Understanding Validity in Structuring Multi-Criteria Decision Problems

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Abstract

The first steps of multi-criteria decision making (MCDM) are typically the decomposition and structuring of the decision problem at hand. As all subsequent process steps of MCDM are based on the initial structuring of the decision problem, the validity of the structure representing the decision problem is of particular importance for the quality of the decision making process. This paper seeks to further develop our understanding of validity in structuring multi-criteria decisions. For this purpose, we link the structuring of decision problems in MCDM to the theory of chunking, which describes how human cognition structures and perceives environmental information. Based on this, we propose that the validity of models representing multi-criteria decision problems can be assessed by evaluating the degree to which they match the structures formed by chunking. We discuss a preliminary framework of how the match between the cognitive and the MCDM model can be tested. To demonstrate how this framework can be utilized in research practice, we apply it to empirically show that algorithmic, bottom-up structuring of MCDM problems leads to valid goal-criteria hierarchies.

Keywords

Multi-criteria decision analysis, problem structuring techniques, validity, chunking.

1. Introduction

Research into decision analysis seeks to improve human decision making by helping decision makers to make their decisions in accordance with principles of rationality (Smith & Winterfeldt 2004). While many decision making methods have been proposed, a common element underlying most approaches is the decomposition and structuring of decision problems. Structuring decision problems is an integral part of decision support because it provides essential tools to enhance human decision making. Structured representations of decision problems (e.g. hierarchies composed of decision objectives and criteria) increase the decision maker's (DM) understanding of the problem as well as his capacity to process information (Aschenbrenner et al. 1980; Forman & Gass 2001). Furthermore, such structures are useful for the implementation of so-called “divide-and-conquer” strategies, where a decision problem is divided into its components which are separately evaluated and then put back together to derive an overall solution for the decision at hand (Shanteau 1988). The basic idea underlying problem decomposition is that smaller parts of the problem can be more easily handled by human information processing capabilities than the entire problem at once. Accordingly, “divide-and-conquer” strategies are not only used by human experts (Shanteau 1988), but also in prescriptive decision making (Saaty 1990).

Due to these reasons, the first steps of multi-criteria decision making (MCDM) are typically the decomposition and the structuring of the decision problem at hand. These initial activities of MCDM are of particular importance for the accuracy (quality) of the resulting decision (Winterfeldt 1980; Saaty, 1990) because all subsequent process steps of MCDM are based on the initial structuring of the decision problem. Hence the structuring step has a significant effect on the outcome of the MCDM process (Brownlow & Watson 1987; Borcherding & Winterfeldt 1988; Brugha 1998).

Though the structuring of decision problems is a critical step within MCDM, there exists no agreed-on procedure for structuring MCDM problems. On the contrary, most problem structuring methods have been criticized for being “artistic” and lacking scientific rigor (Winterfeldt 1980). There are several reasons for this lack of scientifically sound structuring methods. First, only few methods for the structuring of decision problems have been proposed. Second, only little research tried to assess the quality of problem structuring techniques. This second reason might be related to a third one: it is neither clear what constitutes a “good” decision structuring method nor how the quality of a structuring method can be assessed.

Based on a literature review, at least four different quality criteria for structuring techniques can be identified. In quantitative research, and also in qualitative research, *reliability* and *validity* are essential criteria for quality. Reliability usually refers to the degree to which a measurement is reproducible and validity to the degree to which a measurement is truthful (Golafshani 2003). In the context of structuring techniques, W. Trochim (1989b) proposed that a diagram or map is reliably if it is “repeatable” and valid if it reflects reality. As diagrams are not ends in themselves but are used in applied research to improve decisions, *effectiveness* and *efficiency* are also important criteria (Maier and Stix 2013): A problem structure is effective if it improves decision quality and the diagramming technique is efficient if it requires little resources to generate a structured representation of the problem domain at hand. In sum, we might distinguish at least four criteria for assessing the quality of a decision structuring method: A good structuring method *efficiently* and *reliable* produces *valid* representations of decision problems, which increase decision making *effectiveness*.

While all these quality criteria are important and hence deserve attention, this paper focuses solely on validity. The problem of validity in the context of decision structuring is that there is usually no “physical reality” which we try to represent with a diagram. If the validity of a diagram is the degree to which it reflects reality and there is no physical reality to compare with, how can we assess its validity? Moreover, what should a diagram actually represent if there is no physical reality to model?

The purpose of this article is two-fold. First, we aim at answering the questions raised above. That is, we will discuss what a problem structure in MCDM should model and, building on that, how the validity of a diagram can be assessed. Second, we apply our approach for testing validity to the structuring technique proposed by Maier and Stix (2013). This allows us not only to assess whether this technique leads to valid goal-criteria hierarchies for MCDM but also demonstrates how the framework presented in this article can be utilized in research practice.

The remainder of this paper is structured as follows. The next Section discusses the theoretical background of structuring MCDM problems. This includes a discussion on the cognitive foundations of structuring decision problems, a short overview on how to structure MCDM problems and a preliminary framework of how the validity of diagrams can be assessed. Section 3 demonstrates how this framework can be applied. For this purpose, we assess the validity of two goal-criteria hierarchies, which had been constructed using the structuring technique of Maier and Stix (2013). Finally, we summarize the findings and list recommendations for further research in the last Section.

2. Theoretical background

In most multi-criteria decision problems, there exists no objective, physical structure which can be "measured" to construct a model of the decision problem at hand. Instead, the structuring of multi-criteria decision problems focuses on modeling cognitive representations of decision problems, or on facilitating the construction of such cognitive representations. Therefore, any approach for assessing the validity of decision structures must be based on a theory of how decision makers mentally structure their environment. Different theories have been proposed which aim at answering this question (Gobet 1998). Most of these theories have in common that they assume that humans form groups of related concepts/information pieces, which serve as basis for information processing. As these theories differ in details which are not relevant in this context (e.g. the degree to which these groups are held in long-term memory), we discuss only one of them, the *chunking* theory.

2.1 The cognitive foundations of structuring decision problems

Chunking is an important process of human perception, memory, learning and problem solving, and has been described as a key mechanism of human cognition (Gobet et al. 2001). As defined by Gobet et al. (2001) a chunk "is a collection of elements having strong associations with one another, but weak associations with elements within other chunks". Accordingly, chunking is the mental process of forming groups of related elements. These groups of elements are usually meaningful for the subject and may be named or unnamed. The process of chunking may occur deliberately (goal-oriented chunking) or unconsciously (perceptual chunking).

Chunking represents a strategy to deal with limited information processing resources. The amount of information, which humans are able to store in short-term memory, is limited. Miller (1956) proposed that humans are able to store 5 to 9 information pieces in short-term memory. Newer research suggests that human memory capacity is even smaller, about four information elements (Cowan 2001). Chunking allows humans to overcome this limitation of their short term memory. Instead of storing single information elements in short term memory, information elements are grouped and only group identifiers, the chunks, are placed in memory. If even the number of chunks exceeds the capacity of short term memory, the chunks can be combined to form higher-order chunks, leading to the formation of a hierarchy of chunks (see Figure 1 for a simple example of such a hierarchy). By keeping only the high-order chunks in working memory, an amount of information exceeding the working memory's capacity can be stored. For retrieval, the high-order chunks in the working memory are resolved. This way, chunking can increase the information humans can store and process (Egan & Schwartz 1979, Sakai et al. 2003).

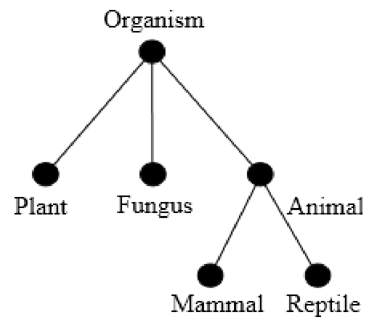

Figure 1: Chunks arranged in a hierarchical structure

Chunking is not only a strategy to deal with limited short-term memory, but is also related to the organization of long-term memory and to domain expertise (Gobet 1998). Regarding domain expertise, chunking theory aims at explaining how more knowledgeable individuals are able to extract more information from the environment than less skilled subjects, though they have the same information processing capabilities. This perspective on chunking assumes that experts have a large number of chunks related to their domain of expertise available in their long-term memory. This enables experts to rapidly characterize the information they perceive by directly linking perceptions to chunks in their long-term memory. Hence, experts are able to store, recall and process more information than novices because they have access to large amount of chunks, which enables them to process information on a more abstract level (Egan & Schwartz 1979). In sum, the research in chunking proposes that chunking is not only the mechanism underlying expertise, but also enables humans to increase their information processing capabilities without increasing their cognitive resources.

2.2 Structuring multi-criteria decision problems

In multi-criteria decision analysis, several methods have been proposed to capture the mental structures of decision makers. Many of these methods have in common that they rely on analysts (decision analysis experts), who work together with decision makers (domain experts) to create a model of the decision at hand. Usually, these processes follow a top-down approach, where a highly abstract overall-node/goal is broken-up into a group of more concrete sub-elements. This process is iteratively repeated for each sub-element, until the hierarchy is sufficiently detailed (see for example (Saaty 1990)).

Based on Trochim’s (1989a) concept mapping technique, Maier and Stix (2013) proposed a completely different approach for structuring multi-criteria decision problems, which resembles the bottom-up approach of chunking. Instead of relying on an analyst’s intellectual capabilities, skills and knowledge to structure decision problems, this process builds on group techniques, quantitative data analysis and algorithmic data processing for creating goal-criteria hierarchies. Its goal is not to simply capture a decision maker’s mental model of the decision problem, but to assist the development/improvement of the decision maker’s internal model. The process is organized in five process steps, where each step builds on the results of the preceding step to finally derive a hierarchical representation of the decision problem at hand. The individual process steps are usually conducted in workshops with a small number of participants. A facilitator guides these workshops but, unlike an analyst, does not contribute content. As this process serves as basis for Section 3, we shortly discuss each step in more detail:

Step 1 - Preparation: First of all, a qualified facilitator is selected. Then, the workshop participants are sampled from decision makers, stakeholders, consultants, etc. Finally, the brainstorming statement is prepared, which describes the problem domain as well as the intended contributions of the participants (e.g. generating a list of criteria relevant for the decision at hand).

Step 2 - Identification of criteria: In the second process step, a list of criteria is brainstormed based on the brainstorming statement of Step 1. Other techniques like document analysis or interview techniques can be used as well.

Step 3 - Structuring of criteria: The third process step aims at revealing the structure of the problem domain. For this purpose, a distance matrix D is constructed which reflects the pairwise relatedness between all criteria. Usually, card sorting procedures are used as easy-to-use and economic techniques to measure pairwise distances between criteria (for more information on card sorting procedures see (Rosenberg and Kim 1975)).

Step 4 - Automatic construction of a preliminary hierarchy: The fourth process step is the construction of a preliminary hierarchy. This can be done either by manually analyzing the card sorting data or by using the two-stage clustering described by Maier and Stix (2013) to convert the similarity data into a preliminary hierarchy. The algorithmic approach comes with the advantage that it is fast and avoids conflicts between participants.

Step 5 - Finalization of the hierarchy: In the last process step the criteria tree is finalized. The participants are asked to discuss the preliminary structure, to correct improper clusters and to agree on cluster names. The final output is a diagram in form of a tree which represents the hierarchical structure of the decision/problem domain.

2.3 Chunking theory as framework for assessing the validity of diagrams

Independent from the concrete method used for structuring MCDM problems, any structure of a multi-criteria decision problem should reflect or support the decision makers thinking about the given problem. Otherwise, the model might be more confusing than helpful and hence offset the advantages of decision structuring. Therefore, we propose that the validity of a diagram is the degree to which it reflects the decision maker’s mental model of the decision problem. That is, it should reflect the decision maker’s hierarchy of chunks representing the decision problem or domain. Accordingly, the literature on chunking provides a rich framework to test the validity of MCDM structures. In more detail, a test of a structure’s validity consists of a task which is performed by subjects, a number of measures to capture the subject’s (hierarchy of) chunks, and a benchmark structure, which is used to gather reference data. In the following, each of these components is discussed in more detail.

First of all, a task is necessary, which allows us to gather data about the subject’s internal model. In the literature on chunking, the most used tasks are recall tasks. For example, Gobet and Simon (1996) presented subjects chess positions, which they had to recall from memory. Other tasks which can be used include partitioning/grouping tasks, where the subjects are asked to form groups of related elements, identification tasks where several structures are presented and subjects have to identify the structure which best matches their inner model, copy task where participants are asked to copy an original structure which they can access as often as they want, etc. (see Gobet & Simon (1998) for an overview).

Several measures can be employed to gather information about the subjects' internal models based on task data. For example the sequence of actions while performing the tasks, timings of actions, counting measures or ratings can be used (Sakai et al. 2003, Gobet & Simon 1996). To give an example, in a task where participants are asked to recall a number of items, one could measure the sequence of items recalled (items within one chunk are more likely to be recalled one after the other than items from different chunks), the absolute number of elements recalled (as a measure of completeness of the internal model), the time span between two items recalled (it is easier and hence faster to consecutively recall two items belonging to one chunk than two items from different chunks) etc.

The problem with such measures is that they are only meaningful compared to some reference point. For example, imagine that a sample of subjects is able to recall in average 22 criteria out of 30 criteria arranged in hierarchy. As long as there is no reference point, one cannot say whether this is a good or a bad value. Therefore, either between-group or within-subject design are necessary, where benchmark structures are used to gather reference data. There are several ways to construct such benchmark structures. In the literature on chunking, random arrangements of elements often serve as reference point (Gobet & Simon 1996). A similar approach is to slightly change the original structure by randomly replacing some elements (Trochim 1989b). Another idea is the use two structures, which have been generated by two different structuring methods, to directly compare these two techniques (Trochim 1989b, Maier & Stix 2013). This approach can also be used for stepwise improving a structuring technique, by comparing several structures which have been generated by slight variations of one structuring method (Maida et al. 2012). Regardless of how the benchmark has been generated, these can be used in between-group or in within-subjects designs to test the validity of models representing multi-criteria decision problems.

3. Empirical experiment

In this Section we utilize chunking theory as framework to test whether the hierarchical problem structuring procedure described in Section 2.3 leads to valid representations of MCDM problems. The goal is not only to assess whether this method is an adequate procedure for structuring multi-criteria decisions but also to demonstrate how the presented framework can be applied for validating structuring techniques.

3.1 Method

We used the structuring procedure described in Section 2.3 to construct goal-criteria hierarchies for two MCDM problems: (1) an apartment selection problem and (2) a job selection problem. We used the same structuring approach for both test cases. The criteria were brainstormed (process step 2) by a group of four researchers. For structuring the criteria (process step 3) we asked students to pile the criteria into groups of semantically related items. Then we applied a two-stage clustering procedure proposed by Maier and Stix (2013) to construct hierarchies from the card sorting data. The last process step was omitted.

To test whether this procedure leads to valid structures, we adopted the idea that randomly altering a valid structure should reduce the degree to which it reflects an evaluator's mental model of the problem domain at hand. Therefore, one item of each criteria-cluster was randomly replaced by a criterion taken from another cluster. This was done separately for each test case. The original criteria clustering as well as the randomized clusters served as the basis for an online-survey. A link to this survey was sent to students and personnel of the Vienna University of Business and Economics. In sum (group 1 and 2) 208 subjects completed the survey. These participants were randomly assigned to two groups. The first group received the original structure of test case 1 and the randomized clustering of test case 2 and group 2 vice versa. This research design does not allow us to assess the validity of single clusters. This is because each cluster is compared only to one randomization. Hence, any observed effect on the level of single clusters might be due to chance. However, following a pattern matching approach, we can examine the validity of the clusters on a global level by assessing the pattern of the observed effects (Trochim 1989c).

Three different measures were used to assess the validity of the clusters. (1) The participants were asked to choose the criterion which is least related to the other criteria within the respective cluster. To explain the idea underlying this measure, imagine that item A of a cluster was randomly replaced by an item A'. If the original cluster is a valid grouping of criteria (a "good chunk"), then we expect that more participants in the program-group choose A' as least fitting criterion than participants in the control-group choose item A as least fitting criterion. (2) We measured the time the participants needed for identifying the "least related criterion". The assumption underlying this measure is that it requires less cognitive effort to identify such a criterion in a less valid cluster than in a more valid cluster. This is because in a less valid cluster there is at least one item which does not fit well the mental model of the judge and hence is easily identifiable as "least fitting criterion" for the respective subject. (3) Finally, we asked the participants to rate within-cluster homogeneity on a 5 point Likert-like scale ranging from very good to very poor. The idea here is that the participants respond to this challenge by assessing the degree to which the criteria within a cluster represent a reasonable chunk. Again, we expect that a randomized replacement of one criterion is likely to reduce a cluster's homogeneity and thus its validity.

To keep the research instrument concise, the validity of each cluster was assessed based on one to two measures. Table 1 provides an overview of the research instrument used in this study, which also provides details on which measure(s) was/were used for each cluster.

	Test case 1 (26 criteria in 6 clusters)			Test case 2 (32 criteria in 9 clusters)		
Group 1	Original			Randomized		
Group 2	Randomized			Original		
Measures	Cluster 1-3	Cluster 1-3	Cluster 4-6	Cluster 1-4	Cluster 1-4	Cluster 5-9
	Choice: Least fitting criterion	Time: Least fitting criterion	Judgment: Quality of clustering	Choice: Least fitting criterion	Time: Least fitting criterion	Judgment: Quality of clustering

Table 1: Experimental set-up

3.2 Results and discussion

Table 2 summarizes the results for test case 1. For each measure, it lists the observed values for the control group and for the program group, which test was performed to analyze the data, the resulting p-value and whether the observed effect is in the expected direction, independent from its significance. The validity of cluster one was assessed using the "choice measure" and the "time measure". 6 out of 121 participants in the program group chose the randomized item as "least fitting item". In the control group, 4 out of 91 participants chose the corresponding, non-randomized item as "least fitting item". Though a chi-square test did not find that this difference is significant, the pattern of the observed effect is in the expected direction (relatively more people in the program group chose the item in question as "least fitting item"). Also the t-test for the time needed to make this choice is insignificant, but in the expected direction.

As the validity of each cluster was tested only against one randomization, any finding on the level of single clusters might be due to chance. However, taken together, the measures allow us to assess the validity of the hierarchy on a global level. As can be seen from Table 2, 5 out of 9 measures for test case 1 are significant. Independent of their significance, all 9 measures show effects in the expected direction. Since such a pattern is unlikely due to chance, this indicates that the hierarchy of test case 1 is a valid representation of the problem domain.

Cluster	Cluster 1		Cluster 2		Cluster 3		Cluster 4	Cluster 5	Cluster 6
Measure	Choice	Time	Choice	Time	Choice	Time	Judgment	Judgment	Judgment
Control Group	4 of 91 subjects	40.13 sec	8 of 91 subjects	36.07 sec	22 of 91 subjects	32.71 sec	2.23	2.31	2.21
Program Group	6 of 121 subjects	39.27 sec	17 of 121 subjects	32.81 sec	78 of 121 subjects	24.39 sec	2.98	2.66	3.21
Test	X^2	T-test	X^2	T-test	X^2	T-test	T-test	T-test	T-test
p-value	0.85	0.71	0.24	0.18	<0.001***	<0.001***	<0.001***	0.01**	<0.001***
Pattern	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table 2: Results of test case 1

Table 3 summarizes the results for test case 2. As can be seen, 10 measures out of 13 are significant. Furthermore, 11 measures showed effects in the expected direction. In sum, this indicates that the hierarchical structuring procedure led to valid groupings of criteria for test case 2.

Cluster	Cluster 1		Cluster 2		Cluster 3		Cluster 4		Cluster 5	Cluster 6	Cluster 7	Cluster 8	Cluster 9
Measure	Choice	Time	Choice	Time	Choice	Time	Choice	Time	Judgment	Judgment	Judgment	Judgment	Judgment
Control Group	17 (of 121)	22.73 sec	5 (of 121)	29.89 sec	51 (of 121)	22.27 sec	6 (of 121)	23.85 sec	2.41	1.74	2.48	1.83	1.78
Program Group	45 (of 91)	23.59 sec	64 (of 91)	20.59 sec	67 (of 91)	19.23 sec	17 (of 91)	24.05 sec	3.11	2.29	2.86	3.3	3.16
Test	X^2	T-test	X^2	T-test	X^2	T-test	X^2	T-test	T-test	T-test	T-test	T-test	T-test
p-value	<0.001 ***	0.51	<0.001 ***	<0.001 ***	<0.001 ***	0.06	<0.001 ***	0.91	<0.001***	<0.001***	0.003**	<0.001***	<0.001***
Pattern	Yes	No	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes

Table 3: Results of test case 2

Taken together test case 1 and test case 2, the randomized replacement of criteria led to significant effects in the expected direction for 15 out of 22 measures. Independent of their significance, 20 out of 22 measures showed effects in the predicted direction. In sum, these findings suggest that the process for structuring MCDM problems proposed by Maier and Stix (2013) led to valid clusters of criteria.

4. General discussion and conclusion

In this article, we have argued that structures for MCDM should reflect the decision makers' internal model of the decision problem, or at least assist them in developing/improving such a model. Accordingly, we have proposed that chunking theory provides an adequate framework for assessing the validity of models representing multi-criteria decision problems. We applied the framework for empirically assessing the validity of two goal-criteria hierarchies, which have been constructed using the structuring technique of Maier and Stix (2013). This demonstrated not only that chunking theory is a useful framework for assessing the validity of models representing multi-criteria decision problems, but also how the framework can be utilized in research practice. Furthermore, the outcomes of this study show that the structuring technique of Maier and Stix (2013) produces valid representations of multi-criteria decision problems. However, as the analysis presented in this article is limited to two test cases and to clusters on the lowest level of the two goal-criteria hierarchies, further research is necessary to establish external validity of this finding.

This article raises plenty of interesting areas for further research. For example, the framework presented here is based on only a small fraction of the literature on chunking and cognition in general. Further research might analyze and integrate this literature to extend the preliminary framework presented in this article. Future research might also utilize the framework presented in this article to compare different structuring techniques regarding their ability to generate valid models, which could help to advance the structuring of multi-criteria decision problems from art to science. Such descriptive research would lay the basis for analytical research, which could aim at exploring why certain structuring methods produce more valid structures than others. In the long run, such a research effort might result in a theory of how to design methods for structuring multi-criteria decision problems.

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