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Methodology and Tool to Facilitate Structured Analysis of Multiple Hypotheses

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***Abstract*—This paper describes the final development of a method and technical tool developed to support structured analysis of multiple hypotheses. The developed analysis method is an iterative process combining Morphological Analysis (MA) and Analysis of Competing Hypotheses (ACH). MA is originally developed for structuring a complex problem space, while ACH is developed for hypothesis evaluation. The combination of these, aided by the tool, facilitates problem structuring, visualization of information as well as evidence-based evaluation of hypotheses. Throughout the development of the tool, functionality and methodology have been tested through user studies involving professional analysts from various disciplines. The combination of the two methods into one integrated process supported by the tool proved successful, enabling a structured, traceable and transparent analysis from problem identification all the way to evaluation.**

Keywords—Morphological Analysis, Analysis of Competing Hypotheses, decision-making, cognitive bias, analysis method.

I. Introduction

In the information society, information is spread quickly through all kinds of channels, for instance in social media, where one source suddenly is "retweeted," modified and retweeted again. Who has the time and engagement required to investigate whether different pieces of information spread through different channels originate from the same source, and possible motives that source has for sharing the information? Looking at the information shared in social media, it is quite clear that people primarily share information in line with their existing beliefs (unless the purpose is deception). For instance, it is likely that a convinced vegan will approach and share information about the benefits of eating vegetables to a higher extent than information about the benefits of eating meat. Several vegan friends will result in an information flow biased towards the benefits of eating vegetables.

In daily life, to try to critically assess and sort all information spread through different media channels is an overwhelming task. In order to figure out the world around us, we use shortcuts, make assumptions and base decisions on experiences from situations that appear similar. While these heuristics in many cases help us make quick and often reasonably correct decisions without too much effort, they are unsuitable for tasks where attention to detail and an unprejudiced mindset is essential. Examples of such tasks include forensic analysis and various types of risk assessment. Different analytic techniques are developed to support different stages of the analysis process. Idea generation can be supported by different brainstorming techniques, the problem can be structured as a cross-impact matrix or morphological model, other methods facilitate hypothesis evaluation, and finally analyses are assessed and challenged through various critique-based methods [1]. The analyst may need to use several different methods throughout the analytic process and transfer the results between the different stages.

This paper describes how two methods for problem structuring and hypothesis evaluation are combined into one iterative process supported by a technical tool. The paper describes the finally development and usability testing of the tool (Multi-Hypothesis Management and Analysis tool, MHMA), as well as the iterative process, composed of the two analytic strategies Morphological Analysis (MA) and Analysis of Competing Hypotheses (ACH). MA is used to structure the analytic problem and generate a set of hypotheses. Using ACH, these hypotheses can be compared, based on available evidence. An earlier version of the MHMA tool is described in [2].

The reference case that will be used throughout the paper is the investigation of the explosion on the U.S.S Iowa in 1989 [3]. During a live fire exercise, an explosion in one of the gun turrets caused the death of 47 sailors. The explosion occurred during loading of the gun. The conclusion of the US Navy investigation was that the gun captain Clayton Hartwig was responsible. According to the investigation, Hartwig would have intentionally put an incendiary device between powder bags during loading, igniting the propellant as the powder bags were pushed into the gun. Hartwig's relatives and friends argued that the explosion was caused by a mechanical failure and that the Navy used Hartwig as a scapegoat to shield the Navy against criticism about faulty equipment and lack of training of the U.S.S Iowa crew. The Iowa example is well suited to illustrate the different analytic strategies as well as the functionality of the MHMA tool. Note that the illustrative figures and examples are based on a small and non-representative subset of available information about the investigation, created in order to illustrate the described methods and tool, and not representing a full analysis of the investigation.

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II. ANALYTICAL METHODS

A. *Why structured analysis?*

Decision making research distinguishes between compensatory and non-compensatory strategies. A *compensatory* decision making strategy means that information is processed exhaustively and trade-offs are made between attribute cues [4]. *Non-compensatory* decision making strategies do not process all available information but use simple heuristics which enable quicker decisions. A related concept distinguishes between *System 1* and *System 2* operations. Intuitive judgments can be characterized as system 1 operations that are automatic, involuntary and almost effortless, while deliberate analytic activities, calculations etc. demanding effort and control can be characterized as System 2 operations [5]. There is a widespread view that non-compensatory/System 1 strategies to a large extent reflect how we make decisions on an everyday basis [6]. Analytic activities may involve both System 1 and System 2 operations, however to different proportions. The two different types of strategy and the extent to which they are appreciated relate to different scientific traditions with different views on the nature of rationality and rational choice [7]. The extent to which heuristics and biases lead to better or worse solutions is disputed and promotors for each type of strategy find examples of that the other strategy will lead to an inferior solution [8], [9].

Promotors of non-compensatory decision making strategies argue that in real life we never have access to all information and the human mind is not capable of objectively evaluating all benefits, costs and probabilities [7]. According to the non-compensatory tradition, cognitive biases are not to be eliminated, but may be useful in quickly leading us towards a correct decision [8]. According to Klein's recognition-primed decision model, an expert making a decision recognizes characteristics in a situation, and has developed routines on how to act based on different typical situations [10].

Promotors of compensatory and more structured analytic approaches mean that cognitive biases systematically lead to faulty decisions [11], and that a structured decision making process is necessary in order to overcome these psychological "errors in the decisional balance sheet" [12]. Examples of common biases include relying on confirming information rather than contradictory information (confirmation bias), assigning more credibility to information shared by several people although they all refer to the same source (information sampling bias), relating to recent information although it has nothing to do with the current decision (anchoring effect) [5], or rushing to a quick solution based on a simplistic framing of the problem (framing) [11]. The most important argument against intuitive judgment is risk. A System 1 analysis is frequently correct and demands less effort than a System 2 analysis, but if there is a risk that the wrong decision will result in severe consequences, available information needs to be evaluated in a more structured way. Such examples can be found in medicine, where a too quick diagnose based on a certain symptom pattern while omitting atypical symptoms may result in the wrong diagnosis or that a serious condition remains undiscovered [9]. Kahneman and Klein, normally assessed as on different ends on the compensatory – non-compensatory scale, argue that intuitive decision making based on expertise generally is more reliable than intuitive decision making based on heuristics, however also expertise based judgments have their limitations [5].

A structured method enables us to document and explain how the analysis has been made and thus gives a traceability between information, analysis and conclusions. This is useful when explaining or transferring the results of the analysis, when the analysis needs to be revised due to new information or changes in the environment and for complex analyses where several dimensions need to be considered. Furthermore, for team decision making, uniting around a structured analytic method gives a shared understanding of how the analysis is to be conducted. Team reflection can in itself increase information elaboration and decision quality, by generating alternative ideas and perspectives [13]. However, numerous experiments (with and without computer aid) have shown that teams are also affected by biases. For instance, team judgements are based on knowledge that is common to all team members while they fail to take unique information into account [14]. The team would then benefit from a structured method in the same way as individuals do [1].

B. *Analysis of Competing Hypotheses*

Analysis of Competing Hypotheses (ACH), founded by Richards J. Heuer [15], is an analysis method inspired by how hypothesis testing is used within scientific research to cope with imperfect information management. ACH encourages the analyst/team to separate the generation of information, assumptions, and arguments from the actual testing of hypotheses. Contradictory information is therefore more likely to be evaluated correctly. For example, Lehner et al. [16] report how ACH reduce the confirmation bias for participants without experience in intelligence analysis.

ACH aims to enable a systematic assessment of all the information available, avoid premature hypothesis selection, and to provide a structured justification for the recommended solution. In this sense, ACH is a *compensatory* strategy. The main principles of ACH are that the hypotheses are formulated from existing knowledge, evaluated on the basis of available evidence, and falsified rather than confirmed [15]. The process consists of eight steps:

1) *Identify hypotheses.* Hypotheses should be mutually exclusive, that is, if one hypothesis is true, all other must be false. The list of hypotheses should include all reasonable possibilities, however the analysis still needs to be able to overview. Thus 5-7 hypotheses is a recommendation, especially if the analysis is conducted by pen and paper [1].

2) *List all the important evidence*. That is, evidence that is assessed to have an impact on the evaluation of hypotheses. The evidence is supposed to reflect the thinking of the analyst, why it should include assumptions, arguments and facts.

3) Using a matrix (Table 1), *evaluate each evidence against the hypotheses* according to a predefined classification scale. The core of ACH is the separate analysis of each evidence relative all hypotheses to

TABLE 1. ACH MATRIX OF THE U.S.S IOWA INVESTIGATION

Evidence	Mechanical malfunction	Static electricity	Operation of rammer	Hartwig detonator
Telephone call from turret	+	-	+	/
Self ignition test	/	-	/	/
Expert statement about static electricity	/	-	/	NA
History mechanical problems	-	/	/	NA
Inexperienced gun crew	NA	+	+	+
Hartwig last minute appointment	NA	NA	/	-
Rammer reconstruction	-	-	+	-
Hartwig depressed	NA	NA	+	+

clearly identify the hypothesis with the least weaknesses. The scale for evaluation may differ between analyses. In table 1, evidence is classified as ++ (strongly supports), + (supports), / (neither supports nor contradicts), - (contradicts), -- (strongly contradicts) or NA (Not applicable).

4) *Refine the table* by clarifying hypotheses, adding additional evidence that contributes to the hypotheses evaluation and removing evidence that does not contribute. To what extent is the analysis influenced by assumptions?

5) *Compare hypotheses*. The resulting scores for each hypothesis (number of supporting and refuting evidence) is a *guidance* of which hypothesis is most or least likely. However, the analyst should focus primarily on the contradictory evidence. One critical contradictory piece of evidence may be enough to refute a hypothesis, regardless of the amount of supporting evidence.

6) *Review the results*. Which is the most diagnostic evidence (discriminating between hypotheses)? What is the reliability of the sources and the credibility of the information?

7) *Identify indicators for future observation*. Which information is needed in order to prove the validity of the analytic judgment? Which indicators need to be monitored in order to identify a change in the situation?

8) *Report the results*.

The Swedish Defence Research Agency conducted a between-groups experiment comparing the analytic strategies Critical Thinking [17], Analysis of Competing Hypotheses and no explicit strategy (control group) [18]. 45 participants (students) worked in teams of three with five teams in each condition. The teams received a lecture and applied training session on the method. Thereafter, the teams solved a complex problem where the task was to identify and rank different possible causes to ALS-PD, a rare disease affecting the native population on Guam. The participants had access to an extensive information set from several different sources. However, a hidden profile design was used, where information was distributed between team members in such a way that the team members would have different initial opinions of the most likely cause [14]. The members needed to share and compare information in order to identify all plausible causes as well as to find the most probable cause. Results showed that teams using ACH had a worse understanding of the problem, were worse at evaluating information and had a less comprehensive analysis as well as an inferior solution than both the teams that used Critical Thinking and the control group (no explicit strategy). Furthermore, they had a poorer dialogue, were less committed, were worse at organizing the information, used less information in their analysis and undervalued important information to a greater extent than the control group.

So, why did the ACH teams perform worse than to the control group, when other studies show a number of benefits with this method [16]? A deeper analysis identified that the main difficulty of the ACH teams concerned hypothesis formulation. As the problem used in the study was complex and multidimensional, it was difficult to create simple, mutually exclusive hypotheses in the way that the ACH method calls for. Identifying and deciding how to formulate the hypotheses required a lot of discussion, which resulted in too little time to actually evaluate the hypotheses based on the evidence. The other groups could derive and reformulate their hypotheses iteratively throughout the analytic process and consequently they did not get stuck in hypothesis formulation. When a hypothesis is added into an ACH analysis, all evidence needs to be evaluated towards the added hypothesis. Thus, adding or changing hypotheses along the way can be very time consuming. The critical thinking and control teams could work more iteratively, deriving and refining hypotheses continuously throughout the analysis while discussing aspects of the problem and the possible solutions. The conclusion is that ACH in its original form is suited for problems that are easy to divide into simple one-dimensional hypotheses, such as comparing culprits *or* weapons.

ACH research has generally been focused on to what extent confirmation bias is reduced [16] or how ACH can be supported by tools [19], but not investigating what types of problems are suitable for ACH. Thus, ACH research has to a large extent been based on well-structured problems where problem structuring and hypothesis formulation are not problematic. In some studies, the hypotheses are even given in the task, skipping the hypothesis formulation step and focusing only on evaluation of hypotheses. In the current paper, we argue that combining ACH with Morphological Analysis will facilitate a structured analysis of complex and even wicked problems [20].

There are simple and free tools available on the internet aiding ACH analysis. A common ACH software is developed by Palo Alto Research Center (PARC) in collaboration with the ACH founder Richards Heuer [21].

C. Morphological Analysis

How would you structure a manageable and valid set of hypotheses in order to analyze “How to get genuine democracies to emerge from authoritarian regimes?” Different stake holders will probably have totally opposite opinions about what constitutes the problem as well as the solution (-s). The problem is subjective with floating boundaries, and thus does not have a stable problem formulation nor a predefined solution concept.

This is the essence of a wicked problem [20]. Morphological Analysis (MA) is an analytic method designed to structure these types of problems. A morphological model is created, describing how different dimensions of a problem are connected. The method in its current form was developed by the astronomer Fritz Zwicky [22].

The *dimensions* in a morphological model are variable concepts that constitute different aspects of the problem. If suitable dimensions are not obvious in the modeling phase, one can try to use the classical five Ws; who, what, when, where, why, with the optional addition of how. For the Iowa example, how, who and why may be suitable. Conditions of "how" can be mechanical malfunction, electrostatic sparking, spontaneous ignition of the propellant and incendiary device. Each dimension has a number of *conditions*. The collection of dimensions and conditions constitute the morphological model.

Once a satisfactory morphological model has been created, a cross-consistency analysis is made, making pairwise exclusions of inconsistent combinations of conditions belonging to different dimensions. This results in a reduction of the problem space. For instance, the combination of "incendiary device" and "Truitt" can be excluded, as the device would have been placed by someone involved in loading the gun at the time of the explosion. Throughout the analysis, conditions and dimensions can be added and changed. The results of the analysis are a common understanding of what constitutes the problem, and a number of plausible configurations constituted by the possible combinations of conditions. In Fig. 1, one such configuration is displayed by the underscored conditions. A configuration needs to be composed of at least one condition from each dimension. In the example, "Incendiary device" is chosen as an anchoring condition, meaning that the other underscored conditions are those conditions that are assessed as compatible with "incendiary device." The configuration can be read as a possible scenario: If the explosion was caused by an incendiary device, it was planted by either Hartwig or another crew member involved in loading the gun. This was done in order to commit suicide, possibly in combination with jealousy, life insurance issue or another not yet identified motive. MA aims to describe and structure a problem space, and to identify possible scenarios. However, the method do not contain any procedures for evaluating these scenarios.

The Swedish Defence Research Agency developed its own software to support MA, MA CASPER [23]. It contains functionality for creating and commenting the morphological model and conduct the cross-consistency analysis, however no functionality to evaluate the model, as this is not a part of the MA method.

Dimensions

Conditions

How (cause)	Who (responsible)	Why (motive)
Mechanical malfunction of gun	Hartwig	Human error
Electrostatic sparking	Truitt	Equipment failure
Spontaneous ignition	Other crewmember	Life insurance
Incendiary device	Navy	Jealousy
	No one	Suicide
		Other

Fig. 1. A morphological model of the U.S.S Iowa scenario. The underscored conditions represent a configuration.

III. The Multi-Hypothesis Management and Analysis method and tool

The benefit of ACH is the structured evidence-based approach, enabling traceability between the decision and the information it is based on and reducing the risk of making a decision based on biased preconceptions. The major limitation of ACH is that the problem needs to be divided into simple hypotheses. Separate investigations of suspects, causes and motives are needed, as combined hypotheses containing all three aspects will result in too many hypotheses to overview as well as problematic evidence evaluation if evidence supports only a part of a combined hypothesis. The benefit of MA is the possibility to investigate complex, multidimensional phenomena, whether it is for forecasting or investigation of a historical event. The morphological model enables a common understanding of what constitutes the problem. However, the morphological method does not specify how the model should be supported by information. The MA CASPER tool includes functionality for placing comments on dimensions, conditions and relations. These comments can be used for referring to documentation or decisions that led to the inclusion of the dimension or condition. However, MA does not include a process for evaluation of different configurations or conditions, such as which scenario is most likely to occur.

Combining ACH with MA enables evidence testing against a complex set of hypotheses as created by the morphological model. This is the idea of the MHMA tool. Depending on the task and information available, focus can be on either the morphological part of structuring the problem space, or the ACH part of evaluating the hypotheses resulting from the model. Taking a look on available tools on the market, the Globalytica Th!nk Suite includes one tool for generating multiple hypotheses in line with the MA method and another connected tool to evaluate the generated hypotheses according to ACH [24]. Globalytica demands that the analyst first completes the morphological model and then manually selects the subset of the generated hypotheses that should proceed to evaluation using the next tool. In MHMA, the combination of MA and ACH functionality in one single tool allows an iterative process (Fig. 2) where the morphological model can be revised along the way.

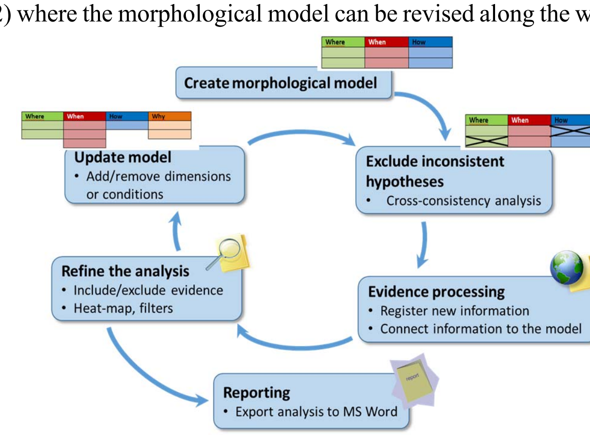

Fig. 2. The multi-hypothesis analysis process

Furthermore, in MHMA the evidence is evaluated towards the conditions of the morphological model rather than complete hypotheses. All generated hypotheses are then automatically ranked based on this evaluation.

The three main functions of the MHMA tool are Hypothesis generation, Evidence processing support and Support for deeper analysis. The different functionalities support an iterative analysis process (Fig. 2). Compared to [2], the process has been revised as the inclusion of new functionality in the tool has enabled a more sophisticated analysis. The user interface is displayed in Fig. 3. The analyst creates a morphological model of the investigated problem. Based on the model, the MHMA tool automatically generates a hypothesis set. The analyst then registers evidence (Fig. 4) and connects them to the conditions of the morphological model, resulting in that the support for the generated hypotheses will automatically be updated by the MHMA tool. The number of generated hypotheses will decrease as the analyst make pair-wise exclusions of incompatible conditions. The MHMA tool contains a number of features for refining the analysis, as well as visualizing how hypotheses are supported by available evidence. The process of modifying the model, adding and connecting evidence and evaluating the result proceeds until no more evidence is reported, or until the analyst in charge makes the judgment that the available evidence is sufficient to decide which hypotheses should be selected for more in-depth analysis.

A. Hypothesis generation

According to the structured analysis process it is recommended that the analyst start by setting up a model that defines the hypothesis space (note that registration of evidence in the MHMA tool is possible even before the process has been started). The hypothesis generation supported by the MHMA tool is based on MA. Thus, the model in this case is the morphological model, which is made up by a set of dimensions corresponding to key features of the investigated scenario, and their possible conditions. Defining a suitable set of dimensions is a non-trivial task, in general performed by analysts or subject matter experts, and it requires domain knowledge. The dimensions what, when, where, why, and how are used as default options in the Globalytica toolsuite, however in the MHMA tool the decision is left for the analyst. A model may need to be modified or revised several times during the analysis process. Revision of the model is supported by the MHMA tool and can be done at any time. The set of hypotheses generated consists of all combinations of conditions belonging to different dimensions. For example, a morphological model with n dimensions, all having m possible conditions each, contains a total of mn conditions. The same table will generate m^n hypotheses. With n = 3 and m = 4, there will be 12 conditions in the model and 4^3 = 64 hypotheses.

The set of hypotheses will most likely contain hypotheses that are inconsistent due to logic, concept definitions or evidence. An example of concept-based inconsistency in the Iowa morphological model is that the placement of an *incendiary device* is the result of an intentional action, and is thus inconsistent with the concept of *human error*. In the MHMA tool, cross-consistency analysis in conducted by excluding incompatible combinations of conditions pairwise. The list of possible hypotheses will be reduced as the hypotheses containing the incompatible combinations are removed from the hypothesis list.

B. Evidence processing

A key function of the MHMA tool is to assist the analyst in managing evidence. Each piece of evidence is registered in the tool with name and, optionally, attributes such as description, classification and source. All registered evidence items are displayed in a table that can be sorted and filtered in various ways (Fig. 5). There is also a filtering functionality for selection of evidence to include in the analysis. Different pieces of evidence can be manually selected (the box to the right of evidence title in Fig. 5) or filtered according to evidence characteristics (reliability, credibility, source etc).

The analyst can connect the evidence to the different individual conditions in the morphological model. Each connection is registered as either supportive or contradictive.

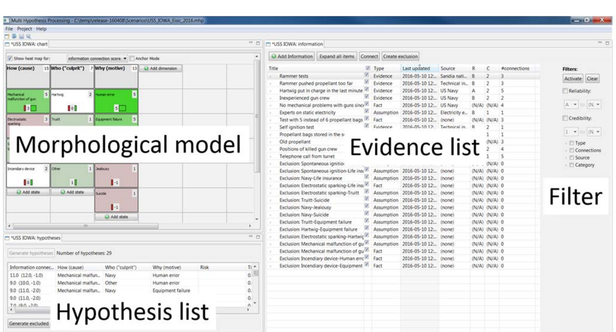

Fig. 3. The user interface of the MHMA tool.

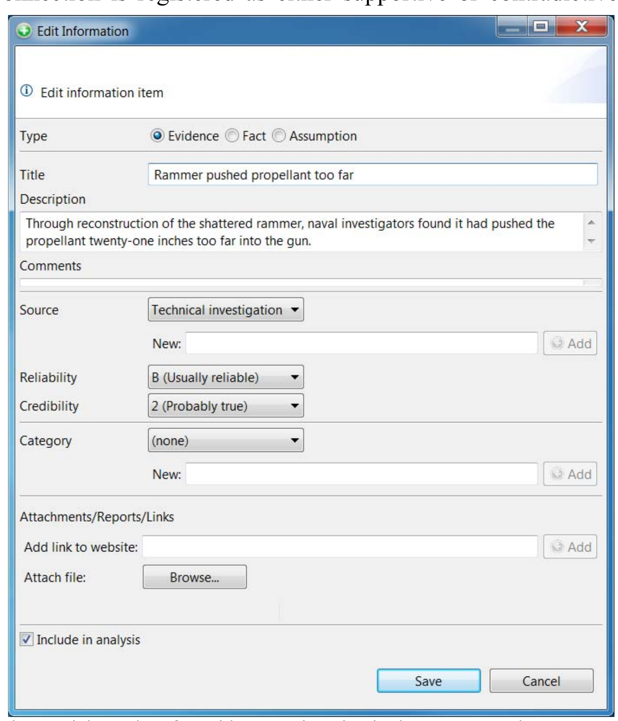

Fig. 4. Dialogue box for evidence registration in the MHMA tool

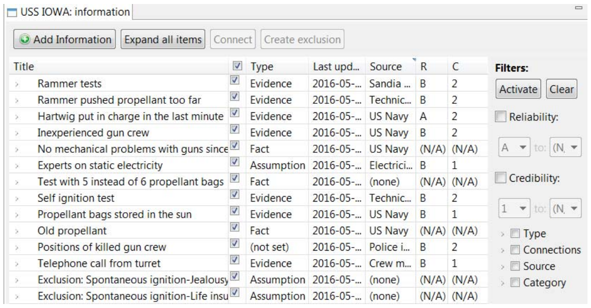

Fig. 6. Screenshot of the evidence list and filtering function of the MHMA tool.

One piece of evidence can be connected to several conditions. For instance, technical investigation from the Iowa explosion identified a possible *malfunction of the gun*, and further supports that the explosion was caused by *equipment failure*. If a piece of evidence supports or contradicts one specific condition, that evidence will also implicitly support or contradict all hypotheses associated with that condition. This enables "semi-automatic" assessment of hypotheses. Instead of having to individually assess the possibility of a connection between every new piece of evidence and every single hypothesis, the analyst can get a satisfactory result from assessing only the possible connection to one or more of the conditions in the morphological model. In a model of 3 dimensions with 4 conditions each, each piece of evidence is evaluated against the 12 conditions, rather than evaluating the evidence against the full set of the 64 generated hypotheses. In addition to substantially reducing the number of manual steps for assessment, this procedure exploits the fact that the conditions of the morphological model can be viewed as the simple, one-dimensional hypotheses that ACH is actually best suited for. The ranking score is simply computed as subtracting the amount of contradicting evidence from the amount of supporting evidence.

C. *Support for deeper analysis*

The MHMA tool includes a set of analytical support features, including

- Ranking of hypotheses. As described above, a ranking score is computed for each hypothesis based on the amount of evidence connected to the conditions constituting the hypothesis.
- Overview of connections between evidence and hypotheses / model conditions
- A heat map view of the morphological model visualizing which conditions have strong support from evidence or is strongly contradicted by evidence.
- A heat map view of the morphological model based on number of different sources supporting/contradicting the states (Fig. 6).
- Filtering of evidence, enabling exploratory analysis by selecting or excluding which evidence that should contribute to the analysis (scoring): What if source XX should be disregarded completely? What if we only include evidence with a certain level of credibility? Available filter possibilities are displayed in Fig. 5.

Fig. 5. Screenshot of a morphological model and generated hypotheses. Heatmap is enabled, visualizing to what extent evidence supports and contradicts the conditions of the morphological model. The score (far left column of the hypothesis list) give the total score for each hypothesis (#supporting evidence – #contradictory evidence).

- The option to comment every step of the analysis: for instance to motivate certain evidence connections, inclusion of morphological conditions and dimensions etc.
- An export feature: the analysis can be exported to a word document including evidence list with attributes, high ranked hypotheses and the morphological model.
- Anchoring functionality, in order to visualize all conditions that are compatible with a chosen condition, similar to the configuration given by the underscored conditions in Fig. 1.

IV. User Studies

During development of the MHMA tool, four user studies were conducted, two as separate activities and two as the last activity of an ACH and MA workshop. Following each user study, user needs were prioritized and also implemented so that the following user test was conducted on a newer version of the tool. The first and second user studies are described in a project report (Swedish) [25].

A. Participants and procedure

Participants in the user studies were professional analysts with experience from different types of analyses, areas and time perspectives. Due to confidentiality, detailed participant data is excluded. Opinions were collected from people with previous experience of ACH and MA as well as from those without. The user studies aided in identification as well as prioritization of development needs.

User study 1 was conducted with six experienced analysts (Mean: 20 years of experience) working mainly within research. The test sessions were preceded by individual interviews concerning the analytic situation and experience of methods and tools for structured analysis. During the test, the analysts worked in pairs. One of the pairs consisted of two analysts with extensive professional experience of using MA. No participant had previous experience of ACH. User studies 2 and 3 were conducted with 10 professional analysts in each study. 18 of these were specialists within different areas while two worked with education and training of analysts. These user studies were both conducted as the last part of a three-day workshop on ACH and MA. During the first part of the workshop, the participants received approximately one day of education and training in each method, using the PARC ACH for conducting the ACH analysis and Casper or Excel for the MA. During the test sessions the analysts worked in groups of three to five persons. User study 4 was conducted with eight professional analysts with experience from different types of analyses. The user test was conducted as individual sessions and was preceded by individual interviews concerning the analytic situation and experience of using method and tools for structured analysis.

During the test sessions, a scenario of the TWA800 accident (airplane crash that occurred 1987) was partly implemented in the MHMA tool. The morphological experts of user test 1 received the more complex Guam scenario (briefly described in the ACH section as well as in [18]) as it was proven that it was a challenge to structure this scenario. After an introduction of the tool and scenario, the participants were tasked to complete the morphological model and the evidence list, connect evidence to the model, perform cross-consistency analysis, and make a judgment as to which was the most likely hypothesis. Throughout this activity, the participants were asked to write down or orally express identified development needs to a member of the MHMA development team which was present as an observer as well as support. Finally, a structured discussion aimed to collect additional development needs, general impressions as well as an understanding of the perceived relevance of the tool for different types of analyses.

B. Results

Results from the user studies were mainly positive. Participants in the studies thought that the tool was easy to understand, that most functions were self-explanatory and that the visual interface was appealing. The idea of combining the methods ACH and MA was considered as a useful approach for solving different analytical tasks, as long as the amount of information that needs to be registered is not too large. The differences in previous experience of the ACH/MA methods was reflected in the understanding of the MHMA tool. The time to learn the functionalities of the tool and understand the analysis process was shorter for users that had previous experience of the methods, especially MA. The quality of the result could not be evaluated as focus was on identifying user needs rather than conducting a complete analysis of the problem. The morphological experts receiving the more complex test scenario managed to create a suitable morphological model in a much shorter time than the more inexperienced users although they received the simpler flight crash scenario. It was identified that especially MA is a method that demands experience, and if a team analysis is conducted, it is preferable that at least one of the analysts has a good experience of the method and can act as facilitator during the creation of the morphological model. Thus, neither the MHMA tool, nor any other analytic tool, excludes the need for education and training on the methods.

Although the MHMA process is iterative, it can be quite time consuming to change the morphological model during the analysis. Similar to the original ACH method, evidence needs to be reevaluated against the added conditions. Therefore, it is worthwhile to put some effort into creating a satisfactory morphological model early in the process, although minor changes may occur along the way, for instance due to new information.

The combination of MA and ACH proved successful, and as hypothesized, generating and evaluating the hypotheses through a morphological model eliminated the limitations of ACH regarding hypothesis space. Furthermore, the MHMA tool was appreciated by the experienced morphological analysts for the possibility to evaluate the model against available information. Depending on the different types of analytical tasks that the participants were facing in their daily work, they valued different aspects of the tool. Some analysts were to a larger extent focused on the problem structuring part, and thus requested more advanced functionality for creating the morphological model, while hypothesis ranking was considered totally unimportant. Others were more interested in decision support for evaluating different alternatives, resulting in discussions of if and how the scoring system should be modified in order to enable a fair and reliable evaluation. Analysts pointed to that the analysis support given by the tool needs to be *transparent*, so that the analyst can remain in control of the analysis.

The major development needs identified and also implemented in the final version of the tool can be summarized as: 1) *Improving the ability to display and evaluate uncertainty and reliance on different sources in the analysis*. This was implemented as classification of evidence according to reliability and credibility and possibility to filter which evidence would be used in the analysis based on reliability and credibility as well as possibility to choose which sources to include in the analysis. Furthermore, an additional heatmap was added, displaying how many sources that supports each condition in the morphological model. 2) *Enhance functionality for MA*. An anchoring function was implemented, enabling an overview of the morphological model in terms of which conditions that are compatible with (that is, not excluded from) each other. 3) *Improving performance*. A large morphological model, will generate a large set of hypotheses. In order to cope with larger datasets, a database solution was implemented. 4) *Improve usability and simplify cross-consistency analysis*. Users considered exclusion of incompatible conditions especially time-consuming. Interface improvements were made, enabling a better overview of the analysis as well as a simpler procedure for pairwise exclusion. 5) *Improving traceability.* Analysts stressed the importance of traceability, motivate decisions and document information needs along the way. This was implemented as improved abilities to place comments on evidence, dimensions, conditions, connections and exclusions.

V. Conclusion

The most successful outcome of the user studies was that the overall concept of combining ACH and MA in one tool and integrated process proved successful, regardless of whether the analyst chose to focus on problem structuring or hypothesis evaluation. The users found the concept as well as the visual interface appealing, although the tests also showed that knowledge and experience of the methods, especially MA, is important to obtain sufficient quality in the analysis. The tools and methodology seems suitable for a wide range of problems, except for when very large amounts of information needs to be processed, as it is time consuming to manually register, classify and connect evidence.

The user studies produced new insights and generated development needs that had not been identified by the development team, resulting in improvements regarding all the main functionalities of the tool. Keeping simplicity of the tool and transparency of the analysis while adding more advanced functionality such as refining the scoring, filtering and classification of evidence was an ongoing challenge for the development team. Another user study is planned in order to evaluate the most recent developments of the tool, for instance the anchoring function.

As a response to the non-compensatory analysis argument that a compensatory analysis demands more information than we can keep in our minds, the tool seems to vastly reduce that burden, by keeping track of all the hypotheses and information, without needing to reduce our thinking to a few predefined hypotheses, as in the original form of ACH. One must bear in mind, that as for ACH, the output is dependent on the input. A biased evidence set, for instance a lot of evidence concerning one of the suspects will result in a biased scoring. The analyst needs to be aware of that the score is only an indication, while the experience and expertise of the analyst will still be essential aspects of the final decision. Based on the results of user tests and methodology workshops, we believe that MHMA has the potential to enable a transparent analysis, in which evidence gaps and biases will be visible, enabling a shared understanding of a problem and a traceability between analysis and decision.

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