | *Plant Sensors* |
| *Non-Safety Process Sensors* | *Plant Sensors* |
| *Affected System* | *Affected System* |
| *Process Sensors* | *Plant Sensors* |
| *Safety Display & Indication System (SDIS)* | *SDIS* |
|  | *Plant Protection System (PPS)* |
|  |  |
|  |  |
| **Overall System Complexity (Henry-Kafura Metric)** |  |
| $C_T = 350$ | $C_T = 242$ |
| Loosely Coupled: some dependencies | Loosely Coupled: some dependencies |
| System functional complexity of information processing is less likely speculated to reduce. | System functional complexity of information processing is more likely speculated to reduce. |
|  |  |
|  |  |

## 7. System Validation

The proposed design was validated against the stakeholder needs and expectations for future advanced SMR designs. Based on the quantitative results shown in Table 4, this research speculates the following;

i. A reduction in the functional complexity related to man-machine interface systems by adopting multi agent systems to support human performance actions.

ii. A reduction in the number of operating crew per shift of on-site SMR plant operations.

iii. A reduction in human error

## 8. Conclusion

This research used a systems engineering approach to successfully guide the concept of reducing functional complexity in an innovative SMR compared to the reference design (Nuscale SMR). In addition the complexity metric tools used in the system analysis successfully demonstrated that the innovative system functional complexity can be reduced. The outcome of this study provides insights of technical basis for future SMR designers, by considering the aspects of functional complexity reduction. The proposed I-SMR MPS design evaluates that the synergy of both human interaction and multi agent systems roles during monitoring and control of the plant will reduce the functional complexity related to man-machine interfacing systems.

## Acknowledgement

This work was supported by the 2021 Research Fund of the KEPCO International Nuclear Graduate School (KINGS), the Republic of Korea.

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