Applying Fuzzy Logic to Evaluate C2 Systems - Fusion of Heterogeneous Input Data

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ABSTRACT

The comprehensive evaluation of command and control (C2) systems is a crucial factor in identifying strengths, weaknesses, and potential for improvement in such systems. However, research on such systems has shown how different and nonlinear the data in C2 system evaluation can be. These heterogeneous characteristics of data make it very difficult to combine the different variables and calculate new values for an evaluation result. After a detailed search, fuzzy logic was identified as a suitable mathematical approach that meets the requirements for calculations of different variables within an evaluation system for C2. Fuzzy logic in combination with fuzzy trees proves to be a good method to combine different input variables from a C2 system evaluation and to apply logic rules to represent and calculate dependencies. This paper explains the applicability of fuzzy logic in the context of C2 systems and shows examples from a fuzzy C2 system evaluation.

Keywords

Command and Control, Evaluation, Fuzzy Logic, Sets, Rules

INTRODUCTION

Command and control (C2) systems are extremely critical systems that have a significant impact on the success or failure of emergency operations. Past examples have often shown that poorly developed C2 systems can lead to major losses. The fires in California and Germany in the 1970s are worth mentioning from the more distant past (Deutscher Städtetag, 1976; Emergency Management Services International, Inc., o. D.; Stambler & Barbera, 2011). The investigations of these events led to the development of C2 systems in emergency management, which allow the management of large-scale operations involving many organizations. But even in the recent past, investigation reports have shown the critical contribution of C2 systems in managing disasters. For example, the investigation reports of the 2021 flood disaster in Germany show that the C2 systems used in particular reached their limits and that operational C2 was no longer possible in line with needs (Landtag Rheinland-Pfalz, 2024).

Despite the identified high relevance of C2 systems in the context of incident management, action is often taken reactively. C2 systems are adapted after serious deficiencies have been identified. In the best case, these deficiencies become apparent in exercise scenarios; in the worst case, they are revealed by investigations after such a system has failed in a real scenario. Failure in a real-world scenario can mean the loss of property, lives and emergency services personnel. Delayed warnings to the public and overwhelmed emergency services in the catastrophic flooding in Germany led to 186 deaths, as well as two fire brigade members being killed (Bundesministerium des Inneren und für Heimat, 2022; Landtag Rheinland-Pfalz, 2024).

These losses are tragic and must be avoided by all means. The costs of identifying weaknesses in C2 systems should not be that high. Therefore, proactive methods must be applied that recognize weaknesses in the management of incidents, disasters and crises.

One barrier to the proactive evaluation of such systems lies in their enormous complexity. C2 systems are socio-technical systems that depend on a wide range of variables that can be linked in a complex relationship. For this reason, it is extremely difficult to evaluate entire systems and to present their strengths and weaknesses. Even modern research approaches such as computer simulations of disasters and crises therefore ignore the important building block of a functioning C2 system. Many computer simulations simply assume that this function is fully operational and given. This may be due to the fact that C2 systems with extensive and complex processes as well as interrelationships can hardly be mapped with an action and reaction behavior without an in-depth understanding of experts. Fuzzy logic is an extremely flexible and widely usable approach for understanding, evaluating and translating C2 systems into a structure that can be used by a computer simulation. The fuzzy logic approach by Zadeh (1965) and the Fuzzy Tree approach (Janikow, 1998) combine the requirements for representing a C2 system translated into numbers and dependencies.

C2-SYSTEMS AND EVALUATION APPROACHES

C2 systems are often used in a wide range of scenarios. Their area of application ranges from incidents to disasters to crises. A definition of the differences between the various areas of application can be found in ISO 22361. The foundations of C2 systems consist of organizational structures, processes, technical means, but also of people who work in the structures, carry out the processes and use the technical means. This heterogeneous nature of C2 systems clearly shows how diversely these systems can be approached and researched. Modern research approaches therefore often strive for an interdisciplinary approach that combines different research fields (Grant, 2018; Wikberg et al., 2021). Miller (1978) also recognizes systems theory as an effective method of representing and exploring the complexities of the modern world. Systems theory aims to overcome the fragmentation of the individual research disciplines and to create more reality in models and research through an interdisciplinary approach (Lenk & Ropohl, 1978). In the recent past, models have been developed that take this interdisciplinary approach into account and include all system influences. In cybernetic terms, a “generic C2 system” consists of information-processing components that receive data, process it and apply it in the form of measures to a target system in order to control it into a desired state (Landsberg et al., 2023). Another approach using the core system enables the modular and flexible connection of different technologies, services and human actors. The model is divided into three layers: tools, services and agents, which are connected to each other by the core as a central communication and integration platform (Johansson et al., 2024).

C2-Systems

There are many C2 systems in use worldwide in a wide range of fields. Such systems have their origin in the military, which still conducts a large proportion of research in this field today. Emergency services have adapted these approaches to efficiently manage units and operations. The Incident Command System (ICS) is probably the best-known C2 system worldwide in the emergency services sector. It was developed after devastating forest fires in the USA in the 1970s (Stambler & Barbera, 2011). To date, the ICS has been widely implemented and adapted in other countries, such as Australia and New Zealand. Other countries have introduced different incident management systems, such as the “FwDV 100” (Germany), “Führungsbehelf” (Switzerland) or “Guideline for command and control in emergency operations” (Austria), but all of them show fundamentally similar characteristics and important process components:

- Process components:
    - Collection of information and assessment of the situation
    - Decision making
    - Planning
    - Implementation of plan
    - Checking/Verifying
- Characteristics:
    - Data and information as input
    - Measures as output
    - Time as an important factor in incident management
    - Organizational structure and distribution of tasks
    - Humans as an elementary component of the decision-making and execution processes
    - Technical means to support the processes

The generic command and control system illustrates the different components, parts and characteristics (Landsberg et al., 2022). There are boundaries between the different components, which reveal dependencies and influence among these boundaries. **Figure 1** shows simplified and reduced components of a C2 system, the boundaries and the dependencies. A comprehensive explanation of the individual components of a C2 system can be found in a research paper from 2022 (Landsberg et al., 2022). Processes within a C2 system are represented as a recurring cycle. The process always begins with the collection of information and an assessment of the situation. Data required for this can be collected from the target system and the environment by the C2 system itself (incident commander/incident management team (IMT)) or by operational emergency services personnel (forces) acting close to the target system (incident). The IMT works within the C2 subsystem in processes and structures based on the division of tasks in order to make decisions and plan measures. Through an Incident Action Plan (IAP) or through commands, information is passed on to the operational emergency service personnel so that the forces can take action on the target system in order to achieve a target state. The initiation of the IAP is followed by a new assessment of the situation and a check of the actions ordered to ensure that they have been carried out accordingly and are having the planned effects.

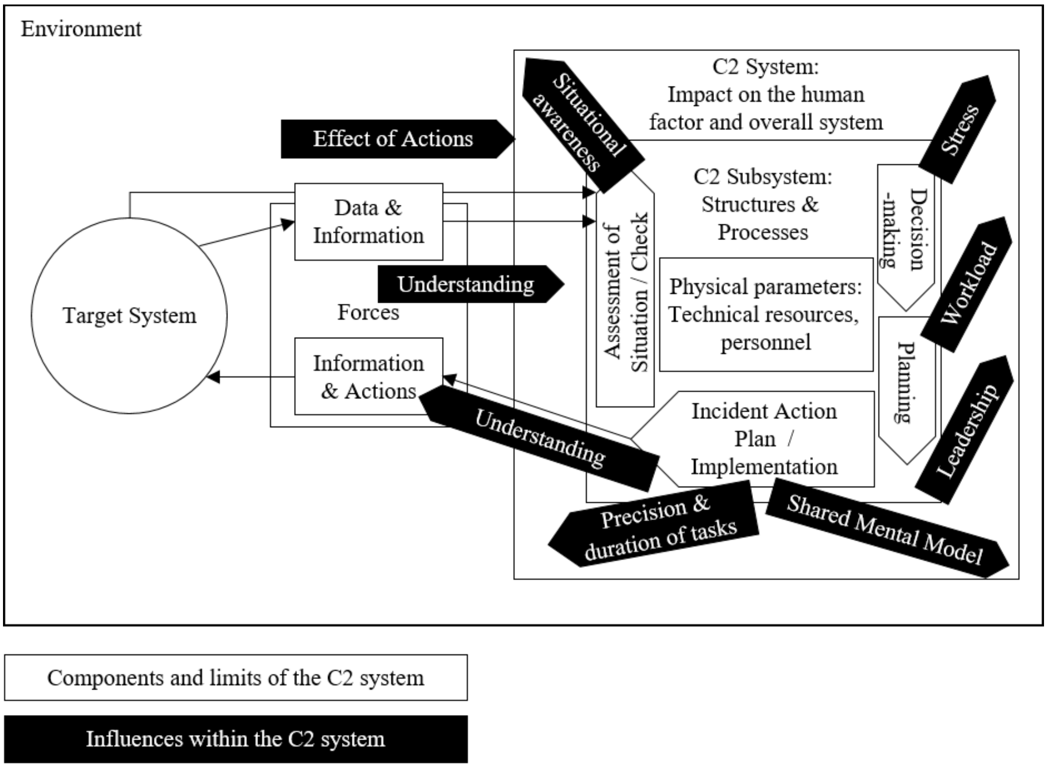

Figure 1. Influences and limits of a generic C2 system

Figure 1 also shows that the internal components of a C2 system (physical parameters, C2 subsystem) have an influence (e.g., situational awareness, precision and duration of tasks) on the overall C2 system, in which people act as important parts. The influences of the physical components, processes and structures have an impact on humans within the system and the overall system performance. For example, sufficient personnel within the IMT can ensure an effective distribution of tasks and reduce individual stress; modern communication and situation mapping systems can increase situational awareness and a well-formulated IAP can improve the understanding of the situation and intentions of the IMT among the emergency services personnel.

Evaluation Approaches

To date, many good approaches have been developed that make evaluating the individual influences of C2 systems possible. These different approaches can be found in the corresponding research disciplines, such as situational awareness and understanding (Boyd, 1987; Endsley, 1995), decision-making (Brehmer, 2006; Klein et al., 1993), system thinking (Lawson, 1981), workload and stress (Hart & Staveland, 1988) as well as leadership (Butler et al., 2020). These mentions are, of course, only a selection of the research available. The collective work by Berggren et al. (2014) also provides a good overview of this field.

The impact on the overall system can be illustrated well by the indicators developed in the military context. The Command and Control Measures of Effectiveness Handbook (Bornman, 1993), the Headquarters Effectiveness

Assessment Tool (HEAT) (Defense Systems, Inc, 1984) and the Army Command and Control Evaluation System (ACCES) (Halpin, 1996) should be mentioned here. The measurements developed in these tools often refer to ratios and times.

The following indicators can be given as examples:

- Proportion of measures implemented on time
- Processing time of orders
- Processing time for issuing orders
- Percentage of requested command clarification
- Subsequent changes per issued order
- Loss ratio of forces

Kalloniatis (2023) offers another example of the evaluation of C2 systems with an agent-based approach based on an extended Kuramoto model. The evaluation focuses on the synchronization activities of various actors in C2 systems and the related cognitive efforts. The agent-based simulation shows that more networking and synchronization leads to greater harmonization of C2 activities, but this can also lead to a disproportionate investment of cognitive effort. A medium network provides a "sweet spot" and puts harmonization and costs in an optimal relationship.

These evaluation approaches show possibilities for the partial assessment of C2 systems. In particular, the C2 system level can be evaluated using such approaches. The question arises how these individual components can be combined to enable an overall evaluation of a C2 system. How can the complex structures and processes within the C2 subsystem be linked, and how can the corresponding influences be modeled? A major problem with these links is the heterogeneous composition of the indicators at each level. The units of the indicators, for example, are thoroughly different. Some are absolute values (physical parameters), while others are relative and in percentage or dimensionless form. Often, experts also have to determine which value of an indicator is to be considered good or bad. It is becoming clear that an overall evaluation of a C2 system can function more easily if all indicators can be implemented on a single dimension and in a single numerical system. One possibility for this is offered by fuzzy logic and fuzzy trees, and this mathematical approach is explained in the following section.

APPLICATION POSSIBILITIES OF FUZZY LOGIC IN THE CONTEXT OF C2

The binary system of 0 and 1 forms the basis of our digital world and is one of the most elegant and fundamental representations of information. Technical systems are controlled on the basis of the binary system. Fuzzy logic is an extension of the classic binary system, which is based on Boolean logic. While the binary system describes states in a strict either/or principle (e.g., 0 or 1), fuzzy logic allows a gradual rating between these extremes. Fuzzy logic was developed to better model complex systems and human thinking, as many issues in real life are not clearly binary (e.g., the degree of situational awareness). Modern fuzzy logic was developed by Zadeh (1965), a mathematician, electronics engineer and computer scientist. He aimed to create a system that could capture this vagueness in mathematical models. Fuzzy logic thus reflects the real way humans think better than precise binary logic, as intuitive states such as “approximately”, “about” or “very” can also be represented.

“Fuzzy trees” combine the principles of fuzzy logic with the structures of decision trees to model decision processes and data classifications with uncertainty and gradual transitions. They were developed to overcome the limitations of classical decision trees, which often make sharp (binary) decisions. Since fuzzy logic can become extremely complex with a large number of input values and rules, the fuzzy trees also help to structure fuzzy applications and make them comprehensible to humans.

Fuzzy Sets and Logic

To clarify the exact mathematical relationships of fuzzy logic, Zadeh's approaches are briefly explained. Unlike classical set theory, where an element either belongs to a set or does not, Zadeh's fuzzy sets allow elements to have a degree of membership between 0 and 1. Zadeh provides an example involving the classification of real numbers to clarify the concept of the function. If X represents the set of all real numbers and A is defined as the group of numbers that are "much greater than 1" different membership values can be assigned to various numbers. For example (Zadeh, 1965):

- $f_A(0) = 0$: The number 0 does not belong to A at all, as it is less than 1.
- $f_A(5) = 0.001$: The number 5 has a very low degree of membership in A , as it is only slightly greater than 1.
- $f_A(500) = 1$: The number 500 fully belongs to A , as it is significantly greater than 1.

Operations are adapted to handle partial membership. A new set C can be derived from the fuzzy sets A and B. This new set C includes the elements of A and B, making it the union set $C = A \cup B$. The membership function of C takes the maximum value of the membership functions of A or B. Thus, the creation of the new function C is expressed as:

(1) $$f_C(x) = Max\ [f_A(x), f_B(x)], \qquad x \in X$$

This function is generally also known as the OR operator:

(2) $$f_C = f_A \vee f_B$$

Another way to create a set C from the fuzzy sets A and B is by using the intersection, $C = A \cap B$. This set consists of elements that belong to both A and B. To determine the degree to which an element belongs to the intersection C, the smaller membership value of the elements from A and B is chosen:

(3) $$f_C(x) = Min\ [f_A(x), f_B(x)], \qquad x \in X$$

This function is generally also known as the AND operator:

(4) $$f_C = f_A \wedge f_B$$

The membership function of the complement of a fuzzy set A is defined as:

(5) $$f_{\bar{A}} = 1 - f_A$$

The assignment of different values to sets, which can be both quantitative and qualitative, provides the necessary flexibility when combining a wide range of input parameters from a C2 system. The basic idea of fuzzy logic involves the purpose of converting linguistic variables into numbers and, figuratively speaking, calculating with words instead of numbers. In addition to fuzzy sets, fuzzy logic is therefore another basic method that enables calculation with logical operators and fuzzy sets, as shown by the formulas (2), (4) and (5). Rule-based if-then mechanisms allow an overall effect to be an output set for the effect of several elements that are described with fuzzy quantities and are related to each other. In this fuzzy inference process, the relationships between given input and output sets are defined.

Fuzzy sets and fuzzy logic will be explained using the following example in the context of a C2 system. The example is highly simplified and therefore does not claim to model realistic relationships. The example looks at the use of a new digital management tool at the physical C2 level. We assume that the tool fundamentally supports the C2 process and is therefore important for efficient incident management. The vulnerability of this C2 tool should therefore be determined in the context of the incident management process. Different sets can now be assigned to the input variables:

Table 1. Input variable sets

Input	Set 1	Set 2	Set 3
Probability of failure	high (1/100)	occasionally (1/10000)	never (0)
Replaceability/ resilience	not at all	compensable	replaceable

As the examples of the various different sets of variables show, these can be defined both qualitatively and quantitatively. As replaceability is not defined quantitatively, it is described qualitatively in the following:

- **Not at all:** The tool cannot be replaced by an alternative C2 tool. The failure means a stop of the effective C2 process.
- **Compensable:** The tool can be compensated by an alternative C2 tool. However, the compensating tool does not achieve the performance of the failed tool. The C2 process continues with limited performance.
- **Replaceable:** The tool can be completely replaced by an alternative C2 tool. The C2 process continues without restrictions.

The input variables and sets can now be linked with if-then rules to be assigned to a new output set (vulnerability). The sets for the vulnerability result are defined as in **Table 2**.

Table 2. Output variable sets

Output	Set 1	Set 2	Set 3
Vulnerability	highly vulnerable	vulnerable	invulnerable

- **Highly vulnerable:** The C2 tool is highly vulnerable. Failure without compensation is likely.
- **Vulnerable:** The C2 tool has a vulnerability that affects the incident management process.
- **Invulnerable:** The C2 tool is invulnerable and its effectiveness in C2 system is assured.

The variables and their sets can be linked with if-then rules, as shown in **Figure *2***. A rule enables the generation of the output set based on the associated membership functions. As an example, three rules are shown in **Figure 2**. Of course, further rules can be created as needed for the necessary inferences.

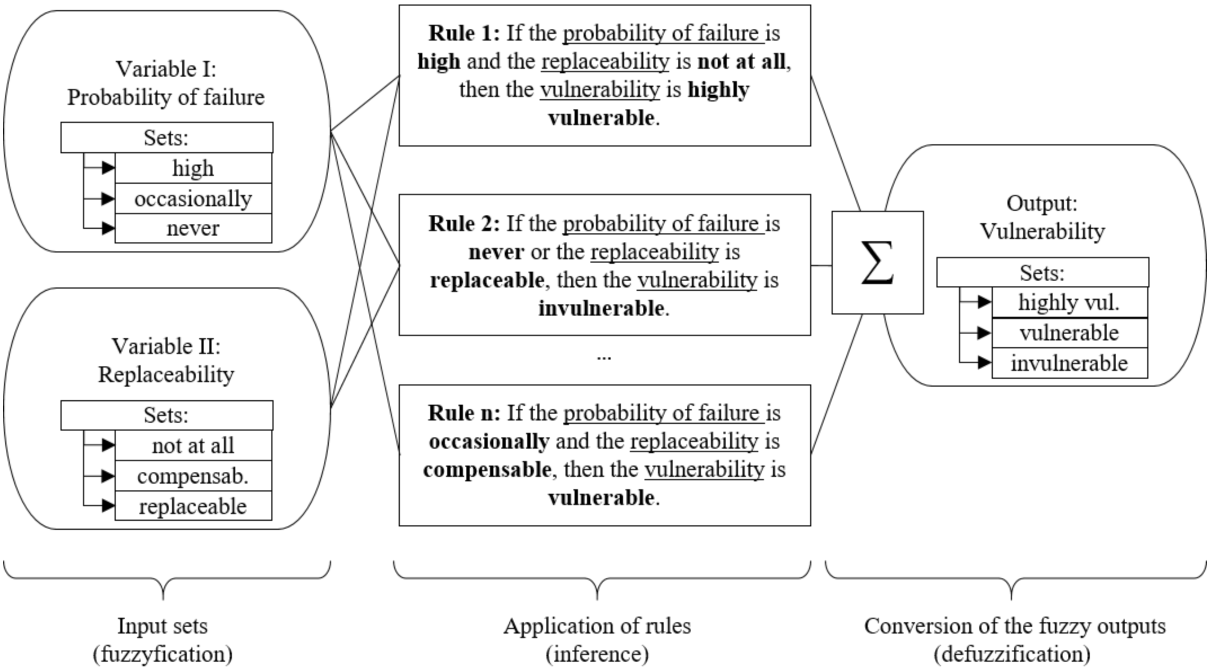

Figure 2. Rules of fuzzy sets

Figure 2 shows how the process of calculating the individual output from the input variables progresses using the method of Mamdani and Assilian (1975). First, the input data is mapped to appropriate fuzzy sets with the help of membership functions. This step is also referred to as “fuzzyfication”. In the next step, the fuzzy rules are applied to generate new fuzzy outputs. These are always represented in a single output set, and the step is known as “inference”. In the last step, “defuzzification”, the fuzzy outputs from the inference stage are converted into one crisp output value. The calculation of the individual output sets and thus the output of a single output value can be based on different methods. One of the most common methods for defuzzification is the “centroid method”. The calculated value equals the center of the area (center of gravity) under the composite membership function of the fuzzy set output variables.

The centroid method is particularly suitable for defuzzification in the case of the evaluation of C2 systems for several reasons. It represents the uncertainty in the semi-quantitative evaluation by providing a good balance between all possible values of the fuzzy sets and the corresponding membership grades. The method prevents extreme values and therefore provides a reliable balance in the evaluation. Alternative methods for defuzzification should also be mentioned: These include, for example, the methods “Bisector”, “Middle of Maximum”, “Smallest of Maximum” and “Largest of Maximum”. **Figure 3** illustrates the calculation method of the centroid method.

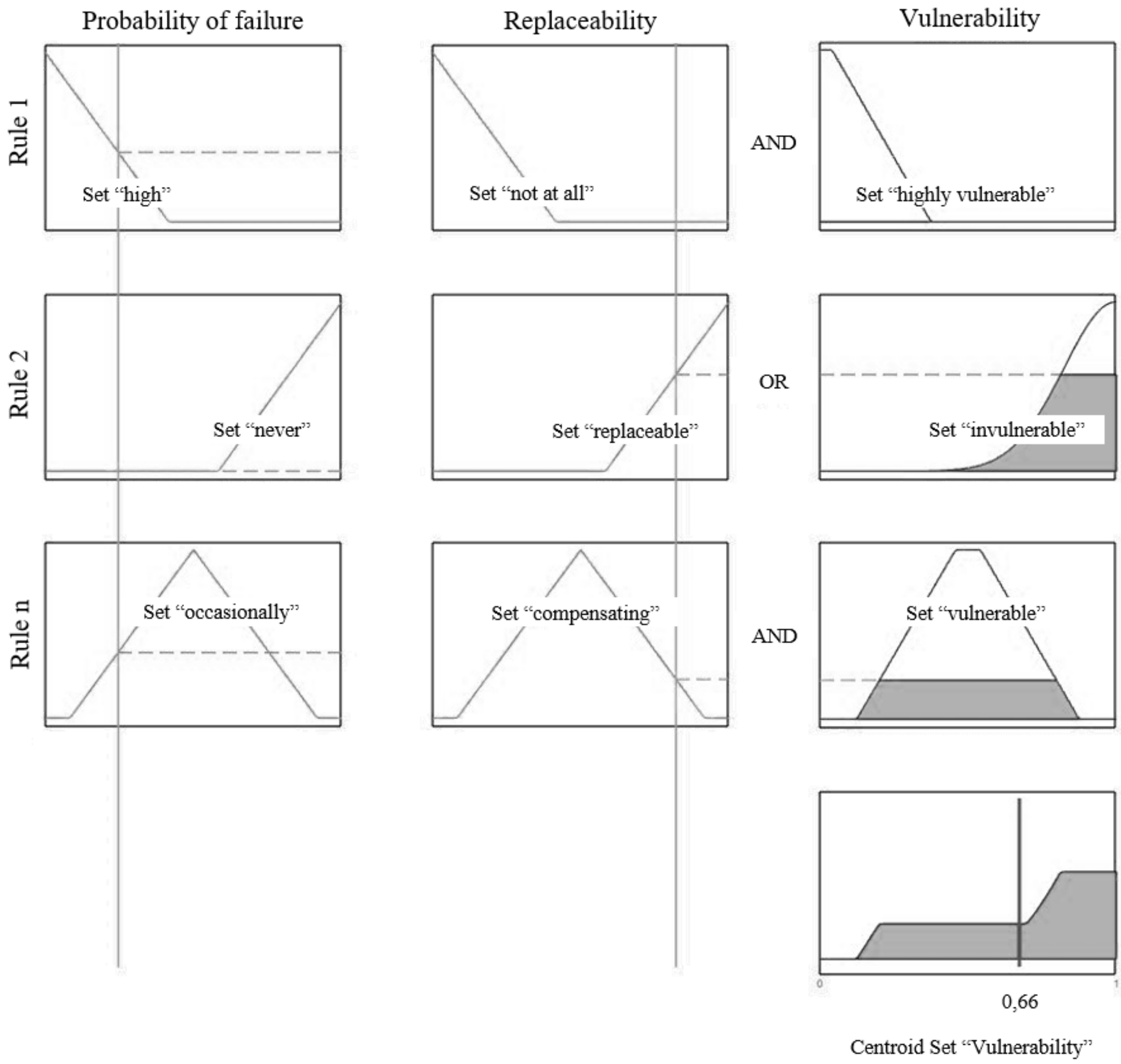

Figure 3. Illustrated centroid calculation method of the fuzzy output set

Individual vulnerability sets of the rules are merged, and the final vulnerability value is calculated using the centroid method. The figure also shows examples of the different shapes that the membership functions can take. Different functions can be used according to the needs of the data, depending on whether the data shows trend or core variables or whether there are, for example, large uncertainties around the edges.

Of course, the application of a large number of rules can make an evaluation system for C2 very precise. However, many input variables and rules within one fuzzy inference system (FIS) also have disadvantages. The relationship between variables and rules becomes unclear and incomprehensible to humans when there is only one FIS with many inputs. For example, a FIS with three input variables, each with three membership functions, would have a maximum of 27 (3^3) rules. Adding just one more variable increases the possible number of rules to 81 (3^4). This means that there is an exponential increase in the number of rules, which can quickly lead to a lack of overview and to a black box. An existing method for breaking down these complexities of many input variables and rules can be found in the use of fuzzy trees.

Fuzzy Trees

Fuzzy trees are particularly well-suited for organizing input variables in a way that makes rules and relationships clearer to humans. This is achieved through their ability to represent hierarchical structures where each node encapsulates a fuzzy concept, which can then be interpreted in terms of linguistic or logical rules. The tree structure itself is a natural way to visualize relationships and dependencies between variables. This makes it easier to trace how specific inputs influence outputs, and how changes in one variable affect the overall system. By categorizing and organizing inputs, fuzzy trees reduce the cognitive burden on humans trying to understand or interact with the system. Rather than processing all variables simultaneously, users can focus on specific branches or levels of the tree.

The concept of fuzzy trees is explained in **Figure 4** using a highly simplified example.

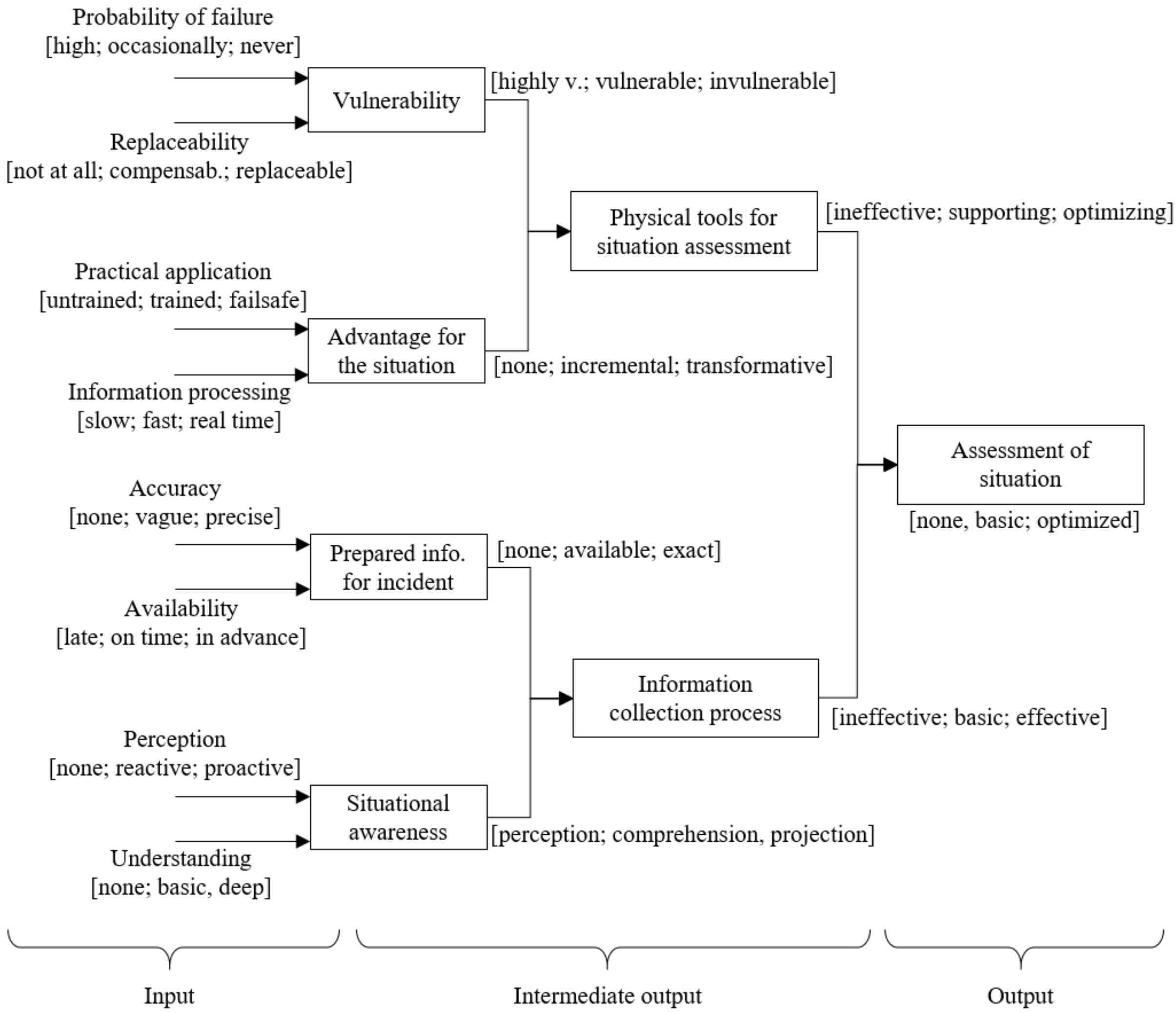

Figure 4. Fuzzy tree example

Figure 4 also includes the FIS-example (see **Figure 2**) as input. In the fuzzy tree, this individual FIS is now included in a larger overall context. In this example, probability of failure & replaceability are two of a total of eight input variables, each consisting of 3 sets and leading to a single output variable. The sets are shown in square brackets below or behind the variables. In this case, the output is the process component "assessment of situation" of the C2 subsystem. As can be seen from the **Figure 4**, the individual variables in logically arranged FISs contribute to partial results from FISs at a higher level in the hierarchy. The output of each FIS at a lower hierarchy level is used as input for the FIS on the same node at a higher level. This hierarchical composition makes it much easier to understand the influence of the variables, and at the same time makes it possible to evaluate partial performances that are shown as intermediate outputs. This consideration of intermediate outputs enables the required diagnostic capability in the evaluation of C2 systems.

The approach shows how flexible and well-structured different variables can be arranged. By calculating with sets and logical rules, it does not matter what units or limits the relevant data and values in the fuzzy tree have. In summary, fuzzy trees not only allow for the organization of input variables but also enhance the interpretability of complex systems. They make rules and relationships more transparent to humans, which is particularly valuable in the evaluation of C2 systems, and where it is critical that applications need to be explainable.

FUZZY C2 SYSTEM EVALUATION

Figure 1 shows how complex C2 systems are, at how many different levels they can be evaluated, and how many interdependencies there can be. Past research on C2 systems also clearly showed how many different factors and research disciplines are necessary for a comprehensive evaluation. Systems theory sees this interdisciplinary approach of combining many relevant research disciplines as a key to the modern research landscape. However, different research disciplines naturally produce different characteristics of input data, which requires merging the research data: At the physical level, quantitative data is usually used; probabilities play a major role in risk management; and statistics are an important tool in psychology. Other variables within a C2 may be described by percentages, grades or words. Fuzzy logic makes it possible to combine all these variables and set them in relations and dependencies.

Limits of Fuzzy Logic in C2 System Evaluation

For a precise overall evaluation system, the individual FIS and the overall fuzzy tree must, of course, be precisely specified and fine-tuned. This begins with the identification of the input variables, continues with the definition of membership functions and the creation of rules, and finally, it must be determined exactly how the output value of a FIS is calculated as realistically as possible and which FIS it may affect. This fine-tuning can and should be done with experts in the relevant field to define variables, boundaries, high points and shapes of the functions in the FIS. For example, relevant values for fuzzy systems in the financial sector (financial assessment) were taken from existing metrics (A,B,C ratios) or surveys (Maltoudoglou et al., 2015). The greatest strength - flexibility in dealing with qualitative and quantitative data - also reveals a weakness of fuzzy logic. The choice of membership functions and the definition of if-then rules is heavily dependent on a clean expert definition. In order to make this selection and definition valid as well as representative, a large number of corresponding experts must be involved, which can result in a great investment of time and effort. Especially when dealing with complex fuzzy trees. In addition, the subjectification of input and output variables limits the scale levels to the ordinal scale. It is not possible to distinguish the real distances between the variables as on an interval scale, so quantitative comparability is limited.

Validation of the C2 System Evaluation

When validating a Fuzzy C2 system evaluation, the structured Fuzzy Tree is beneficial because the individual FIS can be validated separately before evaluating the overall system. In particular, because of the subjective component, a mixed-method approach should be used for the validation. Workshops and surveys with practitioners (e.g., emergency services) can help to validate the rules and relationships based on experience. Existing research that has already investigated correlations within C2 systems can also be used. Since the composition of the fuzzy tree may show where research into correlations is lacking, systems research with fuzzy trees can also suggest a more detailed investigation and validation of specific areas. The validation of these areas can in turn be done through scenario simulations or by real-world scenario matching if appropriate data collection is possible. In particular, scenario-based simulations can be accompanied by sensitivity analyses to validate the effects of changes within the system.

DISCUSSION & FUTURE WORK

The evaluation of C2 systems is an extremely complex research field that can only be addressed by bringing together a wide range of research disciplines. The systems theory approach is proving to be an important strategy for research projects in this field. The problem of a lack of compatibility and transferability of data is usually associated with the combination of many different research data. For a very long time, we have been searching for a suitable mathematical method to be able to process the complexities and differences in C2 systems with data, rules and numbers. We found what we were looking for in the adjacent field of resilience research: Here, fuzzy logic in combination with fuzzy trees is successfully used to develop resilience metrics.

Fuzzy logic offers a new way of connecting and viewing the individual components and processes of a C2 system and to evaluate them all together. The linguistic application and composition of rules to create inferences is for humans intuitive, easy to use and understandable. Due to its robustness, fuzzy logic is less sensitive to minor inaccuracies in the data. Because of its flexibility, fuzzy logic can be applied to nonlinear systems where mathematical models are difficult to derive. In addition, intermediate results in the form of numbers can display the individual performance data within a fuzzy tree. The description of C2 systems using rules and numbers also makes it possible to allow the consideration of C2 systems with their strengths and weaknesses in computer-based simulations. The precision and speed of information processing can be linked to the components of the C2 system, and can lead to more realistic results in the simulated activities of an incident management team in computer-based simulations of crises or catastrophes.

Compared to existing evaluation approaches (see section Evaluation Approaches), the application of fuzzy logic with fuzzy trees can be seen more as a kind of meta-evaluation. The approach makes it possible to combine the results of individual quantitative, qualitative or mathematical evaluation methods in order to evaluate the strengths and weaknesses of an assessed C2 system. For example, Kalloniatis (2023) mathematical approach can help to determine the correct synchronization effort for C2 activities in the system under investigation. Based on this, a FIS can be used to enter the degree to which the investigated C2 system exactly meets these requirements for synchronization.

However, much work still needs to be done before C2 systems can be fully and precisely described using fuzzy logic. Having many variables and FIS make it necessary to have many work packages for the individual research disciplines, in which the relevant values, their limits, the course of membership functions and the correct rules are defined.

For our C2 system research, the aim is to design a comprehensive fuzzy tree and to integrate precise FIS to represent the most important system-theoretical components and relationships. For this purpose, existing models of C2 systems are reconstructed with a fuzzy tree. This fuzzy tree can be used to evaluate a C2 system in such a way that its strengths and weaknesses can be identified in a diagnostic manner. At the present state work, the fuzzy tree is structured on the basis of the “Generic C2 System” (Landsberg et al., 2022) and the “Core System” (Johansson et al., 2024). At the highest system level and at the highest level of the fuzzy trees, this results in evaluation categories such as situation assessment, information analysis, sharing & transfer, decision making, planning, implementation, checks as well as tools, services and agents. At the lowest C2 system and fuzzy tree level, a total of 62 input variables were identified, which are processed in an overall system with 60 FISs. The input variables range from situational awareness, understanding of information and orders, to stress & workload within the C2 structures. A total of 522 rules were defined in the fuzzy tree to describe the dependencies of the variables. The intermediate outputs of the 60 FIS will enable the evaluation of C2 systems to reveal diagnostic weaknesses and strengths of the evaluated C2 systems.

CONCLUSION

Fuzzy logic is a powerful tool with which a uniform language can be spoken from heterogeneous and non-linear research data from different research disciplines. This variety of different data occurs clearly in modeling and evaluating C2 systems. Relevant components occurring in a socio-technical system like in the case of C2 are broad as well as complex and reach from quantitative values of physical parameters such like computing capacities and bandwidths over times and precision for task completion to cognitive factors like workload and situational awareness. Therefore, fuzzy logic is an excellent way to define and connect the individual components of C2 systems. The brief and simplified examples in **Figure 2** and **Figure 3** have demonstrated in an understandable way how fuzzy logic works in combination with a fuzzy tree. However, the actual fuzzy trees designed on the basis of C2 system models are far more extensive. A large fuzzy tree with many FISs requires many variables and rules to be fine-tuned to each other. Consequently, extensive research with experts from corresponding fields has to be carried out to generate precise and valid FISs within the fuzzy tree.

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