Development of Probabilistic Risk Assessment Methodology Using Artificial Intelligence Technology 3. Automatic Fault Tree Creation Tools for Failure Mode Level Fault Tree

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Abstract: Probabilistic risk assessment (PRA) of nuclear power plants is a laborious task to perform since step-by-step, systematic, and comprehensive processes are required to input necessary data. It needs highly skilled PRA modelling technicians who can fully understand a vast amount of the design documents and reliability of the structures, systems, and components. One of promising break-through technologies for the issue of practical use of PRA is Artificial Intelligence (AI) technology. Therefore, this study is intended to develop PRA methodology using the AI technology. For this purpose, the authors have been conducting a three-year program including the development of AI tools for automatic fault tree (FT) creation. The AI tools are intended to enable any users to easily perform PRA with the same quality less depending on user's PRA skill. This paper describes updates of the AI tools for automatic FT creation, as a second step progress. Topical update is function extension of FT creation from a component level in the first step to more detailed failure mode level. This update enables to consider the change of the system area influenced from each component failure mode that is described as a basic event in the FT. The image recognition process in the FT creation from the design documents was improved to consider power supply systems in addition to piping systems by extracting power supply components and lines from the paper source-based single-line diagram. And more, user-interface was improved for the convenience of human annotation.
These updates were demonstrated and verified with using the AI tools. And effectiveness of work time reduction was quantitively evaluated through trial human work.

Keywords: Probabilistic risk assessment, Fault Tree, Artificial Intelligence, Failure Mode Level Fault Tree

1. INTRODUCTION

Application of PRA is widening and diversifying not only the key methodology for regulating safety but also risk-informed design methodology [1]. On the other hand, PRA of nuclear power plants is a laborious task to perform since step-by-step, systematic, and comprehensive processes are required to input necessary data [2]. Furthermore, it needs highly skilled PRA modelling technicians who can fully understand a vast amount of the design documents and reliability of the structures, systems, and components. Meanwhile, counter measures against systematic and comprehensive PRA processes have been conducted to reduce human work of PRA. For example, Computer-assisted automatic FT construction methodologies were logically studied by various approaches [3] to [8]. But issues of vast amount of the design documents and reliability of the structures, systems and components are remain. One of promising break-through technologies for the issue of practical use of PRA is AI technology, because of AI data pick up and analyze technologies reaches to act as human understanding for design documents and necessary data of nuclear power plants. Therefore, this study is intended to develop PRA methodology using the AI technology. For this purpose, the authors have been conducting a three-year program including the development of AI tools for automatic fault tree (FT) creation [9]. This AI tools are intended to enable any users to easily perform PRA with the same quality less depending on user's PRA skill.
This paper describes updates of the AI tools for automatic FT creation, as the second step progress.

2. Updates of the AI tools for automatic FT creation

AI technology of data pick up, especially, template matching, line segment detection and optical character recognition/reader, can contribute labor saving for PRA modelling technicians, because of these AI technologies reaches to act as essential human understanding/identification for design documents of nuclear power plants. Therefore, the authors have been developing the automatic AI tools to create FT from the design documents such as paper source-based piping & instrumentation diagram, single-line diagram, etc. The automatic AI tools for FT creation process are composed of the following steps;
・Identification of component and piping

・Identification of system function
・Integration of FT data
・Conversion for input format of PRA analysis code

These steps are implemented using AI technology and rule based automatic programs with annotation graphical user interface tool. For example, AI technologies such as image recognition and optical character recognition are adopted to identify component and piping from piping & instrumentation diagram image.
As the first step of the development of the tools, the authors prototyped the tools for the front-line system FT creation with component level of detail. The components and piping extracting function were constructed by combining annotation software, free AI software, and free AI library. In addition, as a data creation function, an automatic execution processing program by Python was constructed for the basic event ID generation function and the FT data creation function.
As the second step, topical update of the AI tools for automatic FT creation is function extension of FT creation from a component level in the first step to more detailed failure mode level. This update enables to consider the change of the system area influenced from each component failure mode that is described as a basic event in the FT. The identification process in the FT creation from the design documents was improved to consider power supply systems in addition to piping systems by extracting power supply components and lines from the paper source-based single-line diagram. And more, user-interface was improved for the convenience of human annotation.

2.1 Function extension for failure mode level FT

Failure mode level FT creation process using the updated AI tools is shown below;

[Step 1: Identification of the component and piping for FT creation]
In this process, the component and piping of the design documents are extracted by the AI tool. The modeling scope of the FT creation is set consistent to the system that is required for success of top event, and the area where the target component and piping exist on the design documents is specified. This is a task that should be determined by humans. However, the AI tool can assist human work, such as Graphical User Interface (GUI) function that displays design data (piping & instrumentation diagram, single-line diagram, etc.) on the screen and a function that makes it easy to detect and specify the target with a mouse. In the case of front-line cooling system, the blocks on the system diagram are also identified the parallel system that is consisted of "AND" relationship. For power supply system FT creation, destination of the power supply is identified as start point. After the identification is complete, the AI tool outputs the Excel format list file for setting the name of component and piping and basic events.

[Step 2: Setting the name of component and piping and basic events]
In this process, the name of the component and piping, component level basic event, failure mode level basic event and the influence area are set using the Excel format list file. This is a task that should be determined by humans. However, it can assist human work, such as excel format list file including the trimmed picture of component and piping to support the recognition. The Excel format list file also prepare the dictionary data to set the name of component and piping and basic events.

[Step 3: Component level FT data creation]
In this process, component level FT data is created from imported Excel format list file by the AI tool. The FT data is generated to be a textual input to FT creation software such as SAPHIRE [10]

[Step 4: FT data expansion to failure mode level]
In this process, component level FT data is expanded to failure mode level FT data from the information of imported Excel format list file using the execution processing program by Python. Specifically, as a simple example of expansion to failure mode level FT, assumption of the correspondence between the component level basic event IDs and the failure mode level basic event IDs are shown in table 1. In this case, since the failure mode level basic event IDs should be connected in "OR" relationship, term of the failure mode level basic event IDs corresponding to the component level basic event ID are substituted in "OR" relationship as shown in the right side of figure 1.
And the influence area of basic event is also set to failure mode level FT data. Specifically, as a simple example of influence area of basic event, assumption of the correspondence between the component level basic event IDs, the failure mode level basic event IDs, blocks and influence areas are shown in table 2. In

this case, since the basic event ID "A01-BK" should be set "1 level upper block" depending on the influence area, "A01-BK" is moved to one level higher as shown in figure 2.

[Step 5: FT creation]
FT can be created using FT creation software provided in SAPHIRE etc. Since the basic event data contained in each block and information such as the logical relationship between blocks have been determined by the above process, it is possible to create FT data in the PRA code format.

Table 1. Example of correspondence between the component level basic event ID and the failure mode level basic event ID

component level basic event ID	failure mode level basic event ID
A01	A01-FS
	A01-BK
B02	B02-CL
	B02-FO

Table 2. Example of influence area of basic event

component level basic event ID	block	failure mode level basic event ID	Influence area
A01	BLK1	A01-FS	Same block
		A01-BK	1 level higher block
B02	BLK2	B02-CL	Same block
		B02-FO	Same block

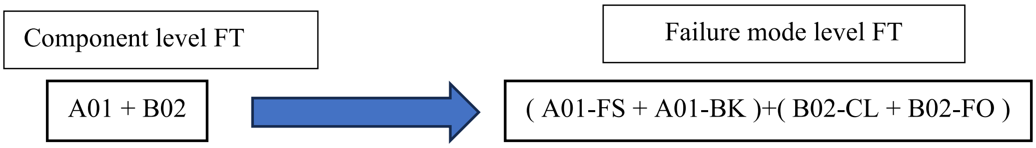

Figure1. Example of expansion to failure mode level FT

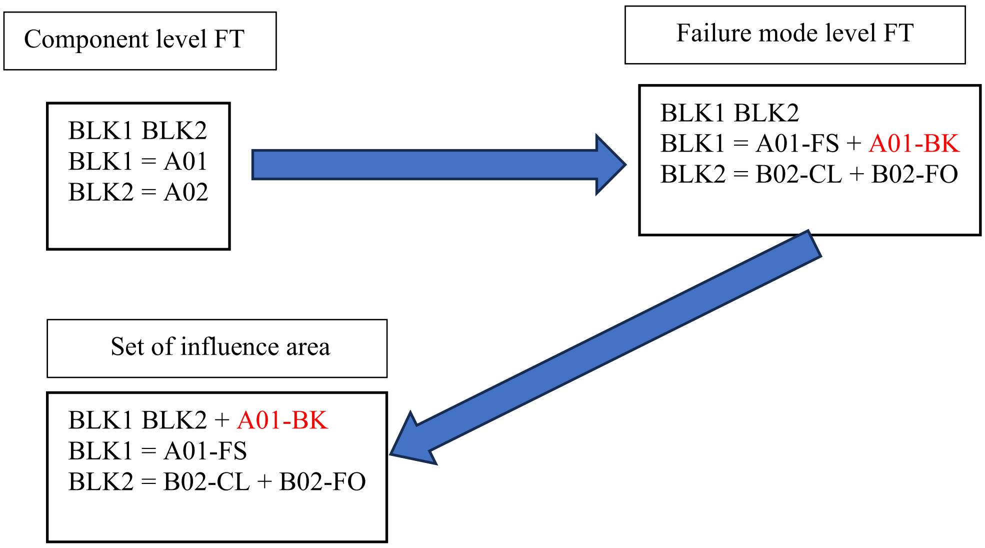

Figure 2. Example of set of influence area

The authors demonstrated to check the function of the updated AI Tools for FT Creation with comparing PRA analysis data and results of the sodium fast reactor.
Figure 3 shows the example of GUI view of identification of the component and piping for FT creation in step 1. This step is the same as component level FT creation of the first step of the development in [9].
Figure 4 shows the partial example of the Excel format list file for Setting the name of component and piping and basic events in step 2. 2 types of zoomed pictures are included in the list to support identification.
Figure 5 shows the example of FT created using FT creation software provided in SAPHIRE in step 5.
From these demonstration results, the authors confirmed the function of the updated AI Tools.
To verify the updated AI tools, the authors checked the logical structure and quantification results by comparing the FT using the updated AI tools and the FT created by PRA modelling technicians. The logical structures of both FTs were verified by comparing the gates and the fundamental events under the gates. And quantification results of both FTs were verified by comparing minimal cut set which is the minimum combination of basic events that generate top events. From these verification results, the authors confirmed that the updated AI Tools can create logically the same FT as PRA modelling technicians.

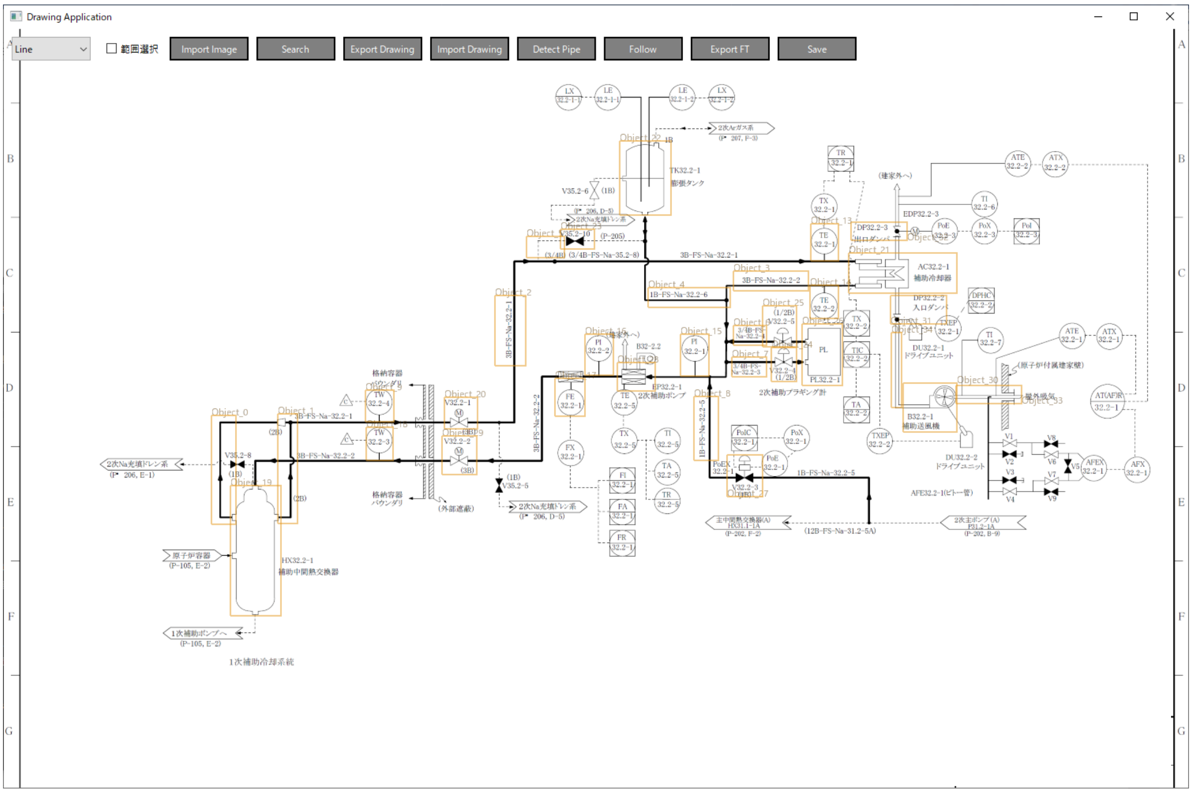

Figure 3. Example of GUI view of identification of the component and piping for FT creation

Figure 4. Partial example of the Excel format list file
for Setting the name of component and piping and basic events

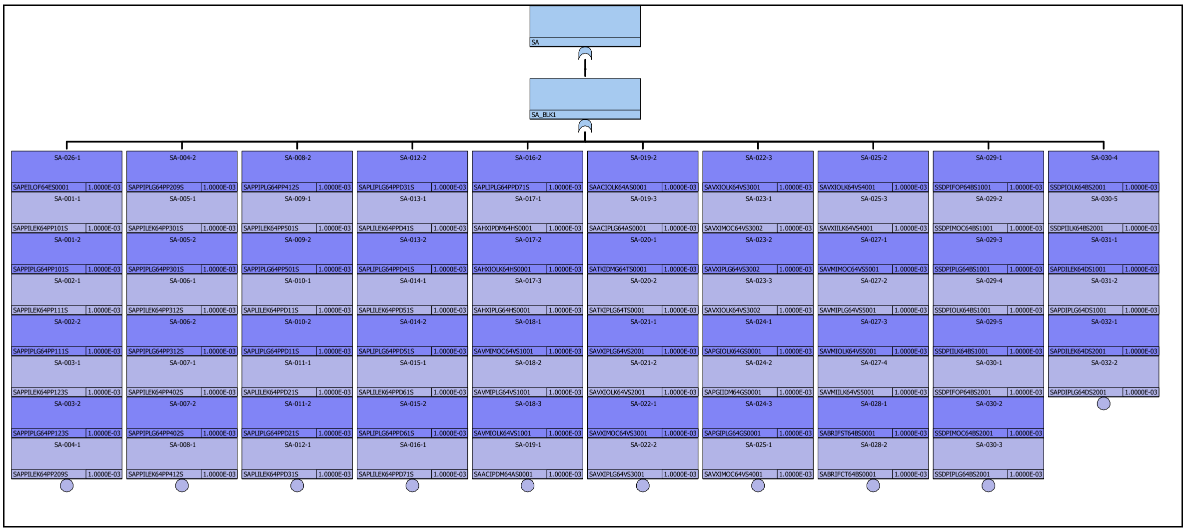

Figure 5. Example of FT created using FT creation software provided in SAPHIRE

2.2 Function extension for identification of power supply systems

To extend the function for the power supply systems of single-line diagram, the AI tool was updated to extract the components with tracing the connection from the power supply destination to the upstream power supply source. In addition to the main power supply, the power panel also has connections to the backup power supply, so the branch structure can be traced.

Identification process of power supply systems using the updated AI tools is shown below (also shown in figure 6);

Step 1: Identification of power supply destination.
Step 2: Extraction of the components with tracing the connection from the power supply destination to the upstream power panel. Extracted components are connected in "OR" relationship.
Step 3: Extraction of the components with tracing the connection from the power panel to the upstream power panel or power supply source. If 2 power supply sources are connected in the power panel, extracted components of branches are connected in "AND" relationship.
Step 4: Repeating step 3 to the boundary of modeling area.

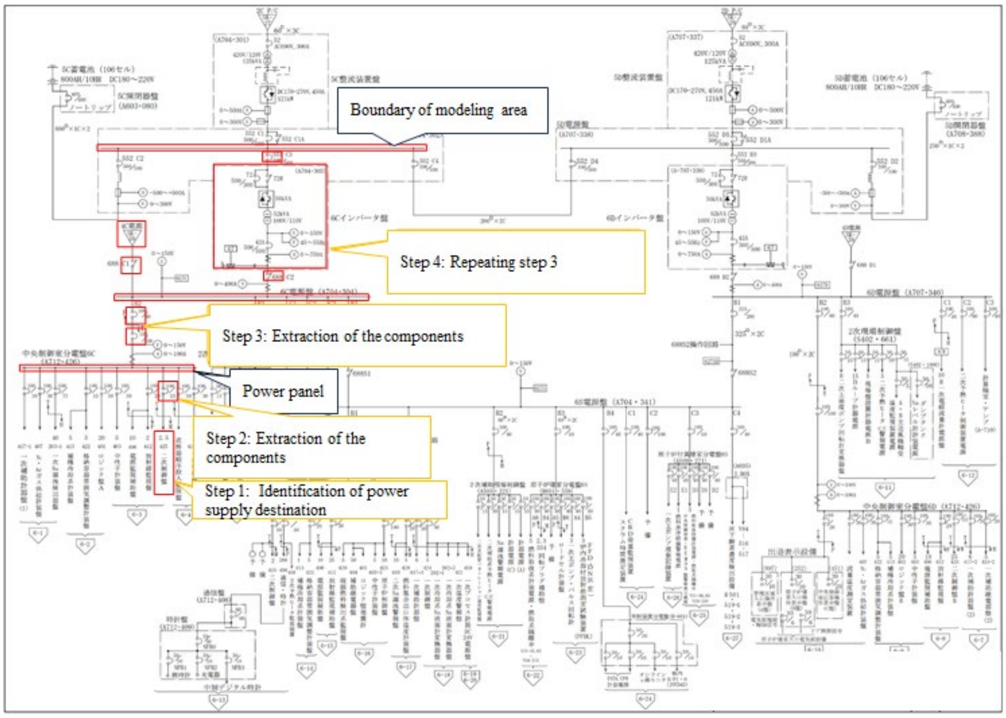

Figure 6. Identification process of power supply systems

The authors demonstrated to check the function extension for identification of power supply systems with comparing PRA analysis data and results of the sodium fast reactor. Failure mode level FT creation process using the updated AI tools is the same as 2.1.

Figure 7 shows the example of GUI view of identification of power supply systems.

Figure 8 shows the example of power supply system FT created using FT creation software provided in SAPHIRE.

From these demonstration results, the authors confirmed the function of the updated AI Tools.

To verify the updated AI tools, the authors checked the logical structure and quantification results by same manner as 2.1. From the verification results, the authors confirmed that the updated AI Tools can create logically the same FT as PRA modelling technicians.

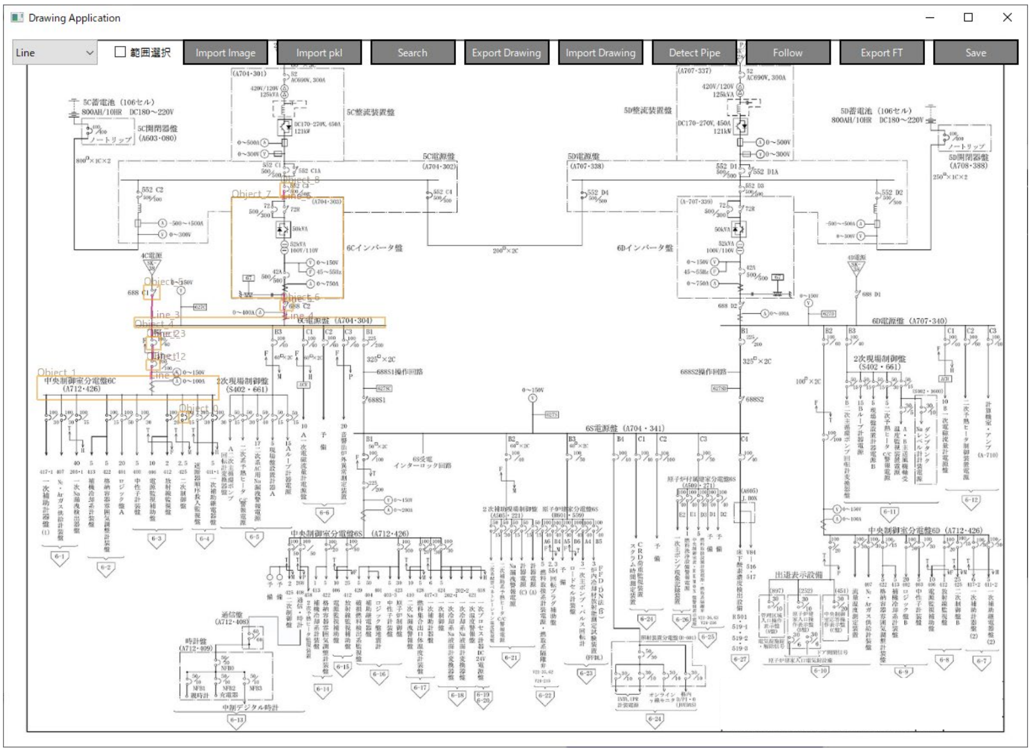

Figure 7. Example of GUI view of identification of power supply systems

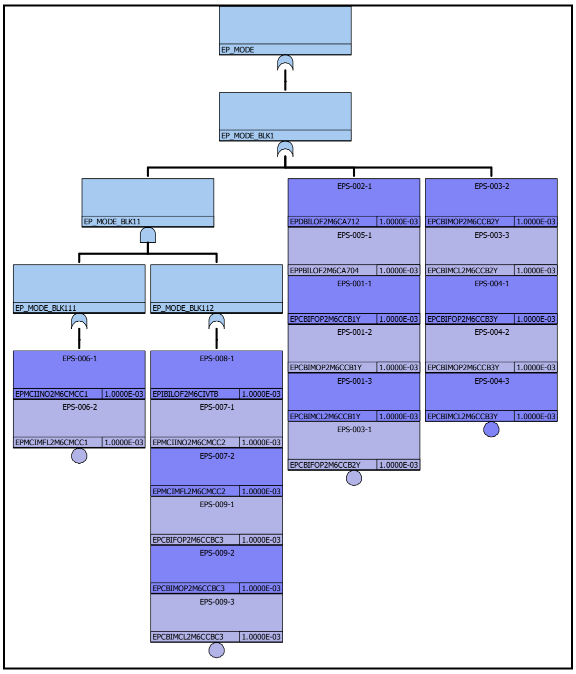

Figure 8. Example of power supply system FT created using FT creation software provided in SAPHIRE

2.3 User-interface improvement

In the first step of [9], open-source annotation software called LabelImage [11] was used for the user interface. In the second step, proprietary annotation tool is used to improve the convenience of human annotation. This tool can create rectangles, straight lines, and polylines (multiple consecutive straight lines). Furthermore, this tool can link to PySide6 [12] as a library. This tool can be flexibly linked with external tools, and the functions of external tools can be called up and used during the process of setting the scope of modeling area and identification of components. Regarding the link approach, it is possible to call the function as an external program, or to cooperate as a library.

This interface improvement also contributes to flexible selection of AI library for extraction of the components and piping. To facilitate the application of the AI tools for automatic FT creation to various systems and no template design documents, the object detection technology was studied for extraction of the components and piping instead of template matching technology [13]. In recent years, deep learning technology has progressed on large-scale models that use a technology called Vision Transformer [14], and this technology has become possible to accurately detect similar objects from images without a large amount of training data. In this study, the applicability of object detection technology was investigated by using Vision Transformer structure called CLIP (Contrastive Language-Image Pretraining) [15].

Figure 9 shows examples of circuit breaker and switch as highly similar components. And Figure 10 shows the results of trial circuit breaker extraction. There were no cases where switches were erroneously extracted as circuit breaker. However, some circuit breakers were missed in the extraction. This was because the components and the characters were very close to each other and were recognized as part of the component image. By specifying the circuit breaker with characters close to each other as the extraction target, all the circuit breakers were extracted. In this way, the Vision Transformer-based CLIP can be expected to extract components that are difficult to identify using template matching. As mentioned above, user-interface improvement has made it possible to link with various AI models and libraries. By incorporating new AI models and libraries, the extraction function of this tool can be enhanced.

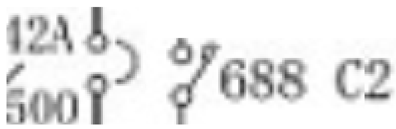

Figure 9. Examples of circuit breaker (left) and switch (right) as highly similar components

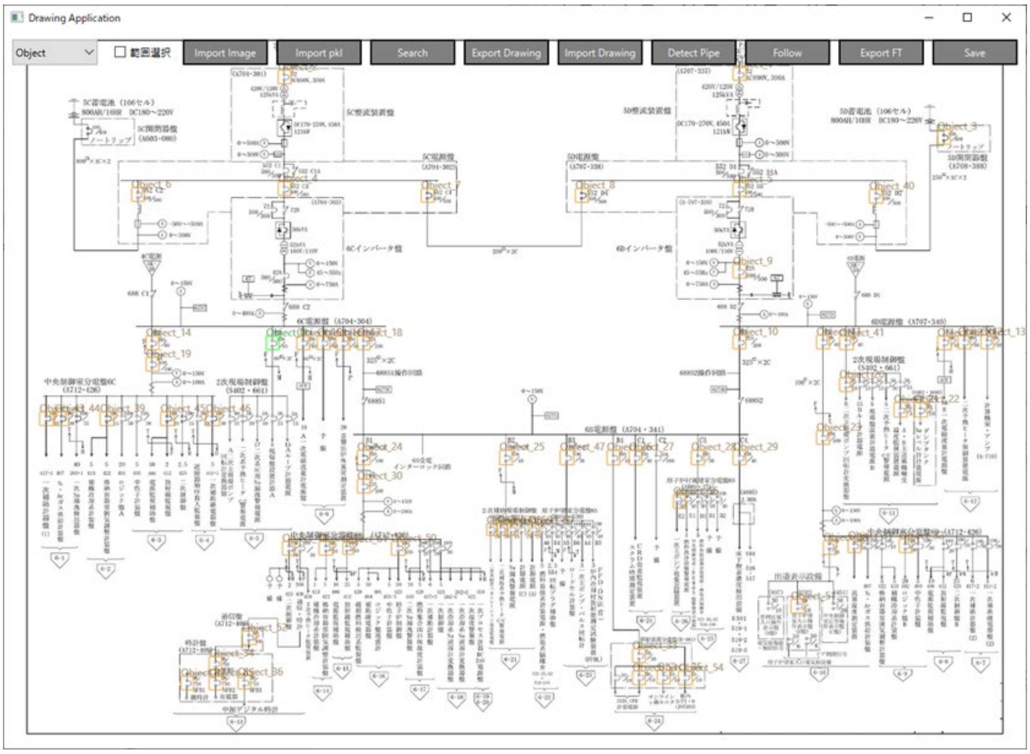

Figure 10. Results of trial circuit breaker extraction

3. Quantitative evaluation of FT creation time through trial human work

Effectiveness of the AI tools was quantitively evaluated from the viewpoint of the reduction of human work. Specifically, the work time required to create a FT with using the AI tools was compared with the work time required to create a FT without using the AI tools. In this comparison, PRA modelling technicians created FTs from the design documents of the secondary cooling system and the secondary auxiliary cooling system of the sodium fast reactor and measured the work time. The secondary cooling system is more complex system than the secondary auxiliary cooling system. In the case of both systems, component level FTs and failure mode level FTs were created to evaluate the influence of detail level of FT.
Figure 11 shows the work time results of component level FT creation. The AI tools contributed to reduce the work time in both system cases, and this tendency was even greater for more complex system. This is because that complex system needs more component extraction time.
Figure 12 shows the work time results of failure mode level FT creation. The AI tools also contributed to reduce work time in both system cases. But this tendency was even lesser for more complex system. Although user-interface improvement from the first step AI tools contributed to reduce the work time, more detailed FT needed the work time to identify the component names and blocks. This issue will be improved in the next step.

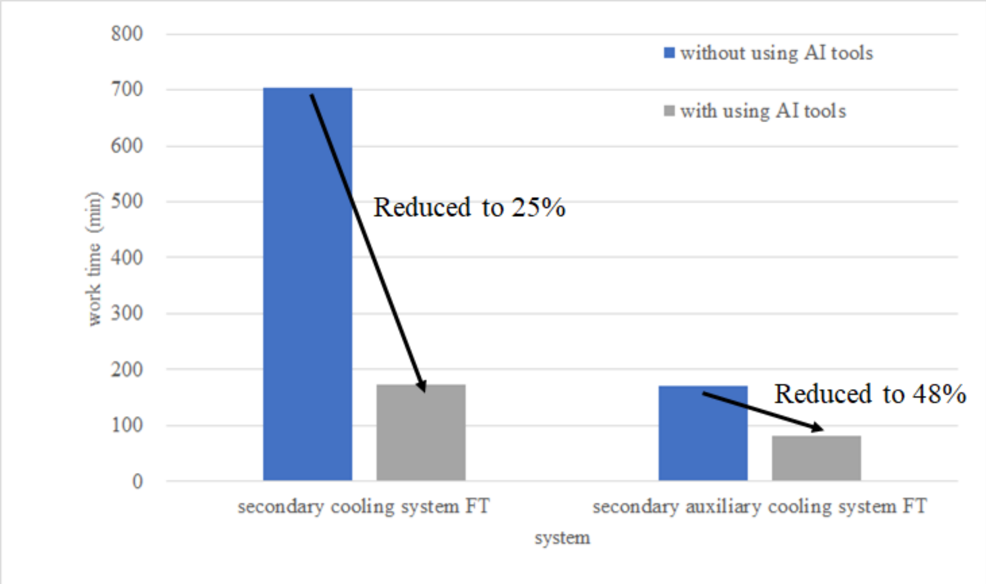

Figure 11. Work time results of component level FT creation

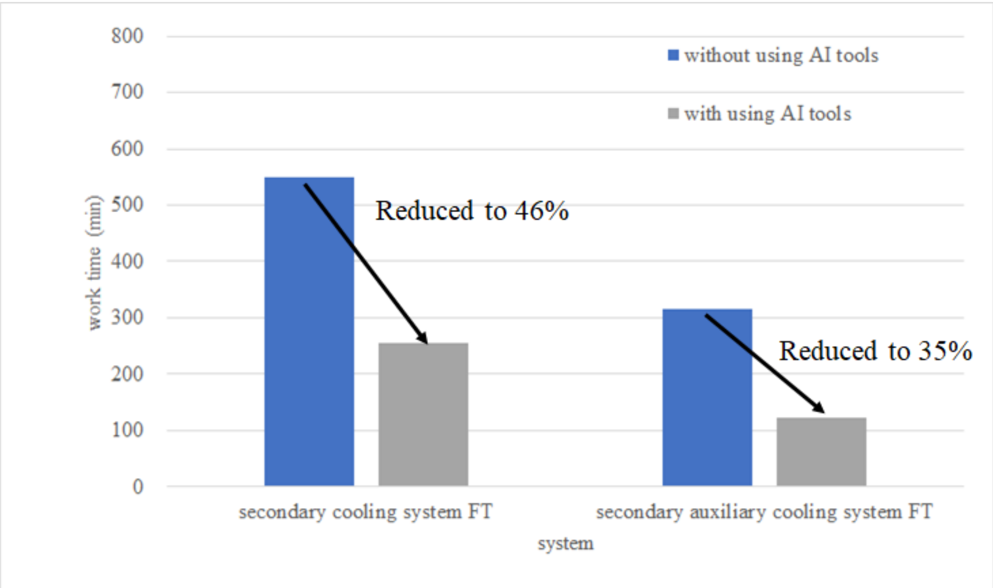

Figure 12. Work time results of failure mode level FT creation

4. CONCLUSION

The authors have been conducting a three-year program including the development of AI tools for automatic FT creation. The AI tools are intended to enable any users to easily perform PRA with the same quality without user effect.
As the second step, topical update of the AI tools for automatic FT creation is function extension of FT creation from a component level in the first step to more detailed failure mode level. This update enables to consider the change of the system area influenced from each component failure mode that is described as a basic event in the FT. The identification process in the FT creation from the design documents was improved to consider power supply systems in addition to piping systems by extracting power supply components and lines from the paper source-based single-line diagram. And more, user-interface was improved for the convenience of human annotation.
These updates were demonstrated and verified with using the AI tools. From the demonstration results, the authors confirmed the function of the updated AI Tools. From the verification results, the authors confirmed that the updated AI Tools can create logically the same FT as PRA modelling technicians.
Effectiveness of work time reduction was quantitively evaluated through trial human work. From the results of quantitative evaluation, the authors confirmed that the AI tools contributed to reduce work time.

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