Identification and Assessment of Current and Developing PRA Technologies for Risk-Informed-Decision-Making (RIDM)

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Abstract: This paper presents the results of an analysis of the strengths and limitations of existing probabilistic risk assessment (PRA) tools employed in the nuclear industry. A questionnaire engaged nuclear PRA professionals and inquired about tools they are using for various aspects of PRA. The questionnaire requested anonymous feedback and insights on applying legacy, conventional, and other PRA tools. A review/survey was additionally performed of existing resources to supplement the questionnaire and develop a comprehensive analysis. The questionnaire and survey reveal the needs of the PRA community are evolving, and the tools need to reflect on this change by developing multi-purpose tools to expand the traditional PRA scope. The needs of the PRA community include time-dependent aspects, external hazard analyses, and human risk assessment (HRAs). The feedback gleaned from the questionnaire emphasizes the scope expansion, the re-evaluation of current algorithms, the need for integrated post-processing, and the facilitation of collaboration.

1. INTRODUCTION

Probabilistic risk assessments (PRAs) are systematic models used to identify and analyze risks associated with complex systems such as nuclear power plants (NPPs). The essential components of a conventional PRA are (1) event trees (E.T.s) and the frequency and probabilities of the initiating event and top events, respectively, and (2) fault trees (F.T.s) and the failure probability of components. PRA tools were developed to support F.T. and E.T. modeling generation and quantification. The needs of the PRA community have evolved since the original tools were developed. However, technologies and algorithms available at the time-limited these legacy tools. Current technologies improved in computational power and capabilities, potentially enhancing the ability to model plant risks, especially regarding external hazards. The advancements of new tools and technologies require a re-analysis to discuss their advantages and limitations, potential contributions to external hazard PRAs (XHPRAs), and effects on the risk-informed-decision-making (RIDM) process.

A questionnaire on PRA tools in the nuclear industry was created to understand practitioners' insights on the advantages/limitations of existing tools and how other tools supplement the conventional PRA model. This paper synthesizes and presents the feedback, supplemented with a review of existing literature to develop a comprehensive analysis of the current state of practice on PRA tools and other tools in the nuclear industry. These results are presented as tables in section 2.2.

2. QUESTIONNAIRE ANALYSIS

2.1 Questionnaire Characteristics

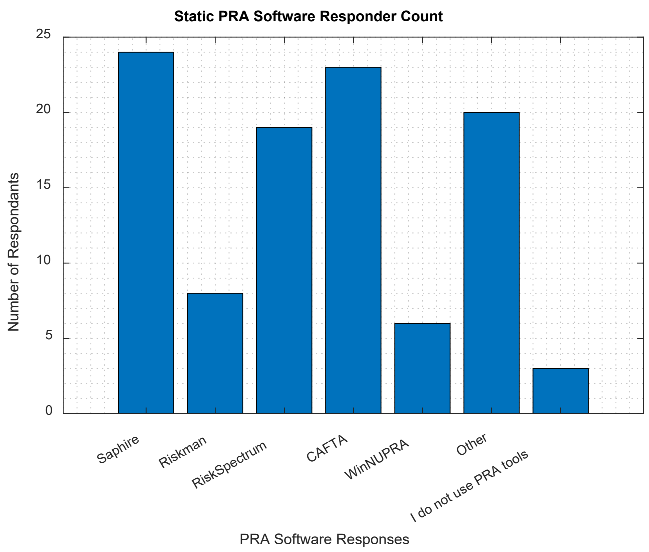
The questionnaire contained seven questions. Question 1 was multiple selection, while the remaining questions were open-ended:

1) What static PRA software do you have experience using? Select multiple if applicable.
    a. SAPHIRE
    b. Riskman
    c. RiskSpectrum
    d. CAFTA
    e. WinNUPRA
    f. FRANX
    g. Other (Please Specify)
    h. I do not use PRA tools

2) What are the strengths of the PRA software/tools you are using/have used? If you discuss multiple tools, please connect each tool to its strengths.
3) What are the limitations of the PRA software/tools you are using/have used? If you discuss multiple tools, please connect each tool to its limitations.
4) What other tools or software have you used to supplement the PRA tools/software you identified above? Why have they been needed? If you discuss multiple tools, please connect each tool to its necessity.
5) What types of PRAs have you worked on when using the tools/software/methods identified above? (e.g., internal events, internal flooding, fire, seismic, high winds, external flooding, human risk assessment (HRA), data analysis, level II/III,...)
6) What types of nuclear power technologies do you work with when using the tools/software/methods identified above? (e.g., LWRs, SMRs, gas reactors, breeder reactors, molten salt reactors,...)
7) Please provide additional comments regarding the potential for new or existing PRA tools (used within or outside the nuclear industry) to meet the evolving needs of the nuclear industry.

The questionnaire was sent to 431 members of the international PRA community in early 2022 and recorded 52 responses. The questionnaire was sent to practitioners within industry, academia, international labs, government agencies, and independent contractors, although the demographics of respondents are unknown due to anonymity. Based on the responses to question 5, respondents are engaged in a diverse scope of PRAs such as internal and external hazards, levels 1-3, or dynamic PRAs at various power levels. Additionally, the questionnaire gathered practitioner insights on the advantages and limitations of PRA software and other tools. Figure 1 visualizes question 1, displaying the number of respondents with experience in established tool labels.

Figure 1: Questionnaire Response



2.2 Advantages and Limitations of PRA Tools

The presentation and synthesis of current PRA tool insights are based on the anonymous responses collected from the questionnaire and a general survey of established and novel PRA tools from the literature. The following tables contain descriptions, advantages, and limitations of various tools mentioned by respondents and other significant tools not explicitly mentioned by respondents but included by the authors. Footnotes indicate the tools included by the authors. The advantages/limitations of respondents are subjective based on the practitioners' professional/technical opinions. Some respondents have explicitly mentioned a functionality for a select tool in the questionnaire, despite other tools having the same functionality. The conflict is due to the respondent's subjectivity on what they consider noteworthy. Select users also acknowledged that they were not neutral responders. Some respondents may also view a characteristic as an advantage, while others may view it as a limitation. This is due in part to having differing professional opinions based on preferences/expectations. For example, respondents may consider the computational speed of a particular tool as fast (and thus consider it an advantage). In contrast, others view the same tool as slow (and consider it a limitation). The conflicting insights are placed in merged cells for the corresponding tool in the tables below.

A few users mentioned tool names but did not explicitly provide insights. Therefore, the authors performed a literature survey to supplement the table of advantages/limitations to provide a comprehensive analysis of PRA tools available to the practitioners. In the following tables, all insights not provided by the respondents are obtained through the published insights from external authors and are not necessarily reflective of the opinions of the authors of this paper. The survey also provides tool descriptions and is referenced as such. Reference numbers in the IEEE format indicate descriptions and advantages/limitations from the literature review.

The tools discussed in the questionnaire responses are placed into seven categories. Each category is summarized in one of the tables that follow:

1. ***Conventional PRA tools*** [**Table 1**]– software that focuses on traditional PRA methods such as E.T. and F.T. development.
2. ***Dynamic PRA tools*** [**Table 2**] – software that incorporates thermohydraulic codes or severe accident codes to develop detailed scenarios over time
3. ***Severe accident/thermohydraulic tools*** [**Table 3**] – software that tracks the progression of severe accidents or tools that simulate thermal-hydraulic behavior in transient scenarios
4. ***Supplemental and miscellaneous tools*** [**Table 4**] – tools that provide additional information to PRA models to expand or supplement their scope
5. ***Novel PRA tools*** [**Table 5**] – PRA software that integrates supplemental tools within its model, expanding the scope outside of conventional E.T. and F.T. development
6. ***General-purpose tools*** [**Table 6**]–tools to preprocess the input or post-process the output of PRA tools
7. ***HRA models*** [**Table 7**] – HRA models are explicitly mentioned in the questionnaire that develops a robust PRA model to include human behavior

Key phrases are used in the following tables to capture overarching advantages and limitations expressed in the questionnaire and references for brevity. Keywords/phrases are defined as follows:

- ***Comprehensive/Limited functionality***: Range of capabilities or analyses
- ***Ease of use***: User-friendly interface
- ***Efficient quantification***: The software utilizes a quick and efficient algorithm to quantify models or calculate governing equations, regardless of model size.
- ***Learning curve***: Requires prior knowledge
- ***Low/high computational requirement***: Required computational resource for model development (RAM or CPU)
- ***Pre/Post-processing***: Software capabilities to treat input/output data
- ***Software compatibility***: Ability to interface with external tools
- ***Traceable algorithm***: Software has a transparent methodology that is easily traceable
- ***Well-established***: Extensive training and documentation

Table 1: Questionnaire Responses on Conventional PRA Tools

Name	Description	Advantages	Limitations
SAPHIRE	Predominantly for level 1 PRAs with limited capabilities for level 2 and 3 PRAs for various power conditions [1]	• Free • Comprehensive functionality (e.g., HRA, diverse failure types, common cause failures, event and condition evaluations, connecting PRA layers) • Model compatibility (e.g., Standardized Plant Analysis (SPAR) model) • Software compatibility (e.g., external solvers)	• Difficulty in visually presenting large models • Limited functionality (e.g., structural capabilities for seismic PRAs, sensitivity, parameter definition, version control, post-processing) • Learning curve • High computational requirement for large/complex models
		• Efficient quantification • Well-established • Substantial training documents	
Riskman	Predominantly for level 1 E.T. linking and F.T. generator and quantifier [2]	• Comprehensive functionality (e.g., truncation capabilities, tracks successes, accident sequence oriented) • Ease of use • Software compatibility (e.g., Maintenance State Calculator (MSCAL))	• Limited user base • Limited functionality (e.g., dependency, split fraction tracking, recovery modeling, component level impact, one-top models, F.T. linking)
		• Efficient quantification	
Risk Spectrum	Level 1 F.T., E.T. development and quantification [3]	• Comprehensive functionality (e.g., HazardLite, importance, sensitivity, cutset tracer, E.T. navigation, connecting PRA layers, post-processing) • Ease of use • Efficient quantification	• Higher cost • Limited functionality (e.g., external event assessment, Markov, Bayesian, HRA, risk matrix)
CAFTA	Level 1 F.T., E.T. linking tool with reliability database [4]	• Comprehensive functionality (e.g., fast cutset generation • Software compatibility (e.g., Electrical Power Research Institute (EPRI) risk and reliability workstation: FTREX, SYSIMP, ACUBE, etc.) • Ease of use • Efficient quantification	• Limited functionality (e.g., sensitivity for licensing, grouping event sequence families, post-processing)
WinNUPRA	Level 1 E.T. and F.T. development and reliability analyses [5]	• Comprehensive functionality (e.g., mitigating system performance index (MPSI), fast cutset generation, cutset standardization)	• No longer supported • Limited functionality (e.g., success identification, post-processing)

Table 2: Questionnaire Responses on Dynamic PRA Tools

Name	Description	Advantages	Limitations
EMRALD	Dynamic PRA software that models state changes and evolutions [6]	• Ease of use	• Limited statistical features • In beta version development

RAVEN	Multi-purpose platform for regression analysis, PRA, data analysis, and model optimization [7]	• Comprehensive functionality (e.g., uncertainty quantification, regression, PRA, data analysis, model optimization) • Software compatibility (e.g., VERT, RELAP, MELCOR, etc.)	• Black box workflow [8] • High computational requirement [9]
ADS-IDAC	Dynamic thermal-hydraulic simulator with crew cognition response [10]	• Comprehensive functionality (e.g., event sequence timing, operator response modeling) • Traceable algorithm [11]	• Limited functionality (e.g., risk profile generation, dominant risk identification, uncertainty analysis) [11] • High computational requirement
CFAST	Simulates fire accident progression utilizing the zone model [12]	• Ease of use [13] • Efficient quantification [13] • Large user base [14]	• Limited functionality (e.g., modeling complex structures, entrainment coefficient impact on multi-compartment models, pyrolysis data) [14]
FRI3D	3D fire simulator and visualizer for scenario progression [16]	• 3D modeling • Comprehensive functionality (e.g., Automates manual calculations, data transfers between applications)	• Model limitations for complex room geometries and large horizontal paths [17] • Limited database [17]
Crystal Ball	Monte Carlo simulation and optimization [18] [19]	• Comprehensive functionality (e.g., Uncertainty evaluation)	• Higher cost

Table 3: Questionnaire Responses on Severe Accident/Thermal-Hydraulic Tools

Name	Description	Advantages	Limitations
RELAP	Dynamically analyzes small break loss of coolant accidents (LOCAs) and system transients for level 1 PRAs [20]	• Good plant response representation when data is unavailable [19] • Validated using integral test data [22] • Large user base [22]	• Phasing out maintenance [22] • Command-line user interface [19] • One dimensional [23] • Learning curve • Model setup time
TRACE[1]	Analyzes small and large LOCAs in pressurized water reactors (PWRs) and boiling water reactors (BWRs), modeling thermal-hydraulics in 1D and 3D [22]	• Multi-dimensional flow simulation [24] • Software compatibility (e.g., BISON, MOOSE, PARC, etc.) [24] • 3D modeling [22] • Large user base [24]	• Limited functionality (e.g., irregular heat structure geometry, modeling vessel as single heat structure, pool/thermal stratification simulation) [24] • Higher cost [24]

[1] TRACE was not explicitly mentioned by questionnaire respondents but included by the authors for a comprehensive understanding of current PRA tools. All advantages/limitations are sourced from the literature review.

SCDAP/ RELAP5[2]	Models thermal-hydraulic and severe accident phenomena with mechanistic models [22]	• Detailed modeling for material interaction and relocation [25] • Large user base [26]	• Calculations are not possible beyond the time of primary side pressure boundary failure [25] • Command-line user interface [27]
MAAP	Simulates severe accident scenarios [28] and predicts the progression of NPP accidents in support of level 1 and 2 PRAs and severe accident analyses	• Applicable to LWRs, CANDUs, and VVERs [29] • Comprehensive functionality (e.g., containment spray, sparging effects, post-LOCA effects) [29] • Simulation speed • Large user base [29]	• Requires time step tuning [29] • Limited functionality (e.g., Design basis models, ductwork) [29] • High computational requirement for complex models [29] • Learning curve for beyond design basis [29]
MELCOR	Simulates severe accidents phenomena in light water reactors (LWRs) for dynamic PRAs [30]	• Comprehensive functionality (e.g., sensitivity analysis, flexible system nodalization) [31]	• Simulation speed [32] • Debris is modeled as unquenchable [32] • Containment pressure fluctuations [32]
MACCS	Probabilistically analyzes the impact of radionuclide release at the NPP and the surrounding environment for level 3 PRAs [20] [33]	• Comprehensive functionality (e.g., input data uncertainties, nearfield modeling, treatment of evacuation speed and direction for spatial and temporal response) [34]	• Limited functionality (e.g., Food ingestion model, contamination effects at different times during Summer) [35]

Table 4: Questionnaire Responses on Supplemental and Miscellaneous Tools

Name	Description	Advantages	Limitations
FTREX	External quantification engine [36]	• Flexible options for quantifying cutsets • Ease of use • Efficient quantification	• Command-line user interface • Limited software compatibility
PRAQuant	Accident sequence quantification for single-top construction [37]	• Traceable algorithm	• High computational requirement • Software compatibility (e.g., EPRI tools, i.e., CAFTA, FRANX, SYSIMP, ACUBE, DPC, UNCERT, etc.)
UNCERT	Uncertainty quantification engine [37]	• Comprehensive functionality (e.g., uncertainty and importance) [38]	Software compatibility (e.g., EPRI tools)
XFTA	F.T. quantification engine [39]	• Free • Efficient quantification (e.g., minimal cutsets, binary decision diagram algorithm) [39]	• Command-line user interface [39]

[2] SCDAP/RELAP5 was not explicitly mentioned by questionnaire respondents but included by the authors for a comprehensive understanding of current PRA tools. All advantages/limitations are sourced from the literature review.

		• Comprehensive functionality (e.g., Top-event probability, importance, sensitivity, time-dependent analyses) [39]	
ACUBE	Cutset quantification tool for large probability events [37]	• Comprehensive functionality (e.g., re-quantification scenarios, dependent basic events, re-modularization of cutsets…) [40] • Efficient quantification [40]	• Limited Functionality (e.g., truncation impact information) [40] • Success quantification approximation error propagates in individual sequences [40]
SYSIMP	Importance measurement tool [37]	• Automates computing collective importance [41]	• Input model not readable by EPRI tools [41]
MSCAL	Maintenance state calculator [2]	• Allows online maintenance monitoring for Riskman [2]	• Software compatibility [2]
EVNTRE	Quantifies containment E.T.s for level 2 [42]	• Software compatibility (e.g., Custom codes, level 2 legacy models analysis) • Ease of use	• Considered a legacy tool • Command-line user interface
FRANX	Scenario Progression for level 1-2 spatial hazards such as fire, seismic, etc.	• Comprehensive functionality (e.g., extensive database, maintains hazard PRA logic, integrates events for groups of equipment, inject initiators/scenarios) • Ease of use • Efficient quantification	• Older storage format • Requires CAFTA to run • Model setup time • Learning curve • Blackbox workflow
GOFACS	Uncertainty propagation tool and seismic fragility curve generator [43]	• Comprehensive functionality (e.g., Optimizes linking mechanical models and coupling with seismic hazard, uncertainty management) [43] • Ease of use [43]	• Fragility curves in GOFACS must be built from previously performed experiments outside of GOFACS [43]
PHOENIX	HRA tool modeling crew response tree analyzing human failure events (HFEs) [44]	• Comprehensive functionality (e.g., Human error mechanism modeling, qualitative and quantitative analyses, commission error)	• Learning curve
EPRI HRA Calculator	Quantifies human error probabilities (HEPs) [45]	• Automated reports [46] • Satisfies American Society of Mechanical Engineers (ASME)/American Nuclear Society (ANS) PRA standard [46] • Traceable algorithm [46]	• Limited software compatibility (e.g., EPRI tools) [46]

Table 5: Questionnaire Responses on Novel PRA Tools

Name	Description	Advantages	Limitations
AIMS-PSA	E.T., F.T., and cut set capabilities [47] for external and internal hazards for level 1-3 PRAs	• Customizable and flexible modules • Handles logical loops inside F.T.s • Ease of use • Efficient quantification	• Limited functionality (e.g., modeling correlations for MUPRAs, modeling human and organizational behaviors)

Isograph	Integrated reliability workbench, with multiple comprehensive modules for levels 1-3 [48]	• Comprehensive functionality (e.g., Sensitivity, importance, Markov models, B.N.s, HRA, risk matrix)	• Limited functionality (e.g., no direct external hazard integration, uncertainty modeling, component failures database) • Higher cost
Phoenix Architect	Platform hosting EPRI tools like CAFTA, PRAQuant, UNCERT, etc. [49]	• Integrates multiple tools onto one platform [49]	• Only compatible with EPRI R&R workstation tools [49]
PSAPACK	Generates E.T.s and F.T.s and operational safety management capabilities for level 1 PRAs [50]	• Ease of use	• Command-line user interface • Limited functionality (e.g., RIDM integration, uncertainty modeling)
KANT	Generates and quantifies accident progression event trees (APETs) [51]	• Comprehensive functionality (e.g., internal events and hazards capabilities, dependencies, source term calculations) • Software compatibility (e.g., MER, MELCOR, RiskSpectrum)	• Post-processing
Andromeda	Open-source application framework that interfaces level 1-2 PRA tools [52]	• Open-source • Comprehensive functionality (e.g., model management, model comparison, event sequence diagrams, automated E.T. generation, version control, cartography) • Software compatibility (e.g., python)	• Limited functionality (e.g., quantification, non-rare event consideration)
SCRAM	Open-source PRA tool with E.T. and F.T. with common cause analyses and quantification [53] for level 1 PRAs	• Open-source • Independent code	• Limited functionality (e.g., quantification) • Currently still in development
KB3	Automated F.T. generation from a description of a system. [54]	• Diverse applications	• Limited functionality (e.g., quantification) [54]

Table 6: Questionnaire Responses on General-Purpose Tools

Name	Description	Advantages	Limitations
Excel	Result plotting and pre/post-treatment of data	• Customizable data visualization • Organizes results • Pre/post-processing results	• Not widely integrated into other software • Requires prior knowledge
Programming Language (e.g., Matlab, R, Python, VBA, etc.)	Result plotting and pre/post-treatment of data	• Customizable data visualization • Organizes results • Pre/post-processing results • Evaluates results	• Not widely integrated into other software • Requires prior knowledge

Open Bugs/ WinBugs	Bayesian analysis using Markov chain Monte Carlo Sampling [55] [56]	• Software compatibility (e.g., through shell commands or R) [56] • Free [56]	• Menu user interface [56]
CCFWin	Common cause failure database containing known common cause failures that have occurred in NPPs in the U.S. [57]	• Only publicly available common cause failure database in the U.S.	• Failure database not collectively exhaustive • Potential to double count events

Table 7: Questionnaire Responses on HRA Models[3]

Name	Description	Advantages	Limitations
PANAME	Quantifies performance shaping factor (PSF) weights [58]	• Presentation of results [58] • Well-established [58] • Traceable algorithm [58]	• Limited functionality (e.g., representation of difficult tasks, error reduction, qualitative scenario analysis) [58] • Time sensitivity [58]
HORAAM	Models human actions for level 2 PRAs [59]	• Only the HRA method for level 2 [60]	• Not a full-fledged method [60] • Limited functionality (e.g., doesn't consider severe accident management guidelines (SAMGs)) [60]
SPAR-H Model	Identifies and quantifies HEPs [61]	• Comprehensive functionality (e.g., error reduction insights) [58] • Ease of use [58]	• Limited qualitative analysis guidance [58] • Sensitive PSF rating assignment [58] • Conservative dependency treatment [58]
Alpha Factor Model	Quantifies model parameters using independent and common cause failure factors [62]	• Analyzes all combinations of common cause factors • Increases data collection	• Learning curve

3. QUESTIONNAIRE ANALYSIS

Respondents recognized that tools have improved since the initial development of legacy tools. Tools have also enhanced the users' experiences by migrating from command-driven interfaces to menu-driven or graphical user interfaces and providing better training documentation. This potentially reduces the learning curve and setup time that may have previously acted as a barrier to entry to the PRA community. As previously mentioned, there are inconsistencies in views regarding advantages and limitations among respondents. Quantification efficiency and comprehensiveness/ incomprehensiveness of tool capabilities are the significant functionalities that are inconsistent among respondents due to subjectivity. According to the respondents, the lack of dynamic and post-processing capabilities are the main gaps in current tools. Tool capabilities have expanded for XHPRAs, which require additional functionalities to perform hazard analyses, fragility function development, and plant response. However, respondents have expressed those functionalities need to continue to improve external hazard integration and analysis modules to develop a full scope XHPRA. Although dynamic

[3] Although HRA models are not considered PRA tools, these models were explicitly mentioned by respondents and included to retain the integrity of the questionnaire feedback.

tools exist, most common PRA tools were not designed to integrate a temporal component. Post-processing capabilities are limited due to the diverse options for presenting and sharing results. Currently, general-purpose tools such as python, MATLAB, and Excel are best suited to allow users to convey results to other PRA practitioners, stakeholders, and decision-makers. External hazard scopes vary and require a diverse set of analyses. This poses a potential issue for tool developers in evolving tools to fit the community's needs for XHPRAs. Similarly, external tool interfacing has enhanced, but there is still a gap noted among respondents in the comprehensiveness of software integration. Current tools excel in efficient quantification and fast setup of large and complex models, utilizing the availability of advanced computers and efficient algorithms. Quantification efficiency is still a source of disagreement among the respondents. It should be noted that the insights on quantification efficiency are especially dependent on the practitioners' model complexity and the capabilities of current technologies.

Respondents indicated the scope of PRAs has expanded into level 2 and 3 PRAs and require internal and external hazard analyses. This scope expansion will increase the need for new tools and model complexity, necessitating a re-evaluation of how system failures are viewed and treated and continuing the advancement of algorithm and tool capabilities. Respondents expressed interest in integrating common cause failure analyses as most systems, structures and components (SSCs) are shared, and NPP sites are multi-unit. Component aging and degradation analyses are also required for practitioners as it is essential for external hazards in understanding pre-existing conditions in failure data. A few respondents acknowledged that HRA has a limited scope in XHPRAs but is necessary, especially for hazards with a significant warning time and temporary measures. Respondents also noted that the modernization of nuclear technology and increased users in the global community would increase collaboration. They highlighted the need for improved model management, such as the ability for multiple users to work on a model with version control capabilities simultaneously, the use of digital twins, and model traceability to improve the ability for collaboration. There is an increased emphasis on including dynamic capabilities. Respondents expressed interest in tool integration to facilitate multi-scoped software that can address the needs of multi-level, multi-unit, and multi-hazard PRAs. Although, it is acknowledged that the increased scope may impede software computational speed and model setup.

4. CONCLUSION

Hybrid combinations of conventional, novel, and additional PRA tools are increasingly used to address the evolving needs of the PRA community. A questionnaire on PRA tools was created to understand practitioners' general insights on the advantages/limitations of existing tools and how other tools supplement conventional PRA models. In response to the questionnaire, nearly all respondents highlighted advancements in algorithm efficiency, software compatibility, and ease of use. Incorporating new computational algorithms within the tools has reduced computational speed and capabilities, increasing the convenience of developing models. Integrating comprehensive functionalities and interfacing with other tools has facilitated the expansion of the PRA scope to external hazards. The questionnaire highlights the trends that the respondents would like to see the technology to evolve towards, such as dynamic PRA capabilities and collaboration functionalities. The technology has the potential to also expand the traditional scope of risk-informed decision-making in the nuclear industry by diversifying the identified issues and their mitigation options. It allows practitioners to analyze a wider variety of accidents and allow stakeholders to prioritize accident mitigation, informed by a realistic model. These tools are critical in optimizing the decision-making by testing key assumptions and providing information and insights.

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