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Collecting and Organizing the Influencing Factors of Team Communications to Handle Nuclear Power Plant Emergencies

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Featured Application: The influencing factors can be applied as references to human reliability analysis in the nuclear power plant industry.

Abstract: A nuclear power plant (NPP), as a complex safety-critical system, requires qualified operators working in teams. Interactions between operators in the main control room (MCR) team are important to ensure safe operation. Since communication is the basis of the operators' interactions, team communication is a significant factor affecting teamwork performance. Especially during NPP emergencies, poor team communication may lead to incorrect decisions and countermeasures, causing deterioration toward accidents. Moreover, in an emergency situation, emergency response teams are assembled. This multi-team and critical work condition further emphasizes the need for effective and accurate team communication. We collected the factors influencing team communication in NPP emergencies using a literature review combined with text mining. Our method for extracting the influencing factors consists of four steps; then, by applying topic modeling from text mining, we complemented the influencing factors. The resulting list of influencing factors of team communications for handling NPP emergencies is organized into five elements: individual, team, communication, NPP tasks, and external elements. Discussions on the team communication model, applicability, communication errors, and emergency response teams are also presented.

Keywords: emergency situations; influencing factors; nuclear power plant; team communication; teamwork

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1. Introduction

In the 1950s, the first nuclear power plant (NPP) was operated, and, in 2021, there were 437 reactors in operation and 56 reactors under construction across 33 countries [1,2]. The distinctive merits of NPPs, such as being carbon-free and having extremely high energy density, a relatively small size, low operating costs, etc., have made NPPs an integral part of electricity supply, contributing ±22% on average in the NPP-operating countries, with four countries depending on NPPs for more than half of their electricity [2–5]. However, the radioactivity of nuclear fuels and elaborated technologies required to contain nuclear fission make NPPs a complex safety-critical system [6]. NPP operation has inherent safety risks, manifested by past severe accidents (accidents involving core meltdown) that released radiation harmful to the human body and the environment [7,8].

The complexity and safety concerns of NPPs require qualified operators to work in teams. NPP routine operation is performed by the main control room (MCR) team, consisting of three to five operators, including a team leader who is responsible for the final decision-making and several on-site/field operators [9–12]. The interaction and cooperation among operators of the MCR team are important to ensure safe electricity generation. The basis of the operators' effective and accurate interaction is the communication between them, namely, team communication. Thus, team communication is a significant factor affecting team performance, and its importance was mentioned as early as 30 years ago [13]. Since NPP operation is stable most of the time, the study of team communication during emergencies, rather than routine operation, shall lead to valuable insights. Also, research on teamwork in general exists; however, knowledge of team responses to a crisis is questionable, and many teams, including highly trained teams, perform inadequately with significant variability during emergencies [14].

As a high-hazard industry, NPP safety analysts attempt to reduce risks from those performance variabilities in teamwork (and other human errors in general) using various engineering and human-controlled safeguards [15,16]. Among the various approaches is the hierarchy of controls summarized by the mnemonic ERICPD (Eliminate–Reduce–Isolate–Control–Protect–Discipline). The MCR operators' communications fall under the 'Disciplines' measure in the hierarchy of controls, and 'Discipline' is of the utmost importance [17]. Thus, the MCR team should be trained to avoid operator errors, including communication errors, even in high-stress emergency situations. The ERICPD hierarchy can also be applied during system design to represent how and why a solution was logically chosen while considering the hazards [18]. A hierarchy of controls has been considered for the safety assessment of NPP decommissioning [16].

Poor team communication may lead to incorrect decisions and countermeasures, causing an emergency to escalate into an accident. Moreover, when the MCR team declares an emergency, emergency response teams are assembled. These teams may reach up to three massive additional teams in South Korean NPP operations (depending on the emergency status), and team members can be added as deemed required by the team leaders. This multi-team and critical work condition further emphasizes the need for accurate and on-time team communication. A team communication model is required to understand team communication, such as its influencing factors and processes, and consequently, to analyze and find improvements. In this study, we aim to collect the factors influencing team communication using a literature review combined with text mining, serving as the first step in developing a team communication model. Also, we arranged our influencing factors extraction steps into a methodology that can be applied to similar research.

The current study's scope is to collect the influencing factors of spoken team communication between operators during NPP emergencies. We focused on spoken communications through face-to-face, telephone (landline, cellular, or satellite), and video telecommunication. We addressed spoken communication because, after observing a training session on the emergency management of an MCR team, it was identified as the dominant method. Next, emergencies in NPPs are of interest as they are critical events, and communication-related phenomena are different in normal and non-normal situations. The range of emergencies in this study includes abnormal to severe accidents. The NPP in consideration is equipped with computer-based workstations; thus, the communication-related events related to the digital controls and shared visualizations are considered (such as the reduced person-to-person interactions found in [19]).

The contributions of our study are as follows: the final result, i.e., the influencing factors of team communication in NPP emergencies, can be applied as performance shaping factors to perform human reliability analysis. The influencing factors and their categorization can be implemented to understand teamwork behavior (team decision-making, team performance, etc.) under emergency situations. Our research method of collecting the influencing factors from a literature review and text mining can be applied to similar studies in safety-critical domains.

2. Materials and Methods

2.1. Related Works

We explored related papers regarding the importance of communication in high-risk environments and those that considered communication as an influential factor [20–24]. The most similar work is [20], in which there were two similar properties: distributed teams and high-risk environments. It presented a concise work without mentioning any application domain or focusing on emergencies. The authors of [21] studied team communication and provided rich insights without a specific domain. Emphasis on adverse events was made by [22], who reviewed team resilience and proposed a multilevel model of workplace team resilience. Team resilience is related to our interest in emergency management since it supports a team in maintaining performance during adverse events and high-pressure environments. The authors of [23] found that communication was a useful team process in stressful situations and important in developing a common view of the situation, as part of the so-called "team brain". The authors of [24] identified 4 key variables associated with team function: leadership styles, supportive team behavior, communication, and performance feedback.

Engineering team performance was reviewed by [25], and they found that the skillset/knowledge of team members had the highest impact on team performance. Although [25] discussed team performance during a general engineering project, we were more interested in their analysis of the team factor's impact on the team performance: positive, negative, or mixed impact. The healthcare domain dominated the research on teamwork in general as well as emergencies; however, most of their findings were highly domain-specific, such as physicians' non-technical skills, clinical performance, medical simulation, etc. [26–28].

We found a paper that explored resilience in emergency management [29] and another that reviewed the Functional Resonance Analysis Method, which is an analysis method supporting resilience engineering [30]. Resilience is the capability to adapt one's reaction and performance, especially when facing unexpected situations. In handling NPP emergencies, we expect the operators working in teams to possess resilience; thus, we are inclined to apply resilience engineering principles. Cognition in crisis management teams is discussed by [31]. All the 11 constructs to define cognition were related to the collective sense of a team. A useful method for communication analysis was presented in [32]. In an attempt to find out how teams adapt their communications in critical situations, [32] compared team communication in critical and noncritical situations and analyzed the communication patterns using the Relational Event Model, a framework used in sociology, in which 7 types of communication patterns were defined.

In summary, we found that no related study overlapped with the objective and content of our current study. Although [20] shared a few similarities, the covered literature was narrow, and the focus of their study was different. The other related studies either had a broader scope (team resilience, team performance), were on a different domain (general workspace, healthcare), or had a specified emphasis (stress, cognition). A team decision-making research study from 2021 [33] produced a list of associated and key factors affecting team decision-making performance and a conceptual model for organizing team decision-making performance factors. While in this paper, we used a similar research method, namely, listing the factors related to team communication and proposing a preliminary model of team communication by organizing the factors, the objective and emphasis of both studies are different. Moreover, in this paper, we performed a literature review using the PRISMA method and text mining; thus, we took more comprehensive steps.

2.2. The Method to Extract the Influencing Factors

We collected the influencing factors of team communication in NPP emergencies by performing and analyzing the results of a literature review and text mining. For the literature review, we partly followed the PRISMA method [34], and the papers assessed for eligibility were limited to the NPP domain. To compensate for this limitation, text mining was carried out on the entire set of reference papers. From the papers selected with the PRISMA method, we extracted the main research findings and, from the topics obtained from text mining, we estimated the meaning of the words into reasonable terms related to the research topic. The results were combined to create a list of influencing factors of team communication in NPP emergencies (Figure 1). The methodology of extracting the influencing factors from the literature review and topic modeling is organized as follows.

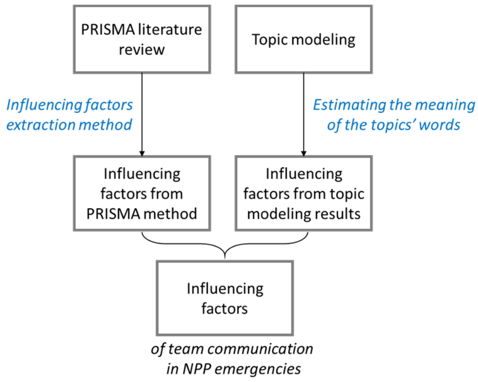

Figure 1. Research method used to develop the influencing factors of team communication in NPP emergencies.

2.3. Extracting the Influencing Factors Using a Literature Review

2.3.1. Preparation and Application of the Systematic Review Method

One of the objectives of analyzing the related papers (Section 1, the part on related studies) was to obtain some pointers to carry out PRISMA. We analyzed the search words and search strategies used in the related studies. The search words and words related to the papers' results were collected. Then, we selected our search words based on our research interests. We selected 33 search words to be searched on Scopus, Web of Science, and IEEE Xplore.

Our 33 search words can be divided into 3 groups: topic, focus, and context, similar to [35]. The topic group covered team communication, divided into synonyms of "team" and similar words of "communication". The theories and methods that are useful to analyze team communication were contained in the focus group. The context group contained the environmental constraints, i.e., emergency. We decided not to limit our search to the NPP domain to assist in preparing for our next research on finding applicable methods from other domains. After trial searches, we moved some search words from the topic to the context category (team performance, team cognition, and team-based problems) because significant reviews on general team communication were not obtained. The search words socio-technical and complex decision-making were also moved to the context group for the same reason.

We also examined the search strategy used in the related works, which is the steps taken to collect the papers from the database to obtain the most relevant papers and reduce the sorting effort. The simplest search strategy is to enter all the search words at once on the search bar of the database, such as that used by [24]. The search words can also be added gradually after analyzing the search results [23]. Entering multiple search words at once applies the "and" logical relationship; this approach has a drawback when we want to include synonym words or obtain general yet helpful papers that do not contain all the search words in their title and abstract. The authors of [29] prepared a different set of search words for each database and [31] added this search strategy with steps for search queries per database. The steps of the search queries were the additions of search words with a similar concept combined using the "or" (logical) relation, and each group of similar search words was combined with the "and" relation [23]. This search strategy solved the previously mentioned drawback because similar words (synonyms or similar concepts) can be grouped, and papers mentioning at least one word from the group can be obtained. However, the analysts have to decide on the number of search word groups and the number of words to be included in a group. Too many groups or words in a group would yield many papers and slow down the selection process, but the contrary might fail to obtain related papers.

Our search strategy was as follows: the search words in a group were linked using "or" and the groups were linked to each other using the "and" relation, similar to [36]. Using this search strategy, we were able to collect the papers that match our research interest, namely, team communication, focusing on cognitive systems engineering-related theories, in the context of emergencies or general team performance-related studies in socio-technical systems (Table 1). We also added the following conditions: papers written in English excluding books, book chapters, graduate theses, posters, presentations, abstracts only, and white papers.

Table 1. The search words used for the PRISMA method.

Topic		Focus	Context
team *	communicat *	situation awareness	emergenc *
crews	collaborat *	sensemaking	critical situation
operators	coordinat *	mental model	safety
	interact *	cognit *	accident
	decision-making	collective *	incident
	teamwork	human error	high-risk
	team concept	team resilience	stressful
		communication patterns	adverse
		heuristic	socio-technical
		naturalistic	team performance
			team cognition
			team-based problem
			complex decision-making

symbol "*" means any characters are allowed, for example, communicat * includes communication, communicate, communicating, and so on.

Next, we proceeded to screen each paper. Upon reading the title and abstract, we excluded the papers that (1) neither analyzed a team nor an emergency, (2) considered an emergency but not at the team level, (3) analyzed a team but not during an emergency, and (4) was not a research paper. Then, we identified each paper's application domains and selected those on the NPP domain. In the end, we selected 72 reference papers (Figure 2).

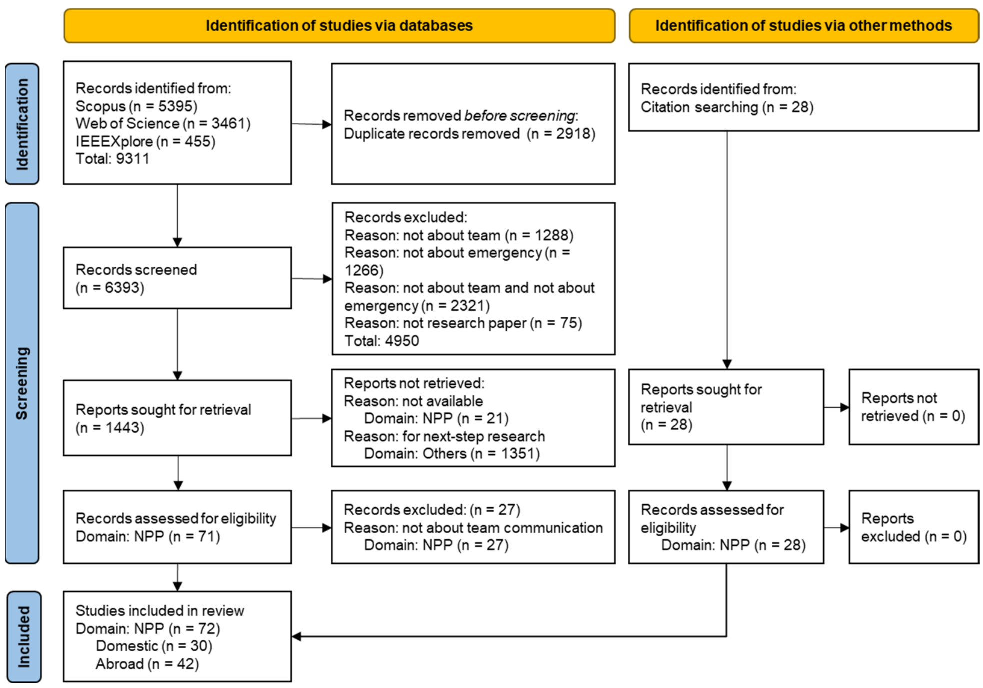

Figure 2. The literature selection process using the PRISMA method.

2.3.2. Extracting the Influencing Factors from the Reference Papers

The method for extracting the influencing factors from the reference papers consists of the following steps (Figure 3).

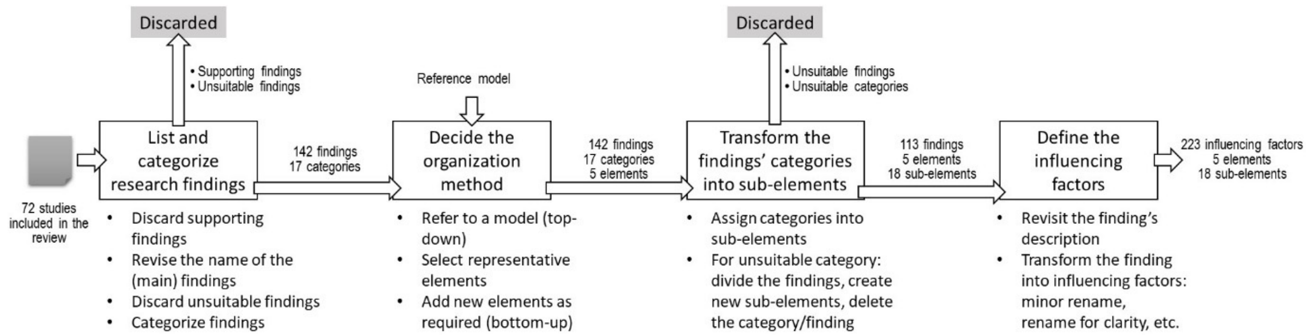

Figure 3. Method used to extract the influencing factors from the reference papers.

List and categorize the research findings. The research results of the reference papers (hereafter, papers) were recorded as research findings. By considering its contributions to team communication, each finding was classified into main or supporting findings. The supporting findings were examined for a second time to determine whether they could be moved into the main findings, and the remaining supporting findings were no longer involved in the study. For example, from [37], we extracted two research findings: "computer-based procedures" and "communication types". The "computer-based procedure" finding is a supporting finding because we were focused on spoken communications between the operators (the form of a procedure affects communication, and it is included in the final influencing factors, but the detailed design effort and display of the computer-based procedure did not). Each paper contributed at least one ("communication types" from [37] and "communication database" from [38]) and up to seven main findings (from [39,40]). Hereafter, findings refer to the main findings.

Next, the findings' descriptions were revisited, their names were revised (if needed, to combine duplicates), and they were allocated to a category. The categorization was a result of clustering similar findings. We described each category to maintain consistency. For example, the "communication types" finding in [37] was a table titled "Communication Types", containing 3 columns: types, definitions, and examples. The types column listed: command, call, and so on, with their definition and examples in the respective columns. We decided to rename this finding as "communication content type", which we defined as "the type of communication content for categorization purposes (coding schemes included)". The findings of [41] on 25 communication dimensions (information questions, help or opinion questions, etc.) and [42]'s team communication information (Command, Action-report, Inquiry, etc.) were also renamed as "communication content type", as well as all findings on speech coding schemes.

After the analysis, we excluded 16 findings because they were not suitable team communication factors, such as the co-working pattern in [43] or other/previous paper's findings that were already included (communication characteristics in [40]); however, when the other paper was inaccessible, we included the findings. We ended up with 142 findings from 72 papers divided across 17 categories. This categorization was created to gather similar findings; thus, the resulting categories were scattered throughout different concepts and did not follow a certain order or dimension. Examples of the categories are cognitive functions, communication actors' structure, communication content type, communication utterances, and teamwork behaviors. We needed to choose a specific context to organize the findings effectively and consistently.

Decide the organization method. The methods available to organize the findings include a bottom-up approach, where similar findings are combined until they form separate clusters, and a top-down approach, where the number of defined groups is specified first and the findings are assigned to one of the groups. We combined both approaches by referring to a model, selecting a few groups beforehand, and then adding new groups as needed. We were influenced by the conceptual model for organizing team decision-making, which consists of 5 elements: situational, decision-making, team, individual, and organizational element [33]. We agreed that individual and team elements should be included since the findings could be distinctly distinguished between them. Then, there were findings about the communication between team members; thus, we need a communication element similar to the representation of the decision-making element in [33]'s model. Some findings pointed at communication as part of or as a means to perform a task; thus, we added an NPP task factor. Lastly, the surrounding environment proved to have influences on team communication; thus, we added an external factor equal to the combination of situational elements and organization elements in [33]'s model. Thus, we decided on 5 elements: individual, team, communication, NPP tasks, and external elements.

Transform the finding categories into sub-elements. We assigned each category to one of the five elements, and it became a "sub-element". Most of the categories could be assigned into the elements smoothly. For example, "cognitive functions", "communication intention", and "non-technical skills" were assigned to individual elements because they are related to an individual's functions. However, some categories became unsuitable to be assigned to any element. For example, the category "communication model", which contained findings from [44–46], could not be assigned to any element since it covered the entire communication process. In this case, we divided the findings and assigned each of them to a suitable sub-element. Hence, the communication model in [45] was divided into "message encoding and message decoding", "decision-making", and "situation awareness". The first item was added to the "cognitive functions" sub-element, and the other two were added to the "non-technical skills" sub-element. We deleted 4 categories, scattered the contents of 3 categories, and removed 1 category entirely ("communication issues/phenomena"), reducing the number of findings from 142 to 113 findings.

Sometimes, while distributing the findings of a no-longer-valid category, a suitable sub-element did exist; thus, we created a new sub-element. For example, after deleting the "team model", the team decision-making model from [33] had to be assigned to another sub-element. After the analysis, we distributed the contents into several sub-elements; however, we could not find any sub-element to cover contents such as "the difference in team members' expertise level" and "experience in same or similar situations". Thus, a new sub-element, "technical skills", under the individual elements, was created. In the end, we kept 13 of the original 17 categories, assigned them to an element (they became sub-elements), and added 5 new sub-elements, resulting in a total of 18 sub-elements across 5 elements.

Define the influencing factors. We revisited the explanation of the findings to transform them into the final form of influencing factors. During this transformation, we maintained our goal of collecting influencing factors that are practical to NPP emergencies; thus, we avoided ambiguous terms and kept a similar level of information. In Table 2, we present the types of transformations from findings to influencing factors and their examples. As a result, we extracted 223 influencing factors distributed into 18 sub-elements.

Table 2. The transformation from findings to influencing factors.

Transformation	Example	
	(Transformed) Influencing Factor	Finding's Title on Source Paper [Source Paper]
Minor rename	Clarity in role/responsibility	Clarity of team members' roles [33]
Rename for clarity	Levels of information processing before speech	A simple model for the differences in statement levels [13]
Rename for generality	Team size and team members	Operations team of a typical U.K. nuclear power station [47]
Specification of the content—the same sub-element	Working memory of colleagues' goals, priorities, and activities. Evaluation of team value of information and knowledge. Periodic newscasting of own goals, priorities, and activities.	Relating cognitive processes to overt behavior. Team-specific: Information distribution, task allocation, and management [48].
Specification of the content—distributed to different sub-elements	Sub-element: Cognitive functions. Influencing factors: Level of stress. Sub-element: Team situation awareness. Influencing factors: Team situation awareness model development and assessment. Sub-element: External. Influencing factors: Workspace comfort, safety culture, quality of digital procedures, quality of interfaces.	Causal conceptual model of team situation awareness [9]
Combine identical concepts	Clarity in role/responsibility	Clarity of team members' roles [33]. Team elements: Role/responsibility [49].

2.4. Extracting the Influencing Factors Using Text Mining

Simultaneous with the literature review, we carried out topic modeling of text mining; however, we analyzed the results after we finished the literature review.

2.4.1. Text Mining for Influencing Factor Extraction

Text mining aims to derive useful information or knowledge from unstructured and vast textual data [50–52]. The authors of [50,51] reviewed text mining tools used in literature review processes, such as search strategies, screening citations, abstracting/summarizing data, and classifying text. Cost-effectiveness analysis showed that citation screening with text mining reduced more than 60% of the title–abstract screening workload compared with other screening approaches without text mining [53].

Text mining has also been carried out together with the PRISMA method, such as in [54,55], where it was applied for full-text screening of injury and energy consumption research, respectively. In our study, however, text mining was applied to complement the research by finding new influencing factors from other domains outside NPP by using a topic modeling algorithm, which is a method used to discover the topics of documents. We applied latent Dirichlet allocation (LDA) for topic modeling, which is a valid, highly effective unsupervised learning method that has been used in various studies (smart service systems, electronic petitions, social media strategy, wearable technology, etc.) [52,56–58].

We carried out the following: data collection, data preparation, topic modeling using LDA, and results analysis (extracting the influencing factors). The data are the title, abstracts, and author keywords of the papers collected using the same search words used for PRISMA. The papers were from the Scopus database, and we included all the papers, not only the NPP domain papers. Data preparation consisted of removing stopwords (insignificant words, from an existing library and manually added from pilot tests), removing words with fewer than 3 characters, and lemmatization (transforming a word into its dictionary form). We calculated the term frequency-inverse document frequency, which represents the importance of a word in a paper and all the data, and then compressed the data.

Using the prepared data, a document–word matrix was created, and LDA was applied using the library from scikit-learn and pyLDAvis [59,60]. In LDA, a document may contain multiple topics, and each topic is represented by a collection of words [57,61]. The term "topic" is an abstract concept in LDA: it is not a common topic such as "nuclear power plant operation", "emergency response team", and so on; it is a list of words the LDA found to be highly related to each other. In essence, LDA calculates the probability of a document belonging to a topic and the probability of a word belonging to a topic, to finally present (1) the best topic for a document and (2) the most descriptive words for each topic [55–58]. However, instead of obtaining the best topic for a document, we were more interested in the topics covered in the entire data.

The document–word matrix was converted into two matrices: a document–topic matrix and a topic–word matrix; thus, a discrete number of topics was required. Using the coherence score of [62] from tmtoolkit [63], we calculated the optimal number of topics. The highest and second highest coherence scores were obtained for 6 and 16 topics, respectively, and we decided on 16 topics. Then, LDA was used to populate the document–topic matrix and the topic–word matrix. Using the topic–word matrix, we obtained the list of words in the 16 topics (Figure 4). We did not perceive the need to name the topic, which is a difficult task [64]; instead, we proceeded with analyzing the words in a topic to extract plausible influencing factors.

Figure 4. The words in topics found using topic modeling.

2.4.2. Extracting the Influencing Factors from the Topic Modeling Results

Semantics was not considered in the topic modeling and words mean different things in different contexts [58,64]; thus, the analysts have to estimate the meaning of the words based on: (1) the knowledge freshly obtained from performing PRISMA and (2) the context drawn from the relations of each word to one another in a topic. For example, from the words "skill", "technical", and "non" of Topic 0 (zero), the analysts extracted: "technical skills" and "non-technical skills" as influencing factors. Some words led to one or more new or existing influencing factors, while some did not contribute at all (domain-specific words such as "surgery", "nuclear", and "aviation" or general terms such as "framework", "method", and "project"). Words hinting at an application domain ("healthcare") and general concept ("task") were not included as influencing factors. As a result, we obtained 3 to 9 influencing factors per topic.

3. Results

We combined the influencing factors from PRISMA and text mining as the final result. The literature review using the PRISMA method reflected a top-down approach, where we input some search words and selected the eligible papers, whereas text mining reflected a bottom-up approach, where the algorithm scanned the content (limited to the abstracts) of all papers and produced a set of topic keywords. Since the PRISMA method was carried out first, many of the influencing factors from text mining were already discovered; still, several new influencing factors were found. We considered these new influencing factors as a result of including all research domains, implying the merits of including other domains. In total, we derived 223 influencing factors (Table 3, please refer to the Supplementary Material for full list of influencing factors).

Table 3. The number of influencing factors identified in this study.

	Elements		Sub-Elements	Number of Influencing Factors
1	Individual elements			50
		1	Cognitive functions	16
		2	Operator roles and gender	9
		3	Communication intention	10
		4	Non-technical skills	12
		5	Technical skills	3
2	Team elements			24
		6	Operator structure	6
		7	Operator social relations	5
		8	Leadership	9
		9	Team situation awareness	4
3	Communication elements			89
		10	Communication utterances	10
		11	Act of communication	21
		12	Communication content type	43
		13	Communication media	5
		14	Communication multi-way	7
		15	Communication location	3
4	NPP task elements			43
		16	Teamwork behavior	28
		17	NPP event analysis	15
5	External elements	18	External elements	17
		Total		223

3.1. Influencing Factors of the Individual Elements

Table 4 lists the individual sub-elements and their influencing factors. We discuss some of the influencing factors below.

Table 4. The influencing factors of individual elements.

Element:	**Individual Element**
	Sub-Elements (Number of Influencing Factors):
Cognitive functions (16)	Mental model; working memory of colleagues' goals, priorities, and activities; intent formation and intent interpretation; message formation and message interpretation; levels of information processing before speech; thought with or without turn-taking; emotion; uncertainty; responsiveness; level of fatigue; level of stress; level of attention; concern for quality; concern for safety; evaluation of team value of information and knowledge; periodic newscasting of own goals, priorities, and activities

Table 4. *Cont.*

Element:	Individual Element
	Sub-Elements (Number of Influencing Factors):
Operator roles and gender (9)	Operator's role as a leader (e.g., SS); operator's technical role (e.g., RO, TO, EO, STA, field); operator's role as a decision-maker; operator's role as an evaluator; operator's role as an implementor; clarity in role/responsibility; role awareness; motivation for the role; gender
Communication intention (10)	Alarm/process parameter/status surveillance; information sharing; comprehension of the nature of an ongoing situation; determination of appropriate responses/assigning tasks; coordination for information collection; coordination for crew attention/directing attention; agreement and disagreement; maintaining reciprocal awareness; handing over responsibility; close monitoring of/guiding other's activity
Non-technical skills (12)	Situation awareness (individual); communication; decision-making; teamwork/collaboration; coordination; leadership/interpersonal competence; attitude/intrapersonal competence; stress management; time-sharing/time-awareness; learning and coaching; compliance to procedure; following work protocols
Technical skills (3)	Experience for the role (technical role: SS, RO, TO, EO, STA, field); training for the role (technical role: SS, RO, TO, EO, STA, field); technical education

The operators' roles are divided into two dimensions: leader–followers (technical roles) and decision-maker–evaluator–implementor. Several papers discussed the operators' role in the MCR team, such as shift supervisor (SS), reactor operator, turbine operator, etc. [42,43,65,66]. We decided to assign the SS as the leader (operator role as a leader) and the rest as followers (operator's technical role), as a team member communicates differently depending on whether he/she is a leader or a follower. The roles in the NPP team as either a decision-maker, an evaluator, or an implementor were discussed in [67]. Considering multi-team operations during NPP emergencies, these divisions of roles are important as well. For example, in South Korean NPP severe accident management, the leader of the MCR, i.e., the SS, became an implementor of the mitigation strategy decided by another team (technical support center), which was created to handle critical accidents.

Communication intention refers to the intention of an individual who starts a conversation; this intention may or may not be perceived as it was intended by the listener (related to the cognitive functions "intent formation and intent interpretation"). Communication intention is known by the speaker, and when it is spoken, it becomes a "communication utterance", and the speaker engages in an "act of communication" (communication elements). This is an example of relations between individual sub-elements and other sub-elements (Figure 5). Included in the communication intentions are those related to NPP tasks as well as common intentions, such as agreement/disagreement and handing over responsibility [24,68,69].

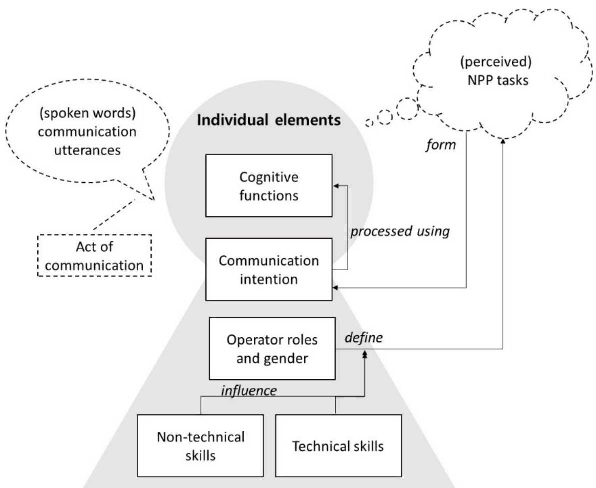

Figure 5. An example of possible relations between individual sub-elements and other sub-elements.

3.2. Influencing Factors of the Team Elements

Table 5 lists the team sub-elements and their influencing factors. We discuss some of the influencing factors below.

Table 5. The influencing factors of team element.

Element:	Team Element
	Sub-Elements (Number of Influencing Factors):
Operator structure (6)	Team size and team members; team structure (communication connection between operators)—normative; operators' relation to others (SNA density, centrality)—descriptive; operators' sequential communication; communication connection: top-down or bottom-up; communication direction: omnidirectional or unidirectional
Operator social relations (5)	Familiarity/experience as a team; training as a team; team diversity; mutual trust; team norms/culture
Leadership (9)	Awareness of the leader's existence; leader's authority; shared goals/team goals; enforcement of procedures; leader's participation; following the leader; supervision; leadership effectiveness; strategy decision types
Team situation awareness (4)	Level 1: observe/team perception; level 2: identify/team understanding; level 3: predict, evaluate, define/team assessment; team situation awareness model development and assessment

Team elements contain influencing factors that emerged from the "working as a team" setting. An illustration of relations between team sub-elements is shown in Figure 6, where the operators are connected through the operator structure by regulations and by social relations, leadership is the property of a leader, and all members maintain team situation awareness.

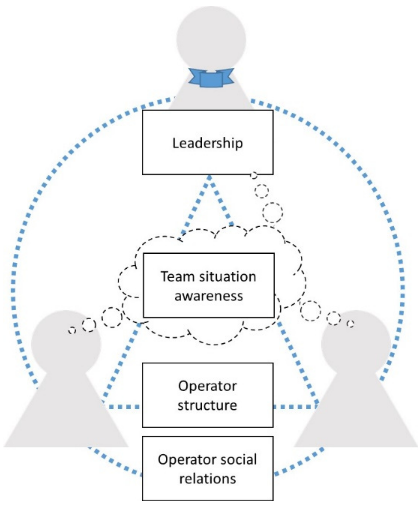

Figure 6. An illustration of relations between team sub-elements.

Despite the pre-defined structure, team members may react differently or deviate from the expected behavior because of the social relationship between them. A tendency toward top-down communication in East Asian countries, where authoritarian culture is strong, was observed in [24], which stated that team members might be reluctant to speak and express their opinions, especially regarding a disagreement with a leader. This behavior is unfavorable during NPP emergencies because not only would the burden be directed solely onto the leader, increasing the probability of erroneous actions, but dangerous consequences might also be avoided when it is perceived and expressed by the team member. The members of the MCR team are trained as a team and high familiarity is favorable since it can strengthen reliability. Although the MCR team members rarely change (an expert joining a simulated training once commented that the team moves similarly to a family), there are occasions when a team member changes [24], breaking familiarity and shaking trust. During those occasions, handling unexpected emergency events will be more challenging and risky.

3.3. Influencing Factors of the Communication Elements

Table 6 lists the communication sub-elements and their influencing factors. We discuss some of the influencing factors below.

Table 6. The influencing factors of communication element.

Element:	**Communication Element**
	Sub-Elements (Number of Influencing Factors):
Communication utterances (10)	Communication utterances transcript; type of utterances; utterance measurement; sentence completeness; communication amount per operator; utterance analysis #1; utterance analysis #2; utterance analysis #3; standard communication protocol; type of speech
Act of communication (21)	Self-judgment; warning; announcement; messages from the plant/new information; repeating known information; request for silence; confirming question; information collecting question (open); information collecting question (closed); provide information/explanation of details; information providing (past); information providing (present); information providing (future); team discussion/briefing; external communication (inter-team communication); command to team members; request for information; affirmation (simple); affirmation (with information); technology problems; people arrival
Communication content type (43)	Call; response or call—ack; call—identification; call—id–ack; command—manipulation; command—others; command—ack; command—confirm; command type; inquiry—identification; inquiry—confirmation; inquiry—help/opinion question; inquiry type; reply; reply—agreement; reply—disagreement; reply—before application; reply—report; reply—ack; observation; observation—ack; suggestion; suggestion—ack; guidance; statement of intent; judgment—decision; judgment—situation; judgment—ack; announcement; announcement—ack; acknowledgment; personnel information; information technology; relation; encouragement; politeness; first-person plural; affection; uncertainty; non-task related; self-speaking or muttering; uncodable; communication content analysis
Communication media (5)	Verbal communication; written communication; device-based: telephone; device-based: fax; face-to-face communication
Communication multi-way (7)	Self-confirmation; one-way communication; two-way communication; three-way communication; four-way communication; analysis of communication multi-way: communication completion; analysis of communication multi-way: communication quality as three-way communication
Communication location (3)	Indoor communication; outdoor/field communication; operators movement

Communication elements distinguish this work from the rest of the team studies; consequently, we tried to collect the influencing factors in this element as comprehensively as possible. An example of possible relations between communication sub-elements is shown in Figure 7.

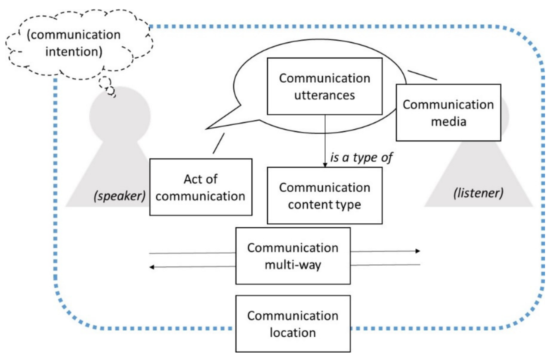

Figure 7. An example of possible relations between communication sub-elements.

The "communication utterances" sub-element covers speech and its analysis, while the "act of communication" sub-element covers the triggers to communicate from the speaker. The "act of communication" is carried out by an individual (the speaker); thus, it is related to the following individual elements: "cognitive functions", "communication intention", and "non-technical skills". Upon noticing the need to talk, the "communication intention" is formed; it is processed through the "cognitive functions" and affected by "non-technical skills", before being carried out as an "act of communication". A "communication intention" can be expressed in multiple "acts of communication" (one-to-n relationship). For example, from the "communication intention" of an "alarm/process parameters/status surveillance", the resulting "act of communication" might be (1) an "announcement", when the speaker announces the readings on the display, (2) "self-judgment", when the speaker adds his/her opinion, (3) "repeating known information", when one of the speaker's tasks is to repeat certain information periodically, although there is no change, or (4) a "warning", when the announcements are ignored and the speaker finds the situation is becoming dangerous, or other acts of communication.

The "communication content type" categorizes "communication utterances" based on the content, resembling a speech–act coding scheme. The difference between an "act of communication" and "communication content type" is that in the latter, no context is assumed or known, whereas an "act of communication" is the product of the communication intention of the speaker. The speaker's identity and task provide a context for the resulting "act of communication". While some of the content types might be similar to the others, in the current research, we gathered the findings from the reference papers as comprehensively as possible.

3.4. Influencing Factors of the NPP Task Elements

Table 7 lists the NPP task sub-elements and their influencing factors. We discuss some of the influencing factors below.

Table 7. The influencing factors of NPP task elements.

Element:	**NPP Task Element**
	Sub-Elements (Number of Influencing Factors):
Teamwork behavior (28)	State assessment—detection; state assessment—observation; alarm surveillance; process parameter surveillance; status surveillance; performance monitoring; information exchange; information sharing; information collection/acquisition; detecting/noticing; comprehension of the nature of an ongoing situation; sensemaking/understanding; fault judgment; decision-making; determination of appropriate responses/strategies; task planning; task preparation; task confirmation; task prioritization; task distribution/allocation; coordination for information collection; coordination for crew attention; team knowledge; action implementation/task execution; supervising/directing personnel; managing workload; performance evaluation; interaction mode
NPP event analysis (15)	Intervention/decision; decision-maker; input to the event; instigated by; team members involved; goal; reason; options and consequences; time; context of operation; problem characterization; understanding of plant and system response; relevant document; compliance to procedures; type of accident/accident level

NPP tasks are included because the ultimate goal of team communication is to perform a specific task. Teamwork behavior is affected by an NPP event (abnormality or accident) and adjusted to the results of event analysis. Consequently, the unfolding of the NPP event and its analysis depend on teamwork behaviors in handling the event.

For teamwork behavior, we gathered the behaviors related to the emergency management tasks in NPP emergencies that require team communication. The teamwork behavior sub-element is related to the "act of communication" and "communication intention" sub-elements (the influencing factors in these three sub-elements might appear similar). The order in how they emerge is as follows: "communication intention" triggers the "act of communication", and then the collection of acts of communication creates a "teamwork behavior". Continuing the example from the act of communication's explanation, the communication intention of "alarm/process parameters/status surveillance" may trigger an act of communication such as "announcement", "self-judgment", "repeating known information", "warning", and so on. The speaker may start with an "announcement", and the listener may demand more information (the act of communication: "information collecting question—open question information"), to which the speaker may continue with "self-judgment", and so on. This collection of acts of communication is an example of a form of teamwork behavior known as "state assessment—detection" since it started with detection from the speaker.

The NPP event analysis mostly contains the performance categories of [70] and the data analysis method of [71]. We created this sub-element because the influencing factors are related to each other (with a certain event as the connector). Also, an NPP event such as an accident triggers countermeasure tasks that are different from routine tasks. These tasks further cause the need for team communication in emergencies.

3.5. Influencing Factors of the External Elements

The external element contains one sub-element, identically named the external sub-element (Table 8). The external elements influence team communication through the constraints of the surrounding environment. For example, external interruptions in the form of phone calls or noises may cause the team leader to pause an ongoing team briefing or to repeat an announcement louder. Some influencing factors highly related to team communication are those regarding communication devices, such as familiarity, availability, accessibility, ease of use, and accuracy.

Table 8. The influencing factors of external elements.

Element:	**External Element**
	Sub-Elements (Number of Influencing Factors):
External elements	External interruptions; workspace comfort; safety culture; reference document; standards and regulations; quality of paper-based procedures; quality of digital procedures; quality of interfaces; quality of information display; use of automation system; quality of software; communication device familiarity; communication device availability; communication device accessibility; communication device ease of use; communication device accuracy; recent/drastic changes in the above factors

4. Discussion

4.1. Team Communication Model Development

We collected the influencing factors on team communication during NPP emergencies and organized them into five elements. While analyzing the influencing factor categorization, we found that sub-elements are related not only to the sub-elements under the same element but also across other elements. An example is the apparent relationship between "communication intention" (individual elements), "act of communication" (communication elements), and "teamwork behaviors" (NPP task elements). These relationships between elements formed our preliminary model of team communication (Figure 8).

Several papers also developed a type of team communication model. The authors of [48] developed a task context of NPP to group the performance influencing factors, which consisted of four main groups: human, task, system, and environment. As part of a theoretical study, a team process model is presented in [72], which consists of input items connected to the team process connected to the output items. The modeling of team situation awareness (TSA) was carried out in [9,72,73]. In conclusion, our current team communication model for NPP emergencies is influenced by [33]; however, the similarities end here, we will revise this preliminary model by referring to existing communication-related and cognitive systems engineering-related models to create a comprehensive and systematic team communication model. By tackling the basis of teamwork, namely, team communication, we believe that our work will be a meaningful reference in updating a larger scope model.

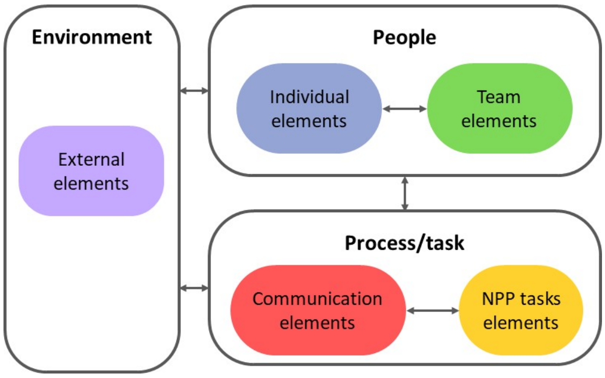

Figure 8. Preliminary version of the team communication model in NPP emergencies.

The preliminary version of the team communication model was developed based on the available data, i.e., the influencing factors identified in the literature review; thus, it is data-driven. The merit of the data-driven method is that the data are traceable to their sources, explainable, and verifiable. However, the completeness of the model is unknown, and new findings could not be obtained. Also, some influencing factors might belong to other elements depending on the point of view of the analysts. In short, this preliminary model of team communication does not satisfy the "mutually exclusive collectively exhaustive" principle; hence, we agreed to proceed with a model-driven method.

4.2. Applicability

The current results of our study, namely, the influencing factors of team communication in NPP emergencies, were developed for the NPP domain; thus, they are domain-specific and might not be directly applicable to other domains. However, our results also might not be directly applicable to a certain commercial NPP in operation. NPPs are designed and operated differently across countries and even across sites in the same country. In our research, aspects such as the number of operators per team, the structure of emergency teams, and other related team factors influence the applicability of our research results. In addition, the team-related settings in an NPP are prone to changes compared with design or technology changes. To address this limitation, we track and describe our analysis methods in detail whenever possible to enable practitioners to tailor our methodology to obtain results applicable to their needs.

In this paper, we extracted the influencing factors using a literature analysis and topic modeling. We are aware that the majority of influencing factors of team communication in NPP emergencies collected in this study may represent a subset of influencing factors of team communication in common situations. However, in the literature analysis, the keywords used in collecting the reference papers contain emergency-related concepts (emergenc*, critical situation, safety, accident, incident, high-risk, stressful, and adverse); thus, we conclude that the resulting influencing factors presented here are related to emergencies. (When a keyword is excluded, for example, "emergenc*", then both emergency and normal situation communication papers will be extracted.) In topic modeling, the influencing factors obtained were derived from all domains (not only NPPs) since our intention was to develop a comprehensive list of influencing factors (similar to the studies in [23,24]). However, we used the same keywords; thus, the resulting influencing factors are also related to emergency situations. In this paper, we focused on emergency situations because of the criticality of the situation; the lack of studies in that field; the questionable knowledge of team responses to a crisis; and the fact that many teams, including highly trained teams, perform inadequately with significant variability during emergencies [14]. As for the topic modeling results, there is a possibility that the influencing factors may be unsuitable for NPPs. Therefore, influencing factor validation from subject-matter experts is required, and we are planning this validation for future studies.

4.3. Communication Errors

Studies on team communication to improve NPP operations are covered under the big umbrella of human factors, which is a multidisciplinary field concerning various methods, data, and principles to design systems that are compatible with the capabilities and limitations of human users [74]. At first, human factors received little attention; however, after the Three Mile Island accident, nuclear accidents were revisited, and human errors were found to be a major component in the root cause analysis [71]. Human reliability analysis (HRA) became the most common approach to address the human error issue by identifying potential human failure events and estimating the human error probability (HEP) using data, models, and/or expert judgment [24]. Since then, NPPs have built a strong tradition of human factors research in safety; however, less attention was given to non-technical skills, such as communication, leadership, and decision-making [75].

Human errors in communication have not received much attention, as presented by the lack of communication-related considerations in HRA methods, although communication error has been considered a primary cause of many incidents/accidents in NPPs and cannot be performed independently from human error analysis [38,43,45,76]. In Japanese NPPs, 25% of human error incidents were due to communication errors, and similar results were observed in the transportation, medicine, and aviation domains [76]. Communication is also considered the center of debate on the resilience and stability of complex socio-technical systems [71]. One communication error analysis method for NPP operators' communication is proposed in [45]. The qualitative method focused on finding a root cause and predicting the type of communication error, whereas the quantitative method focused on estimating the probability of communication errors, which resulted in eight cognitive speaking process error types and their nominal error probability.

In this paper, we presented our current research results, which is a list of influencing factors of team communication in NPP emergencies. We mentioned that, among other contributions, our research results can be considered by HRA analysis as performance influencing factors; however, our goal is not focused on communication errors. Overall, studies on communication error, or human error in general, aim to analyze past errors, calculate their probabilities, and find ways to avoid errors. Those research studies are important and abundant, as there are about fifty HRA methods developed worldwide to estimate human error probabilities [77]. Our research group is interested in complementing those research studies from a different point of view and using different principles: the ones that fall under resilience engineering and cognitive systems engineering. In short, instead of analyzing error data, with the goal of not repeating the same mistakes, our research group aims to analyze routine/error-free operational data and create a model to contain those data, with the goal of, at least, maintaining the same efficient and safe daily operations. When this is achieved, by using the model, we aim for improvements. While the final results of both approaches are the same, that is, to avoid communication errors (and human errors), the methods and principles are different.

This point of view was discussed as early as 50 years ago when empirical ergonomic field studies found that in actual work conditions, skilled personnel (experts) showed a consistent use of strategies as an innovative method in handling complex situations, which HRA analysts might consider as human error or violation [71]. While routine violations can be opportunities for efficient operation, or even safe countermeasures under unexpected circumstances, instead, they are too often judged as errors and sources of accidents. Thus, our research group focused on supporting daily efficient and safe operations of NPPs and although the current research results could not reflect this goal clearly, this paper is the first step in creating a team communication model that will better represent our goal in supporting efficient and safe complex socio-technical system operations by human operators, starting with NPP operators.

4.4. Emergency Response Teams and Emergency Management System in NPP

As briefly mentioned in the Introduction, when the MCR team (team of operators who handle routine operations) observes and declares an emergency, emergency response teams are assembled. The structure of emergency response teams is different by country; in this paper, we discuss the South Korean NPP case. According to the South Korean emergency response plan, emergency response organizations are established based on the scale of an accident [78]. The emergency response teams in South Korean NPPs are the technical support center (TSC), operational support center (OSC), additional local (field) operators and sub-contractors, and the emergency operating facility (EOF) [78]. Their functions are discussed as follows:

- The technical support center (TSC) provides plant management and technical support to the MCR operators and acts as the primary communication center during an emergency. After the TSC is activated, the decision-making responsibility shifts from the MCR to the TSC.
- The operational support center (OSC) provides engineering support for chemical, electrical, mechanical, and instrumentation and control systems, maintenance, firefighting, rescue activities, and other duties. However, in contrast to the clear chain of command between the TSC and MCR, the OSC's authorities are not definite. If the TSC is present, then it holds the highest authority. If the TSC is not yet active but the OSC is ready, it is not clear who is responsible for decision-making. It is possible to delay decision-making until the TSC is ready.
- Additional local (field) operators and sub-contractors may be requested to handle equipment, for example, to move and install portable diesel generators and pumps.
- An emergency operating facility (EOF) is assembled when an accident covers more than two units of NPPs or the situation has deteriorated. Similar to the TSC, the EOF provides plant management and technical support. When the EOF is present, it is responsible for top-level decisions. The EOF is located outside of the NPP site as a precaution in case the NPP site becomes dangerous and hard to reach; however, this raises the need for emergency telecommunication devices. Similar to the concern of the OSC, when both the TSC and EOF are active, the chain of command is clear; otherwise, there is a possibility of miscommunications, recalled decisions, repetitive information, decision delays, and other issues related to team and organization intercommunication.

Although the emergency response plan defines the teams and their functions, ambiguities persist. Moreover, the effectiveness of the emergency response plan can only be tested during a large-scale exercise, as studied in [79]. The shift in decision-making responsibility, the increasing number of people to interact with, and the stress of facing emergency situations, among others, fuel the need to support efficient and accurate intra- and inter-team communication [78]. As learned from the Fukushima NPP accident, due to the number of organizations and tasks involved, the risk of inadequate communication, improper communication, or even a total communication failure might be higher.

Furthermore, the difficulty in verifying and validating an emergency response plan makes the regulators and analysts anxious to refine the plan repeatedly. The efforts to improve the emergency response plan should be accompanied by the creation of a model or framework, such as a team communication model (discussed earlier) and assurance framework, to internally validate the applicability of the plan. Recently, an assurance framework or assurance program has been adopted by large-scale organizations and governments to achieve a high level of safety, reliability, economic benefits, and accountability, among others [80,81].

After the Three Mile Island nuclear accidents sparked the possibility of a nuclear core meltdown, the importance of a knowledge-based decision support system to handle NPP accidents was observed, and prototypes were proposed starting around 30 years ago until recently [82–85]. However, the implementation of such an emergency management system is much slower. One of the main reasons is that the routine operators (MCR teams) are already using an NPP operating system: a digitalized program with computerized control and screen-based interfaces. The experts are divided between the need for another separate system created specifically to handle emergencies or to embed the emergency management function into the current NPP operating system. Both approaches have their own merits and disadvantages. Moreover, similar to the emergency response teams/organizations, the emergency management system should differ by country and NPP design.

Creating a separate emergency management system makes sense especially during severe accidents (nuclear core meltdown) because the goal shifts from prevention to mitigation of accidents, and the existing day-to-day NPP operating systems cannot support mitigation actions effectively (alarms continue sounding, warnings before mitigation actions, etc.). However, forcing the operators to switch to a different system during a stressful situation might increase the probability of human error, albeit the training provided. Moreover, occurrences of severe accidents are very rare, and no two accidents are exactly alike [82]; thus, an emergency management system should be designed to have the capabilities of a wide range of mitigation actions and in-depth knowledge support. Embedding such a sophisticated system into the existing NPP operating system is also arguable. There is no need for the operators to use an emergency management system during routine operations and having additional labels or buttons (to represent the emergency system's functions) to check before taking an action could drain the operators' cognitive resources.

Our research group agrees with the importance of an emergency management system for NPPs, and among other functions, we are especially interested in the functions that support efficient communication and avoid communication errors, which we intend to support in future research on developing the team communication model. Communication is one of the three process models recognized in the design of a decision support system for NPPs; it is as important as decision-making and the management of advice [86].

4.5. Initial Application of Text-Mining

We presented the results of our first attempt at applying text mining to complement the manual, systematic literature review. A topic modeling algorithm, LDA, was implemented to find the research topics of many papers. Topic modeling has many advantages; however, it also has limitations [57]. One of them is the loss of interpretability since the output of topic modeling is derived based on mathematical properties. The interpretation of topic modeling results depends on the analyst's goal, knowledge, and point of view. Moreover, each decision on the parameter settings in the topic modeling algorithm influences the results. By implementing LDA, we also assumed its limitations and issues, such as the difficulty in determining the optimal number of topics.

5. Conclusions

The emergencies in NPPs are handled by teams of operators. In this context, various team-related issues had been discussed; however, we observed that team communication is overlooked. While there are many factors affecting teamwork, team communication is the most fundamental factor of teamwork. In this paper, we aimed to provide a list of influencing factors of team communication during NPP emergencies by performing a literature review analysis and developing a method to collect the influencing factors. The influencing factor analysis was applied in a systematic literature review and topic modeling algorithm of text mining. We organized and described our method for extracting the influencing factors from the reference papers and from the list of topic words as the result of topic modeling in detail to accommodate researchers interested in performing similar studies. The resulting influencing factors were combined, and a total of 223 factors were categorized into five elements: individual, team, communication, NPP tasks, and external elements. This paper marked the first step in our research in developing a team communication model in NPP emergencies, and by finding out the relationships between the elements, we created the preliminary version of the team communication model. We also discussed the team communication model, applicability, communication errors, and emergency response teams.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app14041407/s1, Table S1: Influencing Factors List.

Author Contributions: Conceptualization, S.S. and D.-H.H.; methodology, S.S., S.-Y.Y. and D.-H.H.; software, S.-Y.Y.; validation, S.S., S.-Y.Y. and D.-H.H.; formal analysis, S.S. and S.-Y.Y.; investigation, S.S. and S.-Y.Y.; resources, S.S. and S.-Y.Y.; data curation, S.S., S.-Y.Y. and D.-H.H.; writing—original draft preparation, S.S. and S.-Y.Y.; writing—review and editing, D.-H.H.; visualization, S.S. and S.-Y.Y.; supervision, D.-H.H.; project administration, D.-H.H.; funding acquisition, D.-H.H. All authors have read and agreed to the published version of the manuscript.

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