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Highlights

- We review the growing number of future studies that employ Fuzzy Cognitive Mapping (FCM).
- We trace FCM to their theoretical foundations.
- We provide a step-wise description and discussion of practical methods and pitfalls of FCM modeling.
- Our discussion enables researchers to rigorously apply FCM to Future Studies.
- We provide an overview over future research directions for FCM.
FUZZY COGNITIVE MAPS FOR FUTURES STUDIES - A METHODOLOGICAL ASSESSMENT OF CONCEPTS AND METHODS

Abstract

Fuzzy Cognitive Map (FCM) modelling is highly suitable for the demands of Future Studies: it uses a mix of qualitative and quantitative approaches, it enables the inclusion of multiple and diverse sources to overcome the limitations of expert opinions, it considers multivariate interactions that lead to nonlinearities, and it aims to make implicit assumptions (or mental models) explicit. Despite these properties, the field of Future Studies is slow to adopt FCM and to apply the increasingly solid theoretical foundations and rigorous practices for FCM applications that are evolving in other fields. This paper therefore discusses theoretical and practical aspects of constructing and applying FCMs within the context of Future Studies: based on an extensive literature review and the authors’ experience with FCM projects, it provides an introduction of fundamental concepts of FCM modelling, a step-wise description and discussion of practical methods and their pitfalls, and an overview over future research directions for FCM in Future Studies.

Keywords: Fuzzy Cognitive Maps, Future Studies, Scenarios, Mental Model, System Thinking
1. INTRODUCTION

The toolbox of Future Studies (FS) has recently seen the addition of Fuzzy Cognitive Maps (FCMs), which are used to better integrate expert, stakeholder, and indigenous knowledge by creating scenarios that bridge the gap between quantitative analysis and qualitative story lines [1–4]. FCM were first described by Bart Kosko in 1986 [5], who proposed them as a means to make qualitative cognitive maps, which had originated in social science [e.g. 6–8], computable. In contrast to other cognitive mapping approaches, FCMs enable an analysis of the dynamic properties of the system they represent and the identification of possible future system states and system instabilities. Early applications of FCM often illustrate these capabilities with examples of foresight studies, such as an investigation of the dynamics and likely outcomes of the Middle-East Peace Process [5], of South African Apartheid politics [9], and of US health care reform [10]. However, these examples were published in technical journals that focus on fuzzy mathematics and artificial intelligence, and FCM were initially slow to spread across other scientific disciplines. This is currently changing: Between 2000 and 2010 the number of FCM-related publications has not only seen a tenfold increase [11] but an increasing number of publications are devoted to applications of FCMs across a variety of fields, such as business planning, medicine, and environmental management [e.g.,12,13].

The vast majority of FCM applications, and much of the scientific discussion, however, still takes place outside of the field of FS [11,14,15]. They frequently focus on the extension of the FCM method, among others through machine learning approaches that reduce the reliance on subjective expert judgments and through automated knowledge extraction [16]. The technical nature of these papers is not readily accessible to researchers and practitioners in FS. More importantly, the underlying epistemological stance of many technical FCM publications - the data-driven search for objective knowledge that makes correct predictions possible - is often at odds with FS, which emphasize that the future cannot be known [17]. This further aggravates
the knowledge transfer problem. As a consequence, FCMs may be less rigorously applied and analyzed in FS than is required to advance the field.

This paper aims to address the knowledge gap: based on an extensive review of the state-of-the-art of FCM modelling, drawn from the breadth of available literature and our own experience with complex FCM projects, it introduces the fundamental concepts of FCM modelling and provides a step-wise description and discussion of practical methods for the application of FCMs in FS. Thus it familiarises FS practitioners with the literature, while focusing on scenario-specific issues.

1.1. THEORETICAL FOUNDATIONS OF FUZZY COGNITIVE MAPS

Fuzzy Cognitive Maps [5,9,18] are signed directed graphs: they consist of nodes, so-called "concepts" that are connected through arrows that show the direction of influence between concepts. A positive (negative) arrow pointing from concept A to concept B indicates that concept A causally increases (decreases) concept B. Concepts are verbally described and can contain hard to quantify concepts, such as "environmentalism" or "cultural identity". To reflect the strength of causal links, weights are assigned to the arrows.

FCMs are regarded as a simple form of recursive neural networks [9]. Concepts are equivalent to neurons, but other than neurons, they are not either "on" (= 1) or "off" (= 0 or -1), but can take states in-between and are therefore “fuzzy”. Fuzzy concepts are non-linear functions that transform the path-weighted activations directed towards them (their “causes”) into a value in [0, 1] or [-1;1]. When a neuron “fires” (i.e., when a concept changes its state), it affects all concepts that are causally dependent upon it. Depending on the direction and size of this effect, and on the threshold levels of the dependent concepts, the affected concepts may subsequently change their state as well, thus activating further concepts within the network. Because FCMs allow feedback loops, newly activated concepts can influence concepts that have already been
activated before. As a result, the activation spreads in a non-linear fashion through the FCM net until the system reaches a stable limit cycle or fixed point.

FCM calculation models the spreading activation through the network by multiplying a vector of causal activation with the square connection matrix derived from the FCM graph. Commonly used squashing functions, such as bivalent, trivalent or logistic function restrict the concept states to discrete final states, such as [0; 1] or [-1; 0; 1] or to intervals [-1;1] or [0;1]. Bivalent squashing functions can represent an increase of a concept, trivalent functions can represent an increase or a decrease of a concept and logistic functions can represent the degree of an increase of decrease of a concept [19]. All FCMs have “meta-rules”: several input vectors – so-called input regions – lead to the same final system state [20]. FCMs with continuous concept states, so-called “continuous-state machines” can result in chaotic behaviour [20]. FCMs with discrete concept states, so-called “finite state machines” result in either a fixed state vector or in a limit cycle between a number of fixed state vectors [20,21]. The stable fixed point or limited cycle is typically reached in less than 30 cycles and often much sooner, depending on squashing functions, initial state, and the structure of the FCM [22,23]. Importantly, the number of iterations it takes for the system to settle down cannot be interpreted as the time it takes the real-world system represented by the FCM to reach a quasi-stable state [24]. Moreover, the states of concepts cannot be interpreted in absolute terms, but only relative to other factors in the system, or relative to other system descriptions [24].

FCM have several properties that make them useful for FS: FCMs are based on causal cognitive mapping, which provides an efficient way to elicit, capture and communicate causal knowledge and help respondents to become better aware of their own mental models. Maps can be based on interviews, text analysis or group discussions and can be easily modified or extended by adding new concepts and/or relations or changing the weights assigned to causal links [18]. Inputs from large, diverse, and even dissipated groups can thus be easily integrated in order to overcome the limitations of expert opinions and group-think. In contrast to cognitive mapping,
FCMs furthermore allow a quantitative analysis of the quasi-dynamic behaviour encoded in the FCM models to aid decision making: Planners can agree on plausible combinations of input values for independent FCM variables and calculate the states of depend variables to assess the impact of input variation (e.g. particular policies) and alternative system description (e.g. different mental models of a complex problem). This, in turn, can be linked to a future state that is internally consistent because it is the result of a calculation that simultaneously considers all direct and indirect connections between all concepts. FCM modelling thus address several of the requirements that the Technology Futures Analysis Methods Working group identified for approaches to technology futures studies [25]: it uses a mix of qualitative and quantitative approaches, it provides means to overcome the limitations of expert opinion based methods by enabling the inclusion of multiple and diverse sources, it considers multivariate interactions that lead to nonlinearities, and it aims to make implicit assumptions (or mental models) explicit.

1.2 FUZZY COGNITIVE MAPS FOR FUTURES STUDIES

Methods for FS [25,26] employ multi-perspective frameworks to explore and understand possible futures and their impacts, rather than predicting “the” future. These efforts are not targeted at establishing knowledge about future events, which can neither be known nor falsified before they unfold [17]. Instead, they are focused at understanding parts of the puzzle, such as historic patterns and conditions that may also play out in the future. These insights are used to strategically think about and anticipate future events [17]. Even though FCM have the ability to support this process by eliciting, combining, and dynamically assessing the knowledge and beliefs of individuals, they do not yet belong to the standard repertoire of FS, as Table 1 illustrates.
The few existing studies aim to improve specific FS methods through FCM, such as risk assessment [30] and - more frequently - scenario planning [1–4,27,31,32]. Like all scenario approaches, these studies focus on those aspects of the future that are uncertain and not knowable through information gathering. For these uncertainties, they develop a limited number of possible states, so-called scenarios, that "tell a story of how various elements might interact under certain conditions" [33]. The main purpose of scenario planning is to challenge prevailing mind-sets and avoid the common problem of over- and underprediction of change.

To this end, FCM-based scenario approaches put heavy emphasis on integrating diverse perspectives from experts and/or stakeholders and on eliciting and communicating assumptions. FCM simulations are used to create internally consistent alternative scenarios that reflect the subjective knowledge of respondents (experts or stakeholders) about uncertain driving forces that shape the future. They thus provide a bridge between qualitative and quantitative scenario approaches.

The small total number of FCM-related publications in FS does not yet mirror the quickly increasing numbers in other fields, such as engineering, business planning, medicine, and environmental sciences [11,14]. For example, Business Source Premier, which indexes academic business journals, shows 20 FCM publications since 2010 - predominantly in technical
journals that cover software, computer systems, artificial intelligence, and cybernetics. Accordingly, only two publications use the term "scenario" or any other method commonly associated with FS: Glykas [34] uses FCM scenarios to extend strategy maps so that they dynamically adjust when strategic objectives are set or revised in order to foster the deployment of strategy decisions. Lee et al. [35] use an FCM model to predict outcomes (e.g. revenue, cost) as a result of strategic marketing decisions, such as improvements in customer relationship management or presale activities. Both publications are representative of the majority of current FCM publications: First, contrary to FS, they use the term scenario to characterize a combination of input variables into the FCM simulation model that are under the control of decision makers. Secondly, the publications are technical in nature and provide sophisticated algorithmic extensions of the core FCM methodology, as well as IT implementations. And third, the publications build FCM models based on expert knowledge and provide little specifics on how it is obtained and validated.

Notably, a different picture emerges in environmental sciences that increasingly use FCM to facilitate stakeholder engagement for the development of environmental scenarios: Geobase, a database of academic publications focused at geographical, earth and ecological sciences lists 23 FCM applications since 2000. Of those, 19 articles use participatory approaches to integrate stakeholder insights into planning and analysis and 14 articles apply some form of scenario planning approach. Recent books on the theory and practice of FCM echo this trend. For example, two recent edited books [12,13] include several chapters on FCM usage in the context of environmental modelling and participatory stakeholder approaches.

These studies are practical in nature and typically involve more respondents than those in business and FS. They focus on complex problems, such as local impacts of climate change or the effects of policy decisions on ecosystems and - as a result - stakeholder livelihoods [36–40]. Similar to FCM studies in the business literature, these studies use the term scenario for simulation runs that show the outcome of a single outside trend (e.g. drought as a result of
climate change[38]) or specific interventions (e.g. controlling the populations of a species, managing urban sewage[41,42]. By attempting to identify what will happen under different conditions they take an epistemological approach that is problematic for many FS researchers. Moreover, stakeholder integration is not always targeted at improving insights into the possible future of the system under investigation. Instead, some studies employ FCMs to see how strongly stakeholder perceptions differ from what scientific research and experts have established as correct, to help predict how the stakeholders will likely respond to policy decisions, and to create buy-in for chosen management approaches. By eliciting and integrating a relatively large number of stakeholder views, including those of lay persons they provide important contributions to FCM practice, even though some of it occasionally occurs in an ad-hoc manner that leads to "quick and dirty" results [32].

Regardless of the discipline, present FCM research is still defined by its two different intellectual roots: FCM publications in the more technical tradition of artificial intelligence aim to integrate and model expert knowledge in a single model and make it available to less experienced decision makers. Modellers in this tradition strive to capture objective knowledge from carefully selected experts and put considerable efforts not only in knowledge capture, which typically occurs in one-on-one interviews, but also in resolving expert disagreements because agreement among experts is perceived as an indicator of model quality. FCM modellers in the social science tradition, on the contrary, frequently understand FCM models as a means to facilitate "sensemaking" by helping decision makers to communicate about beliefs, assumptions, and values, by highlighting areas of agreement and disagreement, and by facilitating strategy conversations. Conflicts among experts are highlighted and preserved because they point at possible weak signals that preclude structural shifts. Discussions about conflicts of opinion are expected to improve mental models, result in better strategies, and - if conflicts are resolved successfully - greater buy-in for the strategic decisions that are agreed upon.
As argued earlier, as a consequence of the diverse FCM literature and differences in the underlying philosophies, there is currently little systematic guidance for researchers and practitioners who wish to use FCMs to capture, integrate, and analyse the multiple perspectives of stakeholders and subject matter experts (hereafter named respondents) in complex real-world projects in order to support FS. The following section provides a systematic elaboration of the existing methods and their potential pitfalls, based on a general framework for FCM modelling.

2. A FRAMEWORK FOR FCM MODELLING

FCM model building is a multi-step process that captures causal knowledge in the form of cognitive maps, formally describes these maps as adjacency matrices, and applies neural network computation to refine the model and analyze model results. While these basic steps are agreed upon in the literature [22,23,43], additional steps and detailed approaches to each of these stages differ from author to author. For the purpose of this paper and based on our prior research [2,3,43–45] we propose the following framework that consists of six steps:

- **Clarification of project objectives and information needs** (Step 1). This step includes the definition of the scope of the modelling project, including its topic, model boundaries, and the timeframe under consideration. Furthermore, open questions about the knowledge domain are identified.

- **Plans for knowledge elicitation** (Step 2). This modelling step requires the identification of knowledge sources, as well as the planning the knowledge elicitation techniques to be used.

- **Knowledge capture** (Step 3). This process step includes all elicitation activities that lead to (weighted) causal cognitive maps about the knowledge domain. In addition,
information about the expected dynamic behaviour of the system they represent is collected to enable model tests in Step 6.

- Calibration (Step 4) and detailed (Step 5) design of the FCM model, include the translation of the causal cognitive map captured in Step 3 into an adjacency matrix, the choice of output functions and input vectors, and approaches to dealing with time lags.

- Model use and Interpretation of model results (Step 6).

In most projects, this six-step process is not sequential: An expert identified in step 2, for example, could turn out to be less knowledgeable than anticipated in step 3, thus necessitating a new plan for knowledge capture.

2.1 Project Objectives and Information Needs (Step 1)

The first step to FCM construction is a thorough analysis of the model's objectives. A lack of problem focus and unspecified mission statements (e.g. "model how our market will evolve in the future") can lead to all-encompassing, overly complex models that break the rule poignantly stated by Sterman: "Always model a problem. Never model a system"[46 p. 90]. In order to clarify the objectives of a modelling project, modellers should inquire about problems, desired situations that should remain the same, undesired states that need to change, and the decision alternatives available in the given situation[15]. This not only ensures problem focus, but also serves to identify model elements and stakeholders, whose views and knowledge may be important for the model. A potential pitfall of the first modelling step is to specify objectives in a manner that restricts the input of the stakeholders. Their perception of the key issues in their region, for example, might differ from what the project states. One such example is a study in the Mediterranean aimed at analysing land degradation and desertification. Rather than focusing the stakeholders on these issues through detailed prior information, the modellers chose to allow the respondents to raise issues they considered relevant. Based on their
problems and needs, the stakeholders focused the study on water availability and spatial policies rather than on soil erosion and desertification and thus provided insights into important socio-economic issues [47]. Once the model objectives are known, model boundaries – the variables that should be excluded from the model or considered to be exogenous – should be assessed and documented in a model boundary chart[46]. Also, all information needs that become apparent during the goal analysis should be documented, preferably as question. Finally, the timeframe (present situation, developments in the next 2 years, situation in 10 years, etc.) of the analysis needs to be clarified [15].

2.2 Plans for Knowledge Elicitation (Step 2)

The decision whose domain knowledge should be used for the FCM model is closely intertwined with the decision on how expert knowledge should be captured. Respondents can be identified through snowball sampling, stakeholder analysis and organizational network analysis [48], but may also be predetermined by the client of the modelling project [46]. To overcome individual biases, FCM models should rely on several respondents. The number of respondents needed depends on the complexity of the issue and the diversity of opinions: in recent multi stakeholder studies, between 7 and 46 individual cognitive maps were captured [1,23,49,50]. Each respondent can be expected to introduce 15-30 concepts [15,23,51], many of which will be shared with other respondents. New respondents should be surveyed as long as their input still introduces relevant new concepts and connections to the study [23].

Three different methods for knowledge elicitation are used in the FCM literature.

1) Option 1 - The modeller is the expert: Most (technical) publications on FCMs describe a situation in which the modeller (and author) is also knowledgeable about the domain that is to be represented in the FCM model. This approach, however, is typically ill-suited for multi-stakeholder studies in which the worldviews of a diverse group of respondents need to be captured, and therefore ill-suited for FS.
2) **Option 2 - The modeller surveys the expert(s):** Surveys can take the form of questionnaires [e.g. 50] and semi-structured, face-to-face interviews [23,42] or the form of Delphi-studies [48], and moderated group discussions in which respondents take up and integrate contrasting views [1]. Survey designs are widely discussed in the literature on research methods [52,53]: designs with no group interaction can encourage experts to give detailed information and voice possibly controversial opinions that they would not easily express in front of a group of peers. Survey designs with group interaction can provide a more coherent and complete picture of the knowledge domain than a series of individual interviews because respondents can build on each other's knowledge, particularly if emphasis is put on understanding the rationale behind outlier models, as is common in Delphi studies. Multi-stakeholder studies employ cognitive mapping (see section 3.3) as an survey approach that focuses respondents' attention on a knowledge domain and captures respondent knowledge in great depth.

3) **Option 3 - The modeller analyzes documents:** Content analysis can be used to infer causal maps from written documents [8,54]. Practical approaches are discussed by Carley & Palmquist [51], Nadkarni & Shenoy [55], and Kok [43]. Documents for content analysis can originate in primary research, such as transcriptions of interviews with participants of the FCM study, as well as in secondary research, such as data published textbooks and scientific publications, industry trend reports, and newspaper articles. These documents are useful check stakeholder inputs against accepted scientific facts, to model aspects for which expertise resides in more than one person and is therefore expensive to access (e.g. knowledge about global industry trends) or in cases where stakeholders are not willing to take part in a modelling project (e.g. competitor). A special case of document analysis are situations in which published quantitative data exists that FCM models can built on: Schneider et al. [56], for example, use quantitative OECD data, such as birth rates, to model economic and demographic development of countries. However, this type of detailed quantitative data is rarely available FS and if it does exist, other
modelling approaches that can make use of the high quality input data to obtain equally fine
gained quantitative results are more appropriate.

The three methods for knowledge elicitation can be combined to balance the advantages and
drawbacks of each method. As an example, the modellers’ initial understanding of the problem
domain can be captured in a simple causal map (option 1) that serves as stimulus in respondent
surveys (option 2)[e.g. 23,57]. Combined approaches can help when the availability of some
participants, such as higher level policy makers is limited but their views are essential for the
project. Their expert judgments on either the key concepts or on the basic structure of the FCM
can be used as starting point for stakeholder inputs, as a study of the Danube Delta
demonstrates [1]. However, the process of mixing expert judgments and stakeholder views
needs to be carefully monitored and documented [1].

2.3 KNOWLEDGE CAPTURE (STEP 3) – APPROACHES TO
COGNITIVE MAPPING

2.3.1 Cognitive Mapping Overview

Cognitive mapping techniques have been developed in educational and organizational research
as a tool to elicit mental models for research purposes and to improve managerial thinking and
student learning [8,58]. They are generally accepted as easy to teach and comprehend, though
van Vliet reports that some local stakeholders with limited general knowledge may be
uncomfortable with a structured mapping approach and advises to capture their knowledge
through other means [1]. Respondents who are trained in other systems thinking techniques
may also find it difficult to accept that cognitive mapping in FCM, contrary to the very similar
looking cognitive maps in System Dynamics, cannot capture stocks and flows. They may
therefore need additional coaching. Cognitive mapping rarely captures proven theories, but
helps respondents to share their mental models or "subjective theories"[59], which are highly personal and cannot be easily validated against reality. Knowledge capture activities should therefore help respondents to challenge their mental models [48,60] and improve their subjective theories. To achieve these objectives, causal cognitive mapping typically follows three basic steps [15,22,23]: respondents are briefly trained in cognitive mapping, identify concepts that pertain to the knowledge domain in question (capture of knowledge content) and then document their causal knowledge in "loop and arrow" diagrams (capture of knowledge structures). Methods differ in their details: for example, some authors use simple note cards to capture concepts one card at a time [15,48], while other authors recommend using oval cards to avoid "rectangular" thinking [58] or use lists of concepts during knowledge activation [23]. Some authors capture causal connections and their weight in the same step, whereas others believe this to be too cognitively demanding and do it in sequence. Some authors recommend to support cognitive mapping and modeling of FCMs with software, such as the Banxia company's Decision Explorer®, and, specifically for FCMs, Mental Modeler [61], and FCMapper (www.fcmappers.net). Differences furthermore exist in the extent to which respondents interact with the interviewer and each other: Özesmi & Özesmi [23] describe a process in which the interviewer and the respondent build the cognitive map in a face-to-face meeting, whereas Jetter uses an approach with limited interactions between the interviewer in the respondents, who are instead guided by written instructions and questionnaires [15]. Kok and van Vliet, on the other hand, use a workshop setting, facilitated by the FCM modeller, in which the respondents communicate about their ideas and draw a group cognitive map together [1].

The arguments for and against particular cognitive mapping approaches fall in three broad categories, namely practicability, facilitation of learning, and validity of results. Face to face interviews, supported by cognitive mapping, help respondents to carefully think through their own mental models. Without peer pressure, respondents can take time to question assumptions and articulate knowledge that they may not even be fully aware of themselves. The interviewer can coach them through this process. He can furthermore use multiple interview techniques or
questions to validate responses and make sure that he completely captures the worldview of the respondent. A main downside of interviews is practicability: they are time consuming, require substantial effort by skilled interviewers, and require post processing because most FCM projects aim to come up with one [3,15,23,49] or very few FCM models [1] that integrate the knowledge of multiple respondents (see section2.3.2). If poorly conducted, interviews may also lead to a distortion of responses, e.g. because the interviewer subconsciously imposes his own worldviews or because the respondent wishes to please the interviewer. To avoid these problems interviewers have to provide transparency and gain respondents’ trust so that respondents actively correct interviewers’ misconceptions and openly share their mental models. Respondents should furthermore validate each transformation step (e.g. from interview to interview transcript and from transcript to causal map) as a correct representation of their ideas through so-called “communicative validation”[59].

Proponents of creating cognitive maps in a group setting point out that individuals benefit from new ideas and insights gained from other respondents. The joint mapping process may thus facilitate a higher-order learning that is impossible to achieve in individual interviews [62,63]. It can also improve the buy-in of the group into the mapping results. Group cognitive mapping furthermore has practical advantages: it requires fewer contact hours between interviewers and respondents and directly results in the integrated map needed for most FCMs. Since a large number of concepts and connections are under discussion, the resulting cognitive maps, however, can be messy and difficult to understand for respondents and modellers alike [15,58,62] and may only be able to provide a fast "first stab" at a problem that subsequently needs to be analyzed in more depth [1,58]. Furthermore there are some concerns about the validity of the models as a representation of the group’s cumulative knowledge: During the group session, the average time allocated to each participant is limited, leaving some participants with little opportunity to voice their views [58] and limited means to double check that the group map correctly captures their input. The problem grows with the size of the group, which is why Eden and Ackerman limit the size to up to 14 participants. Group members
may furthermore fail to pool group members' partial knowledge because they have the
tendency to predominantly communicate about commonly shared views and insights and to
address differences only reluctantly[64]. If the group session is not skilfully facilitated, the
problem could be aggravated by hierarchical distance or overwhelming personalities of some
group members [58]. To balance the advantages and drawbacks of individual cognitive
mapping and group meetings approaches can be mixed.

2.3.2 Integration of Individual Cognitive Maps into an aggregated model

To mathematically aggregate cognitive maps, the individual cognitive maps are translated into
square adjacency matrices of the same size, added, and divided by the total number of matrices
[18]. This operation results in a new matrix, the entries of which are the average of the edge
weights assigned by experts. Outlier opinions are thus preserved in the combined cognitive
map, but given little weight. When determining average edge weights, FCM studies typically
treat all respondents as equal [23,65], but to make allowance for different levels of expertise,
credibility weights can be assigned to experts [9], either through subjective judgment of peers or
through the use of proxy measures, such as years or experience or by comparing system
behaviour that is encoded in the expert FCM to the behaviour of the FCM of other experts' [65].
This practice is in line with the tradition of knowledge engineering, which aims to capture the
knowledge of recognized experts to make it available to other people. In participatory studies,
however, that equally value the input of all responds, it is not applied. The mathematical
integration of individual cognitive maps requires some upfront work, such as the clarification of
concept meanings and standardization of concept names. Furthermore, when respondents
characterize the same concept as concept and dis-concept [5] (e.g. "political stability" and
"political instability") one of the concepts needs to be converted. To preserve the direction of
causality, the converted concept's connecting arrow needs to be changed to the opposite
direction. To achieve standardization and integration, Özesmi & Özesmi [23] propose
qualitative aggregation, which combines the concepts mentioned in individual cognitive maps into categories that represent a larger encompassing variable. Integration can be supported by analytical methods for comparing cognitive maps and identifying areas of agreement and disagreement among the respondents [66]. Furthermore, a simple form of text mining was found to be useful for creating a standard dictionary that contains key concepts and their synonyms [15].

The question whether to mathematically integrate individual cognitive maps is subject of debate: If one respondents causally connects concept A and B with a + sign and another respondent connects the same two concepts with a - sign, mathematical aggregation delivers 0. Information on the one aspect that both respondents agree on - that there is a causal link between the two concepts - is thus lost. In a wisdom-of-crowd scenario, where many diverse respondents obtain knowledge and make judgments independently [67], this may not pose a problem: across all inputs, the causal connection that best represents the real-world will prevail and incorrect assertions will simply be noise. Some current FCM research accordingly employs data-driven learning algorithms [21,30,68] that can improve initially crude FCM structures and poorly adjusted weights. Most FCM studies, however, do not employ crowds but have a very limited set of data points and may well lose important insights through aggregation. Research on the subject is currently limited: Jetter [15] found that a mathematically aggregated map, created from the individual maps of eight respondents, modelled behaviour that was expected by the respondents, whereas the map obtained from the same eight respondents in a group meeting generated system states that seemed illogical to the group. The mathematically aggregated map moreover contained more concepts and more connections than any of the individually generated maps used for the aggregation, as well as more concepts and connections than the group-generated map. However, its network density of 0.047 - the ratio of the number of connections in the network over the total number of possible connection - is slightly lower than the density of the group-generated, aggregated map (0.059). This may be interpreted as an undesirable loss of information on connections, as an desirable focus on the smaller number of
connections that truly matter, or as a non-issue because all maps are relatively sparse and the loss in density is small. Given the limited state-of-the-art, mathematical aggregation of individual maps, modeller-generated integration of individual maps, and group generated cognitive maps all seem viable approaches to pooling the knowledge of individual respondents.

It should be noted, however, that total integration is not necessarily the aim. Kok and Van Vliet, for example, chose to preserve different worldviews for a scenario study and kept the very different cognitive maps of two groups separate, instead of merging them, even though they covered the same topic [1]. The same approach can be applied to individual maps: When diversity of opinion is important, such as in FS, respondents with "outlier" opinions can be explicitly asked to participate in the group discussion and their contrasting map can be used as stimulus.

2.3.3 Start Concepts for Knowledge Activation and Standardization of Concept Names

Respondents can only express knowledge that is available in their short-term memory. Cognitive mapping therefore needs to start with a dedicated knowledge activation steps. This can occur by providing a list of clearly described key terms that are relevant to the problem domain as a stimulus [62]. One approach that combines pre-defined key concepts and brain writing was tested by Jetter [15]: Respondents receive two-sided note cards that contain key concepts that are at the core of the knowledge domain or represent a critical (target) concept. The critical concepts to include in the note cards can be identified upfront by identifying the modelling project’s objectives. Furthermore, a simple text mining approach that identifies the most frequently used topic-specific words in a text corpus about the subject matter can be used. The front of each note card names so-called start concepts that are highly relevant for the knowledge domain and gives a short explanation of its meaning. Start concepts that can have different qualities are expressed as adjective and noun ("good parenting" not just
“parenting”) to avoid confusion about the sign of the causal relationship when respondents place concept cards in causal cognitive maps. The back of the card lists synonyms for the concept. In the brain writing step, respondents are asked to add as many additional concept cards to their pile of start concepts as possible. In the subsequent step, they review their cards, combine similar concepts, get rid of duplications, and edit the cards so that they are in the “adjective and noun” format. Throughout the process respondents are reminded that they should not feel obligated to use all start concepts provided and should feel free to add or drop concepts at any time.

Alternative approaches to knowledge activation are the presentation of initial causal models or guided discussions with respondents. The largest pitfall of knowledge activation is to take it for granted and either completely or partially skip it, which severely limits respondents’ ability to express their knowledge.

2.3.4 Capture of Concept meanings

To enable standardization and integration of the concepts mentioned by individual respondents, concept meanings needs to be clear. For many respondents, providing meaningful, non-trivial definitions to clarify concept meanings can be very challenging. One practical approach adapted from Smithin [69] was tested by Jetter [15]: respondents are asked to provide synonyms (or “related words”) for their concepts, as well as words that they consider to be in sharp contrast to the concept. Instructions should point out that the synonyms and antonyms do not have to be logical in the way an encyclopaedia would require, but should be chosen to illustrate the expert views. For example, in a case study on right-wing extremism, a respondent who included “unemployment” as cause for extremism, used “lack of things to do” as synonym and “self-actualization” as an antonym, thus indicating that, in his model, he was less interested in the economic than in the psychological toll of being unemployed.
The effort that should be put into the clarification of concept meanings depends on the nature of the FCM project: Teams of experts sometimes find it easy to communicate because they already share domain specific frameworks and terminology, while respondents with more diverse backgrounds can encounter difficulties. For example, Goodier et al. [62] report that a scenario study with participants from multiple organizations was complicated because discussions frequently focused on "loose or nebulous terminology"[62]. They therefore recommend explaining unclear terms or avoiding them all together. In an interactive workshop setting, clarification of terminology can occur through a plenary discussion during which participants can communicate effectively before each concept is defined in detail and the exact nature of concepts is captured. Most workshops devote about half of the total time on finalising a commonly agreed upon list of concepts. Yet, care should be taken not to focus too much on reaching a complete and shared verbal description of what the concepts represent because discussions on details can turn into an unproductive debate on semantics that is of little value to the participants. Skilled and knowledgeable facilitation can correctly guide this process. If individual maps are mathematically aggregated, however, a more formal approach may be required to ensure that only those concepts are combined that reflect the same ideas.

2.3.5 Spatial organization of concepts

To elicit causal knowledge structures, most FCM studies ask respondents to arrange concepts on a work surface (whiteboard, desk, paper, or computer screen) and to move, drop, and add cards and add causal links between them until they are satisfied with the layout. The literature recommends that respondents spatially organize their concepts [59], but does not provide clear recommendations where to best place them. Özesmi & Özesmi suggest to place all concepts in the centre of the workspace[23]. Jetter [15] found that this can invite respondents to connect "everything with everything" and lead to causal links that are artefacts of the knowledge elicitation process, rather than a part of real mental models. She recommends to place the target variable on the right hand edge of the workspace and all influencing variables on the left
because it seems that the resulting cognitive maps are more focused on the core issues and connections [15]. Her recommendations are in line with practices employed in the context of cognitive mapping for scenario generation [62,70,71]. Future research has to show whether either of these approaches leads to objectively better maps.

2.3.6 Signs and weights for causal links

Once causal links between concepts are established, respondents add concept signs (+ or -) to indicate positive or negative causality. Respondents predominantly map out simple positive causal relationships [15] and even experienced respondents have difficulties with "u-shaped" causal links and other non-linear functions, which are sometimes proposed to capture complex causality, such as diminishing and negative returns ("Fertilizing the field increases yield until it is too much and over-fertilization damages the soil"). Since "U-shaped" causality can usually be expressed in a linear fashion ("Fertilizing the field increases yield, over-fertilizing the field decreases yield"), it seems advisable to limit the cognitive strain on respondents and only offer positive and negative linear causality as a modelling option.

Once the type of causal link is defined, respondents give causal weights. This can be done by using a qualitative scale with three [23], five [22], or seven items [1]. The items translate into simple graphical symbols, such as ++ very strong, + strong, 0 medium, - weak, -- very weak [15,22] or +++ (strongly positive) to --- (strongly negative) [43]. Alternatively, the respondents can give numerical values for link strength in the range of [-1;1]. A potential practical problem is the tendency of stakeholders to use quantitative information that is available to them to parameterise part of the system’s relationships. For example, a respondent who knows the price elasticity of demand and works on an FCM that contains price and demand, may find it straightforward to assign the elasticity value as an edge weight between the two concepts. Yet, in principle, all values in the FCM are relative to the other values, and quantitative information on a number of arrows has to be converted to the same scales that are
applied to other causal links. It is therefore advisable to focus respondents on purely verbal scales, though it is theoretically possible to include information on known relative measures, such as price elasticity.

2.3.7 Capture of knowledge on the dynamic behaviour of the system

Knowledge capture should provide information on how the respondents expect the system to behave dynamically, at least for key variables that are well understood. This knowledge, which is characterized as “dynamical hypothesis” in the Systems Dynamics literature [46], is used in later stages of the FCM-modelling process to test if the FCM model’s system behaviour reflects the respondent’s expectations. Furthermore, thinking about the dynamic behaviour of the cognitive map model may lead to additional respondent insights, such as the realization that feedback loops exist or important concepts are missing. Dynamical hypothesis can be captured by asking experts how the system has evolved in the past (“Why do you think this problem has come up?”, “How different is X from what it was a year ago? Why?”) and how they expect it to change in the future.

2.4 Post-processing: Model adjustment

The causal maps that are generated during cognitive mapping need to be translated into adjacency matrices in order to create an FCM model. However, the initial FCM as drafted by stakeholders frequently needs to be adjusted to enable proper FCM computation and meaningful model interpretations. This may entail deleting relationships, adding relationships, renaming concepts, and/or introducing dummy variables. Potential pitfalls are too little care for post-processing, as well as post-processing without sufficient involvement of respondents - both practices can lead to the creation of FCM models that do not reflect the respondents’
knowledge of the system and its behaviour. Typical problems and strategies to prepare the data for the subsequent modelling steps are discussed in the following sections.

2.4.1 Disregard for Model Boundaries

Reaching a complete and detailed agreement between scientists and respondents on what is part of the system and what is not is crucial and needs to be discussed before starting the exercise. Because the issue is generic and applies beyond the construction of FCMs, we do not discuss it further here. In general when respondents include concepts that are excluded in the model boundary chart or link concepts to exogenous variables, these concepts and causal links must be deleted.

2.4.2 Definitional or overly detailed causal links

Respondents sometimes explain those aspects of the knowledge domain that they consider particularly important or difficult to understand in much greater detail than other areas. A respondent, who believes that “concept A” (e.g., “demand for cars”) directly causes “concept B” (e.g., “total sales of cars”) but assumes that this causal relationship is not self-explanatory is likely to add concepts in between and/or additional paths (see Figure 1).

![Figure 1: Causal map with definitional concepts](image)
When the concept to the far left “fires” (the demand for cars increases), this impulse reaches the next two concepts (demand for new and used cars) with delay and possibly at a point when other influences on them have already weakened. Causal maps therefore have to be checked for potential definitional causal links: when they are strictly definitional they need to be eliminated (here: eliminate “demand for used cars” and “demand for new cars”). When they are intended to express causal impact on a specific, single concept, they can be organized in a so-called “nested” FCM [20]– a sub-model that is calculated separately and delivers an input value for the state vector.

2.4.3 Use of Diagnostic Variables

Respondents sometimes include concepts in their causal maps that have no “Out”-arrows, even though they are clearly not a target concept. This is usually an indicator for incomplete or faulty knowledge capture. In some cases, however, these concepts are diagnostic variables – they are causally connected to the same concepts that influence the target concepts, but independent from the latter and give information about the state of the system. If chosen wisely (diagnostic variables should reflect readily available, objective information), they can give valuable information for the calibration of the FCM. In one study [15], one respondent e.g. considered right-wing extremism (= target concept) to be part of the same general trend that causes violence among teenagers (= the diagnostic variable, easily traceable through crime statistics). Both concepts need to change in the same direction if the FCM’s dynamic behaviour is to correctly reflect the respondent’s worldview.

2.4.4 Conditional Causality

Some causal relations are conditional: Concept A (“Rain”) and Concept B (“Temperatures below 0 C°”) cause Concept C (“Slippery road”) to happen. FCMs need to reflect this either by making sure that the threshold of the activation function of concept C can only be met by A and B
together or by creating a nested FCM that decomposes the concepts in sub-concepts (e.g. 
"temperature" is decomposed in "high temperature" and "low temperature") and thus shows a
more differentiated system behaviour [20]

2.4.5 Time-lags

If respondents draw causal links with very different timeframes, such as months versus years, these time frames have to be synchronized through so-called "dummy concepts" [72]. These concepts are inserted in the more long-term causal link to break it up into several causal links with shorter time-frames. Sometimes mismatches in timeframes are even larger and slow variables like climate change are found along relatively fast variables like policy change and road construction. In these cases, re-opening of the discussion on the meaning of concepts (see Step 2.3.4) is needed. This can, for example, result in a renaming of 'climate change' to a faster variables like 'drought'.

2.5 FCM Calibration and Testing (Step 4 & 5)

The objective of FCM modelling for FS is not to create a "true" model, but a useful and formalized description of the perception of a group of people, such as subject matter experts or stakeholders, of the problem at hand. As such, Sterman’s comments about Systems Dynamics models are also applicable to FCM: "The word validation should be struck from the vocabulary of modellers. All models are wrong, so no models are valid or verifiable in the sense of establishing the truth" [46]. The benchmark for FCM "validation" should therefore be if it adequately describes what the respondents know about the subject matter, which requires them to take a active role in model testing. However, due to cognitive limitations in the face of complexity, respondents may have difficulties to infer the dynamic behaviour of systems even if they know these systems very well [73]. It is therefore well possible that a FCM that perfectly represent a respondent's mental model shows different dynamic properties than what the
respondent can infer from his own knowledge. Quantitative models are frequently recommended because of this ability to uncover far-reaching and long-term effects in complex systems that are not visible to human decision makers [46,74], but testing them is challenging. In the absence of reliable external reference points, such as the FCM model’s fit with historic data or accepted truths, FCM testing should focus on making the model transparent to the respondents and discussing model insights with them. This typically occurs in three steps: calibration, which leads to models that can be run and that demonstrate expected system behaviour for simple cases, model testing, which looks at the model behaviour in more extreme and unexpected cases, and ongoing model use and modification.

To calibrate the FCM model a “simple” cognitive map with bivalent nodes, trivalent edges [18] and the same binary activation function in all concepts is designed. Its system behaviour is tested for a few well-understood cases, which are expressed in the dynamic hypothesis captured from the respondents during knowledge elicitation. If the conceptual FCM’s dynamic behaviour does not match the basic behaviour of the modelled system, mistakes in the structure of the FCM, such as missing concepts and links need to be identified.

Once the FCM is calibrated, it can be fine-tuned by applying causal weights and more sophisticated activation functions, such as sigmoid functions [19]. Also, individual output functions for each concept can be chosen. However, there are good reasons to keeping it simple: the vast majority of FCM publications use simple FCMs, even for complex problems, but nevertheless report valuable insights through FCM modelling [20,23,75,76]. Also, FCM modelling is most useful when other, more refined methods fail: in broad knowledge domains with only partial experts, in situations with little or no relevant historic data, and in cases where most information is qualitative and fuzzy. A potential pitfall for modellers is to forget this and attempt to create overly complex FCM models, when the time would better be invested in more sophisticated modelling techniques.
When the model is completed, it needs to be assessed if its behaviour is plausible and of predictive value in more complex cases. Input vectors for these model tests can be chosen to reflect a particular situation or policy choice decision makers want to investigate [9], or selected to test the impact of important concepts [22,23]. The latter surface through the structural analysis of the FCM, which identifies active, passive, critical, and dampening variables [77] and transmitter, receiver and ordinary variables [7]. Alternatively, a Wilson matrix can be employed [2]. Furthermore, the model's meta-rules can be identified experimentally by randomly varying input vectors [18,20], or - if only binary input functions are used and input states are never clamped - through an analytical approach [78].

At this stage, a disagreement between the FCM model's behaviour and the behaviour that the respondents expect of the model can lead to important insights and does not have to lead to modifications of the model. Instead, respondents may gain insights into their own mental models and accept the model results. Conversations between the modeller and the respondents are a powerful means to help decide if the unexpected behaviour is an FCM model flaw or if the modelled system can be expected to behave that way. In addition, a variety of tests from Systems Dynamics can be applied to FCMs, such as the boundary adequacy test (a test for the adequacy of problem framing), the structure assessment test (a comparison of the model structure with the structure of the real-world problem), the extreme conditions test (a test if extreme parameter values lead to irrational behaviour), and sensitivity analysis (a analysis of concept values, system behaviour and model recommendations when inputs are varied within their plausible range) [15].

The main pitfall when using calibrated FCM is the temptation to see their predictions as the truth about how the future will unfold, when what they truly provide are alternative and often competing ideas on ways in which it may unfold.

2.6 FCM model use and interpretation (Step 6)
The steps for FCM modelling above are applicable to any FCM modelling project that relies on the capture and integration of knowledge from multiple respondents, such as stakeholders and experts. FCM model use, however, differs from FS project to project and no general conclusions can be drawn. Kok and others [1,32,79] employ FCM models as a crucial stepping stone between qualitative story lines and quantitative models and additionally find the method to be well-suited to study feedbacks and test unintended side effects of various policy interventions. The alternative system states uncovered through FCM simulation are used as the basis for further discussion, contrasted against stakeholder opinions, and compared to already existing scenarios in order to provide the input for quantitative scenarios. As such, FCM models are a bridge between the richness of the stories and the quantitative complexity of the models, but by no-means a standalone method. Jetter and Amer [2,3], on the other hand, use FCM models to generate raw scenarios, a subset of which are chosen and subsequently further described in scenario narratives. FCMs are thus the main method for scenario generation. The resulting scenarios are used as a standalone output or as an input for the generation of technology roadmaps. Murungweni et al. [38] take yet another approach: they use FCM models to describe alternative means (e.g. cattle-based or crop-based) to achieving a livelihood in rural Zimbabwe and run these models for three climate change scenarios in order to identify their impacts on rural livelihoods. Similar studies that test scenario impacts with FCMs, rather than generating FCM-based scenarios, have also been done in a business setting, e.g. to see how different business models play out against the backdrop of different possible future states of the business environment [80]. FCM modeling thus offers a wide range of possibilities for the field of FS.

3 DISCUSSION AND OUTLOOK

When they were originally invented, FCM were intended to make complex political, economic, or social problems accessible for a wider audience. Kosko was so convinced of the benefits of FCMs that he predicted in an interview that they would soon become prevalent: “I claim I can
take any article and translate it into a fuzzy cognitive map… In fact, the article does nothing but flesh out the cognitive map. So the prediction is that soon you'll see political articles on the op-ed page, and then they'll have an appendix which is the cognitive map. A few years from now it will be just the reverse. The op-ed page will have the cognitive map and the words will be the appendix”[81]. In the foreword of Papageorgiou (2014), Kosko continues this argument stating that “Every book chapter or essay should have its own FCM instantiation”. Yet, as we argued in the introduction of this article, this vision did not become a reality: FCMs are still predominantly discussed in technical journals, rarely used to model complex human systems based on multiple perspectives, and are only beginning to be applied to the field of FS. What are the limiting factors? This paper identified an abundance of literature on FCMs, theoretically, conceptually, and practically. Yet, the paper also identified a lack of uptake by FS practitioners, possibly because FS approaches have a poor fit with the dominantly positivist research strategies in engineering and science, where FCM originate. Moreover, some FS audiences may find the technical nature of many FCM publications difficult. The paper therefore provided a stepwise overview of FCM practices and a discussion of common difficulties and pitfalls in every step, focusing on steps that are particularly important for FS.

However, some challenges for the use of FCM in FS remain. Most notably, it is undeniable that the capture and processing of respondent knowledge is time-consuming. FS researchers may therefore find it difficult to interest experts, who are scarce and usually in high demand to participate. Accordingly, studies with stakeholders are likely to overrepresent people with strong personal interests in the subject matter under study, thus possible distorting the insights gained. A potential solution to this problem is to obtain smaller chunks of knowledge from many more individuals that, taken together, provide adequate insights. As discussed in section 2.3.2, such a wisdom-of-crowds approach would take advantage of the fact that FCM can be easily aggregated and extended and are, according to Kosko [in foreword to 13], “natural tools to process big data”. There are downsides to such approaches (also discussed in section 2.3.2),
yet future research should investigate the potential of going beyond the relatively small number of participants in current FCM studies.

A second challenge lies in the fact that the future cannot be known. FCM models can consequently not be validated against or falsified by empirical observations until the future unfolds and the model has lost its purpose. While this true for all FS, it is particularly concerning for FCM modeling. It relies on multiple transformation steps that are difficult to retrace and that can give modelers undue influence. Moreover, FCM models are often an input into other approaches to FS, which can propagate errors even further. Finally, being a new method, FCMs do not yet enjoy high credibility among FS researchers and every poor implementation of it potentially challenges the method fundamentally. Building on the strategies outlined in this paper (especially section 2.3 and 2.5), future FCM research should therefore investigate issues of reliability and validity and more clearly report on its approaches for quality assurance.

A third challenge of FCM is the relative lack of knowledge about the fundamental dynamic aspects of FCMs, which separate them from regular cognitive maps and make them highly relevant for FS. Despite recent advances [35,e.g. 82,83] FCM researchers have few approaches, other than trial-and-error, to know if their model will reach a stable state, how many stable states it has, how to select squashing functions, and how to deal with temporal aspects. Moreover, the existing approaches are not yet commonly used by the FCM community.

Given the high level of recent activity in FCM research, it is likely that many of the challenges discussed above will be addressed in the near future. We hope that this paper can facilitate making FCM modelling acceptable and accessible to a wider audience within the foresight community at large.
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Fuzzy Cognitive Maps For Futures Studies - A Methodological Assessment of Concepts and Methods

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