Probabilistic Modelling Approach for Human Actions in Emergency Management at an SMR Multi-Unit Site

Mariela Grinberg[a], Gregorio Acuña[b], Marcelo Giménez[c]

[a] CNEA, Instituto Balseiro - UNCuyo, S. C. de Bariloche, Argentina, marielagrinberg@cnea.gob.ar
[b] CNEA, S. C. de Bariloche, Argentina, gregorioacuna@cnea.gob.ar
[c] CNEA, Instituto Balseiro - UNCuyo, S. C. de Bariloche, Argentina, marcelogimenez@cnea.gob.ar

Small Modular Reactor (SMR) designs are generally expected to reduce the need for operator action through extensive automation and passive safety systems. However, if passive systems fail or become unavailable, FLEX strategies based on mobile equipment may be required to prevent fuel damage or mitigate severe accidents. The scale and complexity of these strategies increase in multi-unit or multi-module sites. This paper presents a probabilistic modelling approach for human actions involved in emergency management at a hypothetical SMR multi-unit site, with emphasis on post-initiator human failure events (HFEs). The scope focuses on human actions required to implement FLEX-type strategies under conditions that may lead to core damage in one or both units. The proposed framework consists of a dynamic probabilistic model intended to support the analysis of alternative on-site emergency management strategies and the development of emergency operating documentation. The method begins with a literature review aimed at identifying human actions from early design information, concepts of operations, and associated HFEs. A bottom-up structure of human actions is proposed, from FLEX system connection or actuation at the unit level to site-level decision-making for shared resource allocation. Different HFEs are then evaluated using the SPAR-H method, including dependency analysis among human actions. The approach is applied to a hypothetical case study and implemented conceptually in EMRALD as a dynamic Probabilistic Risk Assessment tool. Results and conclusions are then discussed.

1 INTRODUCTION

This work is framed within the development of a probabilistic model to represent strategies defined in an on-site emergency management plan (OEMP) for multi-unit sites, with emphasis on the required human actions (HAs). For this study, the OEMP is defined as the set of documents intended to control initiating events and mitigate severe accidents. Its scope includes sites with one or more nuclear reactors and other radioactive material sources, such as spent fuel pools (SFPs). For multi-unit or multi-module sites[1], multi-unit initiating events are also considered, i.e., events that affect more than one unit. Relevant documentation includes abnormal operating procedures, emergency operating procedures, FLEX procedures and guidelines for mobile equipment deployment, and severe accident management guidelines.

On-site emergency management documentation is addressed as an element of Human Factors Engineering (HFEN), taking the facility concept of operations as the starting point, as described in [1]. Together with other HFEN elements, such as organizational structure definition, operating experience analysis, and critical HAs analysis from safety studies, this documentation supports the construction of a map of HAs required under emergency conditions. In a multi-unit site, these actions range from monitoring parameters at site and reactor level to implementing strategies and executing actions in the control room and field.

The literature review conducted for this work shows that available references provide general guidance on the content and structure of emergency management documentation [2], [3], but no specific methodologies for developing emergency management plans were identified. For new facilities based on reference reactor designs, an existing documentation baseline and operating experience may provide

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[1] In this paper, the term *multi-unit site* is used in a general sense. It also encompasses the concept of *multi-module site*, particularly in relation to SMR designs.

an initial basis, adjusted to site-specific features. However, for new reactors, particularly Small Modular Reactors (SMRs), reference designs and operating experience supporting emergency management documentation may be limited or unavailable. This challenge is intensified by the need to address multi-unit SMR sites, a lesson reinforced by the Fukushima nuclear accident.

Design processes for new nuclear facilities integrate multiple engineering disciplines that may progress at different maturity levels. Project schedule pressures may also require some processes to begin before all input information is available. For example, HFEN may identify system-level HAs for normal and emergency operation, while emergency management documentation still requires prior analysis of event control and severe accident management strategies and, ideally, simulator-based evidence. Thus, for new designs without operational precedents, emergency management design activities may involve interdependencies that hinder their development.

Accordingly, and with the broader aim of supporting emergency management documentation, the HAs involved in on-site emergency management must be identified and characterized within the socio-technical system. A dynamic probabilistic model is proposed as a support tool for developing the emergency management plan and associated documents. Within this context, this work addresses the following objectives:

- To define a structure of HAs at different levels of the organizational hierarchy involved in emergency plan management for a multi-unit site of integral pressurized water reactor (i-PWR) SMRs.

- To define guidelines for modelling HAs within a dynamic probabilistic model that supports emergency management plan development.

The scope is restricted to the identification and probabilistic modelling of HAs required under the emergency management plan at an early development stage, considering advanced detailed engineering information and basic HFEN. The analysis is limited to HAs required after a multi-unit initiating event [4]. The probabilistic model is conceived as a design support tool and does not constitute regulatory information. HFE modelling focuses on Performance Shaping Factors (PSFs) affecting different HA types using the SPAR-H - Standardized Plant Analysis Risk Human Reliability Analysis- method [5].

The paper is organized as follows. Section 2 presents the methodology. Section 3 develops the conceptual framework leading to the proposed HA structure. Section 4 addresses the probabilistic modelling of HAs. Section 5 presents an application case involving FLEX system connection at a hypothetical multi-unit site with two i-PWR SMR units. Sections 6 and 7 present the discussion and conclusions, respectively.

2 METHODOLOGY

Because prior literature reviews did not identify references specifically addressing HA identification and modelling in emergency management, a thematic decomposition was adopted, as described in Sections 3 and 4. The approach involved searching and analysing references cited in this work across three topics: HAs in nuclear reactors, HA analysis for multi-unit sites, and dynamic HA analysis. The Litmaps AI tool was used to organize references by connectivity, citation count, and publication year.

Based on this literature analysis and the specific objectives of this work, proposals were developed for the HA structure (Section 3.3) and for probabilistic HA modelling (Sections 4.3, 4.4, and 4.5). These elements are integrated in an application case for a hypothetical multi-unit site with two i-PWR SMRs.

3 IDENTIFICATION OF HUMAN ACTIONS REQUIRED FOR ON-SITE EMERGENCY MANAGEMENT

3.1 HAs in the Context of On-Site Emergency Management

The detailed progression of the Fukushima accident across the multiple units of the Dai-ichi site is documented in [6]. That account includes actions related to unit diagnosis, system status assessment, decision-making, communications with the emergency response center, and execution from both the control room and the field.

As noted in Section 1, different types of post-initiator HAs can be identified within the OEMP. This section identifies and characterizes action types in the OEMP context to support their structuring and subsequent probabilistic modelling. HAs can be conceptualized as operator activities carried out to control and manage system state, based on [7]. Regarding HA categories, [8] indicates that Level 1 Probabilistic Safety Assessment (PSA) actions involve emergency operating procedures, while Level 2 and Level 3 PSA actions require severe accident management guidelines, which are less prescriptive and rely on a different decision-making framework. The same reference notes that pre-core-damage actions are managed from the control room, whereas severe accident management involves the Technical Support Center (TSC), incorporates inputs from multiple organizations, and is therefore more complex. Under severe accident conditions, environmental conditions, including high radiation levels, may also make some activities hazardous or infeasible.

For the objectives of this work, HAs must be characterized in the context of i-PWR SMRs and emergency management at multi-unit sites. Based on [9], SMR reactors are expected to be highly automated, with extended time windows before manual actions are required due to passive system intervention. However, consistent with [10] no public information was found on the concept of operations at a level of detail sufficient to characterize human factors for this reactor type. For i-PWR designs, plant functions, operator authorities, and cognitive roles are not yet disaggregated in publicly available documentation. This limitation is reinforced by the absence of SMR operating experience [11], which would otherwise support human performance assessment and feed back into HFEN design processes. In highly automated designs, HAs are expected to consist mainly of monitoring and backup intervention. However, the same reference indicates that evidence from other industries shows that maintaining vigilance and situation awareness is challenging when operators do not interact actively with the system. The difference between normal and emergency operation in this regard requires further analysis. From a design perspective, an SMR may include passive safety systems that still require a reactor protection system signal to open valves. Consequently, HAs associated with actuation monitoring and manual component actuation may be required as backup measures.

Beyond passive event control strategies, SMR facilities are also expected to include beyond-design-basis and extreme-event strategies analogous to those used in conventional nuclear power plants [12], [13], [14]. In this sense, FLEX strategies for SMRs may be broadly similar to those applied to other power reactor designs for both pre-core-damage event control and severe accident management. Depending on design-specific features, SMRs may provide longer time windows for manual actions requiring FLEX systems.

For multi-unit HA analysis, [10] indicates that lower staffing levels are anticipated compared with larger nuclear power plants, with staff supervising automatic functions and intervening as backup when reactor conditions require.

Based on the above, the following aspects are relevant for identifying and modelling HAs in emergency management for i-PWR SMRs at multi-unit sites: reduced operating crews performing monitoring and control under normal and emergency conditions for more than one unit; event-management cognitive functions, including diagnosis through multiple monitoring sources, decision-making communicated to third parties, and action execution; execution in the control room or field, with field actions particularly related to event control and severe accident mitigation strategies using FLEX systems; and extended emergency time windows for manual actions due to passive system actuation.

In relation to HA identification, from the HFEN perspective, [1] proposes a top-down approach to task identification, beginning with functional analysis and continuing through detailed task analysis. However, it does not address the integration of HAs at unit and site levels, both of which are relevant in the OEMP context, including technical and management support from other departments within and outside the facility. From a modelling perspective, as interpreted from [15], task decomposition is not uniform across HRA analyses.

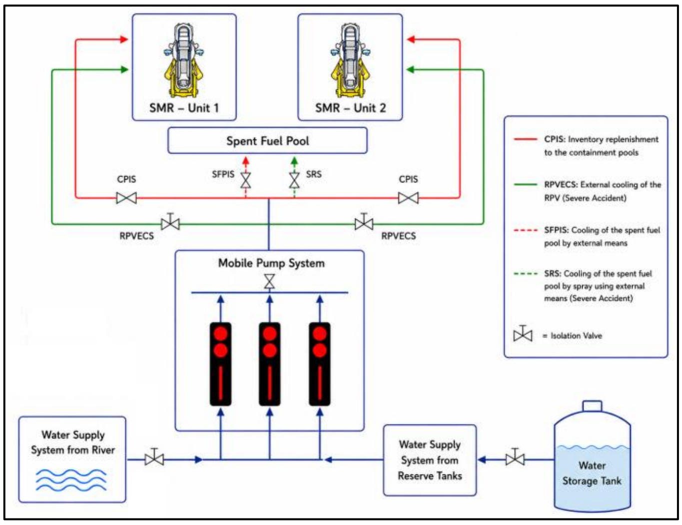
From an HRA perspective, several approaches characterize HAs through the cognitive functions required. The IDAC model proposed by [16] describes the operator problem-solving process in three stages: information pre-processing (I), diagnosis and decision-making (D), and action execution (A). The SPAR-H method structures the analysis around diagnosis and execution.

3.2 Organizational Structure for On-Site Emergency Condition Management

This section presents concepts related to organizational structure for multi-unit sites and i-PWR reactors. Organizational structure is addressed for the purpose of identifying HAs performed by different actors. The impact of organizational structure on HAs belongs to the broader topic of organizational factors and is outside the scope of this work. As noted by [17] the organization represents the actors involved in emergency management, including plant personnel, regulators, government personnel, and subcontractors. In multi-unit events, the tasks assigned to the organizations involved are more complex than for a single unit, increasing the number and intensity of interactions.

As mentioned above, information on organizational structures for i-PWR SMR multi-unit sites is not publicly available. Although organizational structure development is part of the facility HFE process, and the concepts and processes defined in [1] can be extended to a multi-unit site, this work requires a reference organizational structure. The hypothetical case study site shown in Figure 1 comprises two i-PWR SMR units and one shared SFP, with integrated monitoring and control of all three radioactive material sources from the same main control room (MCR).

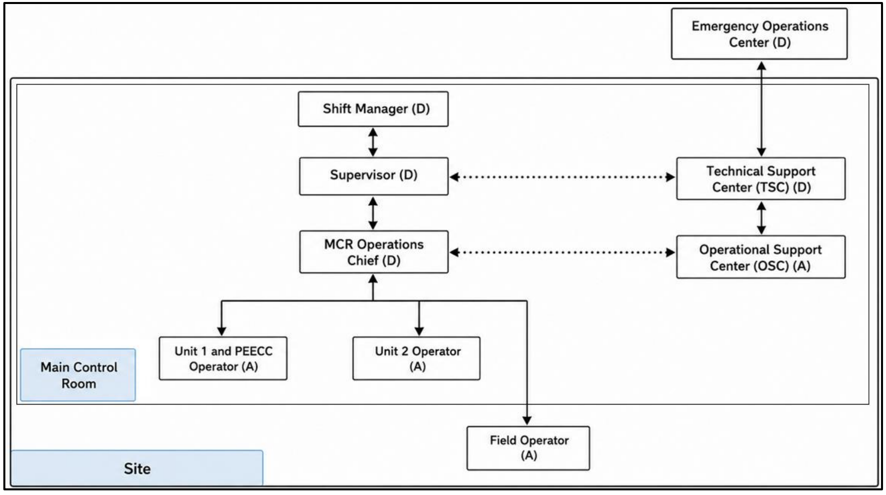
Figure 1: Schematic representation of a hypothetical multi-unit site with two i-PWR SMR units and a shared SFP.



As a reference, the MCR staffing organization at Waterford is considered, as described in [16]. That organization includes a primary system operator, a secondary system operator, and a control room chief, who reports to a supervisor and then to a shift manager. A technical advisor and an emergency communicator are associated with the shift supervisor. The reference [17] also presents an organizational model based on South Korean practice. In that model, each unit has its own set of MCR panels, i.e., functions are separated by unit. In a multi-unit event, the TSC diagnoses and manages the event for both units, with decision-making authority transferred from control room operators to the TSC. Field operators deploy mobile equipment. The Operational Support Center (OSC) provides specialist engineering support in chemistry, electrical, mechanical, and instrumentation and control areas, and performs maintenance, firefighting, and rescue activities. At a higher organizational level, the Emergency Operations Center (EOC) provides off-site technical and management assistance and makes final decisions on mobile equipment allocation priorities and communications with government and civil organizations.

For the hypothetical case study, the proposed organizational structure for emergency management is shown in Figure 2. Principal roles are presented. Lines represent reporting relationships; arrows represent communication flows. Figure 2 also characterizes each organizational block by function, distinguishing between decision-maker and executor roles based on [16]: Decision-maker (D) - exercises leadership and defines the actions to be taken; Executor (E) - implements actions in the control room or field and reports back to the requester.

Figure 2: Organizational structure proposed for emergency management in the hypothetical case study.

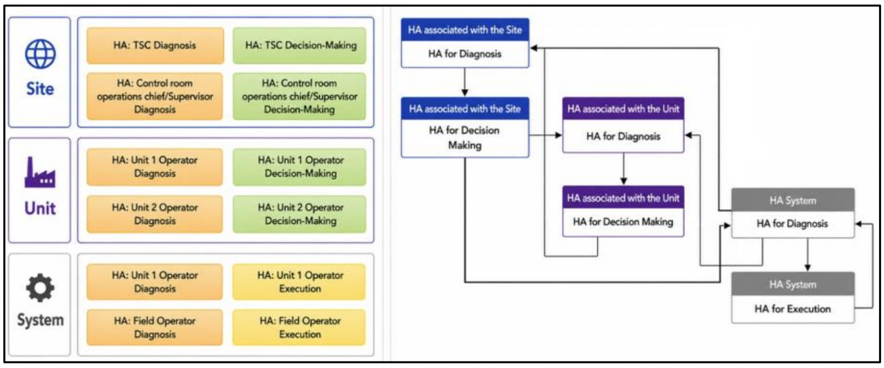


Decision-making authority is described here at a generic level. The scope and authorization of specific decisions depend on their implications and require detailed analysis. For example, the control room shift supervisor may make decisions regarding a system associated with a specific unit. However, if the decision involves allocating shared systems or FLEX systems, the TSC or a higher authority should be responsible. The shift manager would also have jurisdiction over activities outside the MCR, such as site condition monitoring, access control, radiological protection, communications, and related tasks.

3.3 Development of a Human Action Structure for On-Site Emergency Management

To identify HAs required in on-site emergency management, a conceptual structure was developed. Because this work applies SPAR-H for HA quantification, and following the discussion in Section 3.1, diagnosis and execution HAs have been distinguished. However, given the proposed organizational structure, actions classified by SPAR-H as execution must be further differentiated into decision-making actions and execution actions proper. For this purpose, the Hierarchical Task Analysis (HTA) procedure described in reference [18] is applied and integrated with the organizational structure for emergency management. Based on the HTA and the organizational structure proposed for the case study in Figure 2, the HA scheme shown in the left of Figure 3 is constructed. The proposed structure considers HAs at site, unit, and system levels. Actions are also differentiated into diagnosis and decision-making actions at site or unit level, and diagnosis and execution actions at system level. The right side of Figure 3 shows relationships among HAs.

Figure 3: Human action structure for on-site emergency management.



4 PROBABILISTIC MODELLING OF HUMAN FAILURE EVENTS IN ON-SITE EMERGENCY MANAGEMENT

4.1 Identification of Human Failure Events

An HFE can be defined as an event representing the failure or unavailability of a component, system, or function caused by human inaction or inappropriate action, as indicated in the reference [19]. Section 3 addressed HA identification in the on-site emergency management context. Identifying HFEs associated with those actions is necessary to develop a probabilistic model that represents them. However, as noted by [15], there is no direct link between a human action, as characterized in a scenario, and the identification of an HFE. The same reference notes that a HFE may encompass a set of crew functions at any phase of the cognitive process (information pre-processing, diagnosis, execution), depending on the complexity of the objective. For example, if multiple decisions are required to achieve an objective, there will be multiple cognitive stages, and failure in any one of them would constitute the HFE. Therefore, an HFE may encompass several HAs performed by different individuals and may also distinguish phases of the required cognitive process.

Consistent with [15], HFE definition is conditioned primarily by the modelling objective and then by the quantification method. Developing a set of HFEs requires comprehensive task analysis, often involving expert consultation, scenario analysis, plant walkthroughs, and interviews. In design phases, however, HAs are postulated on paper with varying levels of detail as part of the development of emergency management documentation, including emergency operating procedures and severe accident management guidelines. In this work, the objective is to represent different HAs associated with the organizational structure. Exhaustive decomposition could unnecessarily increase model complexity. Similarly, although analysing the cognitive phases affecting task execution is desirable, explicitly distinguishing all of them would also increase complexity. In consequence, HFEs are identified in association with HAs at the site, unit, and system levels, as indicated in Figure 5, without distinguishing among diagnosis, decision-making, and execution actions. For simplification purposes, only the MCR Operations Chief (MCRC) role is considered at the site level.

4.2 Probabilistic Assessment of HFEs

As noted by [20], SPAR-H originated as a simplification and generalization of traditional THERP - Technique for Human Error Rate Prediction- and ASEP - Accident Sequence Evaluation Program- approaches. SPAR-H removes the basic scenarios used in THERP and focuses on two activity types: processing and response. Processing refers to cognitive activities such as detection and decision-making, while response refers to behavioural, action-oriented activities.

SPAR-H evaluates eight PSFs. For this work, only four PSFs are considered: available time, stress/stressors, complexity, and ergonomics/HMI. This selection reflects early design constraints:

detailed information and operating experience related to experience/training, procedures, fitness for duty, and work processes are not yet available for new designs.

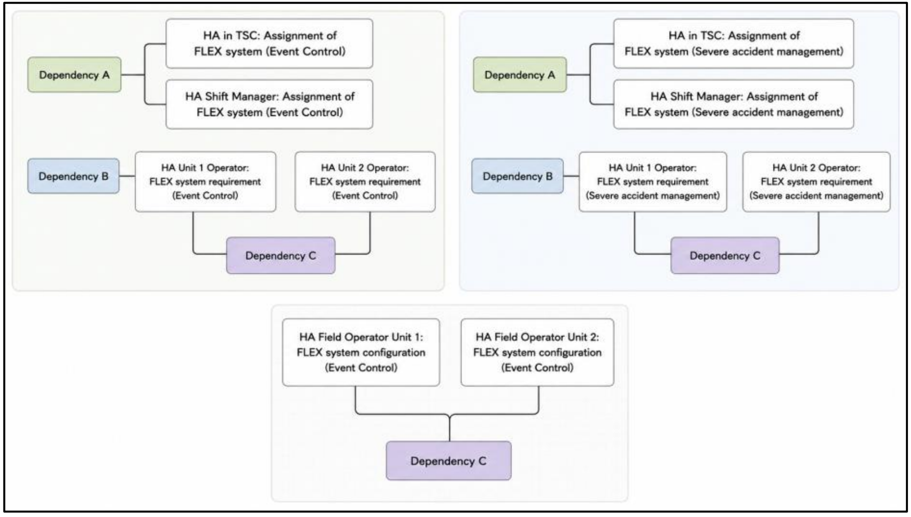
To ensure coherent human error evaluation, the HA structure presented in Section 3.3 is used as the framework. The selected PSFs are evaluated considering two additional aspects: the scenario in which the HA is required (event control or severe accident management) and the location where the action is performed (control room or field). As noted in [8], the generality of PSFs is a strength of this approach, but validation for Level 2 PSA applications is required because they are outside the scope of the SPAR-H guidance. Based on the Level 2 HRA study cited in that reference, not all eight PSFs are applied simultaneously. Regarding the SPAR-H distinction between diagnosis and execution, this work considers that the execution phase may involve either decision-making or physical execution actions, in the MCR or in the field.

A more standardized PSF evaluation is proposed by distinguishing scenarios related to initiating event control from those related to severe accident management. The PSFs are then evaluated at the site, unit, or system level. As an example, Table 3 summarizes the proposed PSF evaluation for application case.

Regarding dependency analysis in HRA, [21] notes inconsistencies in the application of dependencies concepts. The reference states that dependency exists between two HRA variables when they are connected by a direct or indirect causal relationship that changes their conditional probabilities, understood as HFEs and PSFs.

Considering the scope of this study and the concept of causality, different dependency types can be identified at the HFE level based on connections among the actors performing the actions within the organizational structure. Three conceptual dependency types are identified: Dependency A, between the HA performed by the control room decision-maker (e.g., MCRC) and the TSC reference person/responsible person; Dependency B, between the HA performed by the unit operator, mainly associated with diagnosis, and the HA performed by the control room decision-maker; and Dependency C, between HAs performed by field operators. These dependency types are represented in Figure 4.

Figure 4: Proposed dependency types among human actions during emergency management.



4.3 Dynamic Modelling of HAs in EMRALD

Dynamic probabilistic safety assessment (DPSA) methods have been developed because of the limitations of traditional PSA and the increased availability of computational resources, as indicated in [22]. In this study, multi-unit sites require modelling logical conditions such as mutually exclusive events, conditioning events, and event sequence dependencies. Analyst-friendly interfaces are also needed to support model development, review, and traceability. EMRALD is therefore used. According to [23], EMRALD is a dynamic PRA tool developed by Idaho National Lab (INL) to model and analyse the sequence and timing of events leading to specific outcomes in DPSA. It provides a modelling process similar to static PSA approaches, supported by a web-based graphical user interface that enables users to model and visualize complex interactions in dynamic PRA scenarios. The logical elements used to develop the models are described in [22].

5 APPLICATION CASE

5.1 Description of the Application Case

Based on the hypothetical multi-unit site shown in Figure 1, an application case is analysed within the emergency management framework. Following a multi-unit initiating event and the assumed failure of systems required for event control, specifically the cooling function, FLEX A System (FlexA) must be connected to Unit 1[2]. FlexA can supply water to either Unit 1 or Unit 2, but cannot be connected to both units simultaneously; therefore, a resource allocation decision is required.

5.2 Identification of HAs

Following the human action structure proposed in Section 3.3, the HAs identified for the application case are listed in Table 1.

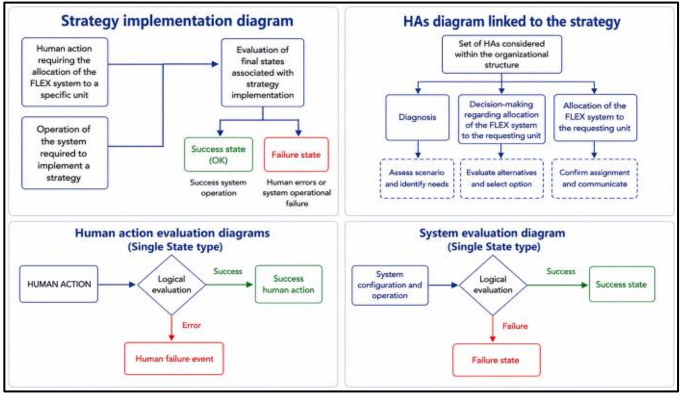
Table 1: HAs identified for the application case.

ID	Description
HA_U1_FlexA/ HA_U2_FlexA	The Unit 1 / Unit 2 operator diagnoses the need to connect FlexA to Unit 1 / Unit 2 and requests the MCRC to manage the allocation of FlexA.
HA_Site_FlexA	The MCRC receives the request from the Unit 1 / Unit 2 operator, performs a site-level diagnosis, and requests the TSC to verify and confirm the allocation of FlexA. After receiving TSC confirmation, the MCRC manages the connection of FlexA to the selected unit. For simplification, interactions with the supervisor and shift manager are not modelled.
HA_TSC_FlexA	The TSC responsible person receives the request from the MCRC, performs a site-level diagnosis, and decides whether to approve the allocation of FlexA to the selected unit.
HA_Field_U1_FlexA/ HA_Field_U2_FlexA/	The field operator diagnoses the status of FlexA and connects it to Unit 1 / Unit 2.

5.3 HAs Modelling in EMRALD

A dynamic probabilistic model was developed in EMRALD with the aim of scaling it to a more complete model representing full on-site emergency management. The model is organized into the modules presented in Figure 4.

Figure 4: Proposed modules for the EMRALD model.



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[2] FLEX A System is used as a generalization and may represent the CPIS shown in Figure 1.

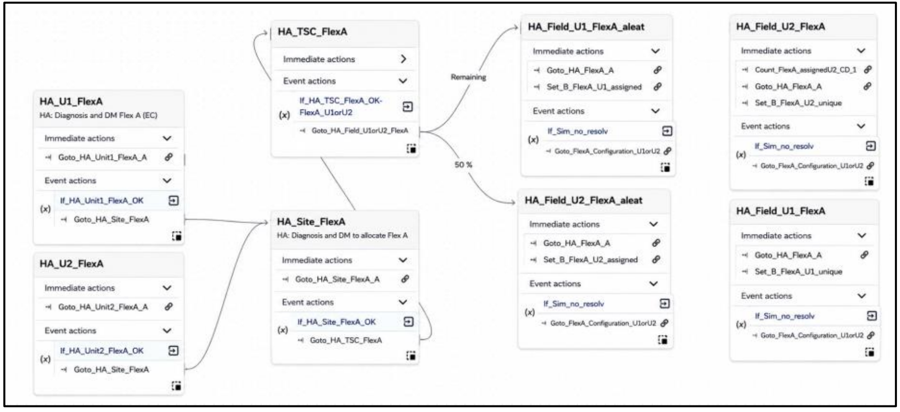
As an example, Figure 5 shows the sequence and dependency structure among HAs. First, after both units request FlexA connection, the MCRC processes the request based on the diagnosis of site conditions and consults the TSC regarding the decision on which unit should receive FlexA. To avoid an additional logical loop, the model assumes that FlexA is assigned to one of the units after the TSC decision. Because the decision-making process itself cannot be modelled explicitly at this stage, the allocation is represented as two mutually exclusive random events, each with probability 0.5. After allocation, the field HA is evaluated. Each HA is analyzed through its own Single State logical diagram, which identifies success and failure states.

The event sequences analyzed in the model can reach five key states, corresponding to successful FlexA actuation in one of the two units or core damage, as a simplification, in one or both units. Table 2 lists the possible three site final states.

Table 2: Site final states for the application case.

ID Site final state	Description
CD_U1&CD_U2	Core damage in Unit 1 and Unit 2
OK_U2&CD_U1	Successful actuation of FlexA in Unit 2 and core damage in Unit 1
OK_U1&CD_U2	Successful actuation of FlexA in Unit 1 and core damage in Unit 2

Figure 5: Human action modelling in EMRALD, considering the site organizational structure.



5.4 Estimation of Human Error Probabilities

Human error probabilities (HEP) were estimated using SPAR-H with the RiskSpectrum HRA code. The PSFs selected for the context of this work were considered. In particular, the application case uses values corresponding to initiating event control scenarios with FLEX systems. Table 3 presents the PSFs assigned to each HFE. Dependency analysis was also included in the HEP evaluation. The following assumptions were adopted for HEP evaluation to obtain more representative estimates and avoid HEP values equal to 1, which would distort the analysis.

H1: The MCRC and the operators of both units are assumed to belong to different crews. This assumption is based on the differentiation of functions between the chief and unit operators in a multi-unit site.

H2: The operators of both units are assumed to belong to different crews, because their functions correspond to different units.

H3: The information available to the TSC is assumed to be the same as the information available to the MCRC in the MCR.

Table 3: Human error probabilities for application case, considering analysis of PSF and dependencies (D: Diagnosis, A: Action).

HFE	Available time	Stress/ stressors	Complexity	Ergonomics/HMI	Dependency		HEP
HA_TSC_FlexA_Error (Site level)	D: Barely adequate time A: T_avail=T_requir	D: High A: High	D: Moderat. A: Moderat.	D: Nominal A: Nominal	A	Moderate	4.2×10^{-1}
HA_Site_FlexA_Error (Site level)	D: Barely adequate time A: T_avail=T_requir	D: High A: High	D: Moderat. A: Moderat.	D: Nominal A: Nominal	B	Moderate	4.2×10^{-1}
HA_U1_FlexA_Error HA_U2_FlexA_Error (Unit level)	D: Barely adequate time A: T_avail=T_requir	D: High A: High	D: Moderat. A: Moderat.	D: Nominal A: Nominal	C	Moderate	4.2×10^{-1}
HA_FlexA_Error (System level)	D: Barely adequate time A: T_avail=T_requir	D: High A: High	D: Nominal A: Nominal	D: Nominal A: Poor			4.9×10^{-1}

6 DISCUSSION

This work develops a probabilistic modelling approach to represent post-initiator HAs included in an OEMP, with specific emphasis on multi-unit sites composed of i-PWR SMRs. Based on the human error values in Table 3 and using a FlexA unavailability due to component failures of 1×10^{-1} as a screening value, Table 4 shows the number of runs reaching each final state. The total number of final states matches the total number of runs. The final state with the largest number of runs is CD_U1&CD_U2. The main contributors are the site level HFE, associated with the MCRC, and the TSC.

Table 4: Run results by site final state for the application case. Identification of human errors or failures contributing to each site final state.

Site final state	HFE or failures	Runs	Summary
CD_U1&CD_U2	HA_Site_FlexA_Error	36	90
	HA_TSC_FlexA_Error	23	
	HA_U1_FlexA_Error; HA_U2_FlexA_Error	18	
	HA_FlexA_Error	11	
	FlexA_Failed	2	
OK_U2&CD_U1	HA_U1_FlexA_Error	5	5
OK_U1&CD_U2	HA_U2_FlexA_Error	5	5

Regarding probabilistic modelling, the preceding sections support three main observations.

a) Implementation of the HA structure: The proposed model represents the HA structure required for complex actions, such as diagnosis and decision-making for assigning a shared system in a multi-unit site. The dynamic model in EMRALD represents interrelationships among HAs and links them to final site states.

b) HA modelling: Although Figure 3 distinguishes diagnosis actions from action activities, including decision-making and execution, this distinction was not explicitly implemented in the model because it would increase complexity without a proportional benefit for the results available at this stage. At the quantification level, however, SPAR-H allows diagnosis and execution to be evaluated separately, with independent PSF assessments for each stage. The current model also does not explicitly represent the decision-making process that culminates in allocating a shared system to one unit, with potential consequences for the other. Although not included in the current iteration, the temporal dimension associated with HA delays, including uncertainty in those delays, can be incorporated in future work.

c) Strategy implementation modelling: In the modelled case, HAs are required from the beginning of the sequence; therefore, the model represents the sequence after the decision-making process up to achieve final site states.

Although the model is simple, it identifies the HFE and failures that contribute to the site final states. The proposed HFE quantification method is appropriate because it evaluates HAs in context, a particularly relevant feature for emergency management plans involving multiple HAs performed at different locations. Considering dependencies strengthens the analysis and enables representation of organizational mechanisms that are not captured by independent HFE evaluation.

7 CONCLUSION

This work defines a structure of HAs linked to the organizational structure involved in on-site emergency management. The proposed structure is based on the characterization of an i-PWR SMR multi-unit site and aims to capture features specific to this type of facility in emergency management contexts.

Developing complex models requires methodological guidelines for model construction, including the use of event sequence diagrams, consistent with [24]. Modular development is also recommended, as illustrated in this work through Figure 4. Guidelines for HFE modelling were also defined. SPAR-H is considered an appropriate initial approach because it is context-sensitive, applicable to control room and field actions, and compatible with dynamic probabilistic models. Future work should compare it with other methods, such as CREAM - Cognitive Reliability and Error Analysis Method-, especially to evaluate differences in the representation of cognitive processes, contextual conditions, and dependencies. The methodological guidelines were successfully implemented in a dynamic probabilistic model for an application case. Although the case study addresses a single strategy, it is situated within an i-PWR SMR multi-unit site and demonstrates the usefulness of the approach for representing resource allocation, organizational coordination, and dependencies among HAs.

In the context of this work, OEMP development is understood as a progressive process associated with the development of a new facility project. As engineering advances, strategies for initiating event control and severe accident management are developed or revised. Engineering information and analysis related to the implementation of those strategies also increase, including the identification of required HAs. Therefore, as OEMP development progresses, new HAs may be identified or further disaggregated, enabling the development of improved estimation models.

Acknowledgements

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