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A Review of the Causal Mapping Practice and Research Literature

by

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A Review of the Causal Mapping Practice and Research Literature

Abstract

Causal maps are an essential tool for operations managers. In the operations management literature, causal maps are known under many names, including Ishikawa (fishbone) diagrams, impact wheels, issues trees, strategy maps, risk assessment mapping tools (FMEA*)* and, cause and effect diagrams. Operations management researchers often use causal mapping as a key tool for building and communicating theory, particularly in support of empirical research.

Causal maps are found in cause and effect diagrams for Six Sigma programs, in Failure Mode and Effects Analysis for risk analysis, in issue tree analysis for guiding consulting projects, in strategy maps for developing strategy, and in research papers for theory building and theory testing. Although causal maps are a widely accepted approach for analyzing critical relationships in a system, brainstorming and structured interviews are the only widely accepted approaches for capturing the information needed to build them.

This paper reviews the causal mapping management practice and research literature and emphasizes the important roll that causal mapping tools play in operations management. The paper then reviews the broader "cognitive mapping" literature and proposes a taxonomy for the literature and suggests opportunities for research.

A Review of the Causal Mapping Practice and Research Literature

1. Introduction

Causal maps are an essential tool for operations managers. In the operations management literature, causal maps are known under many names, including Ishikawa (fishbone) diagrams, impact wheels, issues trees, strategy maps, risk assessment mapping tools (FMEA*)* and, cause and effect diagrams. Operations management researches often use causal maps as a key tool for building and communicating theory, particularly in support of empirical research (e.g., Hays & Hill, 2001; Meyer & Collier, 2001; Narasimhan & Jayaram, 1998).

A causal map can be a useful tool for both practitioners and researchers in many ways. Some of these include:

1. *Diagnosis tool* – Can help the user identify and solve the possible causes of a problem.
2. *Communication tool* – Can communicate causal relationships effectively and efficiently.
3. *Risk mitigation tool* – Can help anticipate unintended consequences and mitigate risks.
4. *Control tool* – Can help identify the best location for metrics and controls.

A causal map should have the following five attributes:

1. *Parsimonious* – Shows no "synonymous" nodes and shows only the "important" arcs.
2. *Complete* – No important nodes or arcs are missing.
3. *Precise* – The definitions of the nodes that accompany the map are precise.
4. *Accurate* – The signs and values assigned to each arc are correct.
5. *Visual* – Similar nodes are close together and arcs do not cross unnecessarily.

The only widely accepted approaches for capturing cognitive data for a causal map are informal brainstorming (Pande & Holpp, 2001), formal brainstorming (Delbecq, Van de Ven & Gustafson, 1975), and structured interviews (Chmeilewski, Dansereau, & Moreland, 1998; Chmeilewski & Dansereau, 1998; Novak & Gowin, 1984). While these methods are effective in many contexts, the brainstorming methods require experts to meet together in a room at the same time (synchronously) and the interviewing methods require significant amount of time from interviewers.

This paper is structured as follows. The next section provides a brief review of many causal mapping methods used in the operations management discipline. The third section reviews the cognitive mapping literature and methods for extracting cognitive maps from experts. The final section concludes the paper.

2. Causal maps in operations management

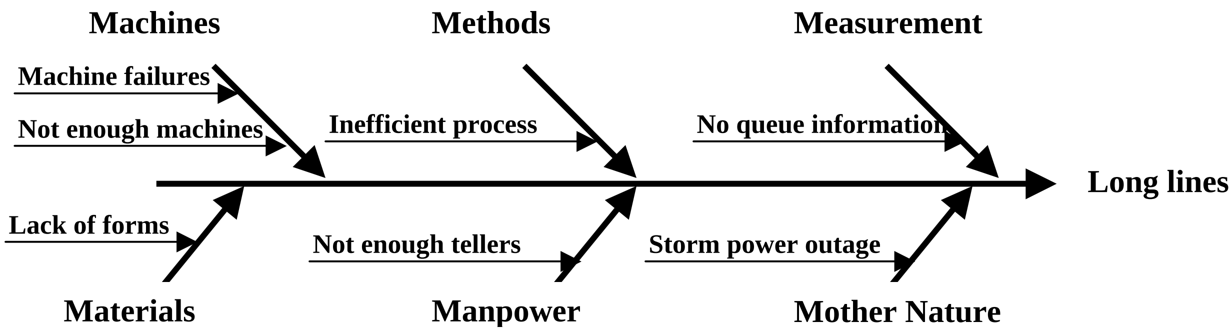
In the operations management practice and research literature, causal maps are known under several names, including (1) Ishikawa (fishbone) diagrams, (2) impact wheels, (3) issues trees, (4) strategy maps, (5) risk assessment mapping tools (FMEA), and (6) cause and effect diagrams. This section briefly overviews each of these six types of causal maps.

The first five of these are hierarchical and are like a “bill of materials” or an “organizational chart” for a problem, an impact, a project plan, a strategy, or a potential causes. The last mapping tools, cause and effect diagrams, is a network rather than a hierarchy, and can even be a cyclic graph with arcs that can form a chain.

2.1. Ishikawa (fishbone) diagrams

The Ishikawa diagram, also known as the fishbone diagram and root cause analysis, is a simple causal map developed Dr. Kaoru Ishikawa, who first used the technique in the 1960s (Enarsson, 1998; Kelley, 2000). The basic concept of the Ishikawa diagram is that the basic problem of interest is entered at the right of the diagram, at the "head" of the main "backbone." The possible causes of the problem are drawn as bones off the main backbone. The categories often used as a starting point include materials, machines (equipment), manpower (people), methods, Mother Nature (environment), and measurement. Other causes can be chosen as needed. Brainstorming is typically done to add possible causes to the main "bones" and more specific causes to the "sub-bones." This subdivision into ever increasing specificity continues as long as the problem areas can be further subdivided. The maximum practical depth of this tree is usually about four levels. Figure 2.1 provides a simple example for analyzing a problem with the length of the teller lines in a bank. As an Ishikawa diagram becomes more and more complex, it becomes more difficult to understand and use. Most quality management authors recommend using brainstorming methods to generate Ishikawa diagrams (Pande & Holpp, 2001).

Figure 2.1 A simple example of an Ishikawa (fishbone) diagram



2.2. The impact wheel

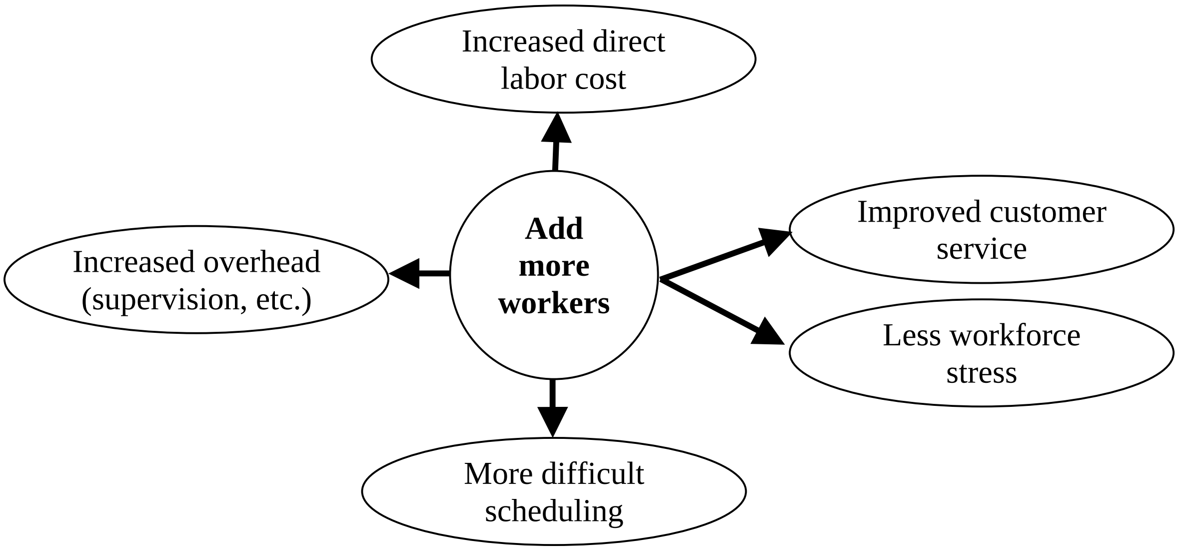
The impact wheel is a simple structured brainstorming approach designed to help managers fully explore the potential consequences of specific events and to identify consequences that they might otherwise fail to anticipate. One benefit of the impact wheel is that it can help managers uncover and manage both unexpected and unintended consequences of a decision. The impact wheel is used by many firms and government organizations and has been found to be a useful method for exploring the future (Anonymous, 2004).

The facilitator writes the name for the change, or event, in a circle in the center of the whiteboard and then engages the group participants in a discussion of three points.

- The inferences – The “impacts” of the change (drawn like spokes of a wheel).
- The probabilities – The likelihood (probability) for each impact.
- The implications – The cost and benefit of each impact.

The group then focuses on each impact and repeats the process. This approach can be supported by environmental scanning (to consider external issues), scenario development (to consider best-case, worst-case, status-quo, and wild-card scenarios), and expert interviews (to gain insights from subject matter experts). Figure 2.3 provides a simple example for the impact of adding more tellers for the bank.

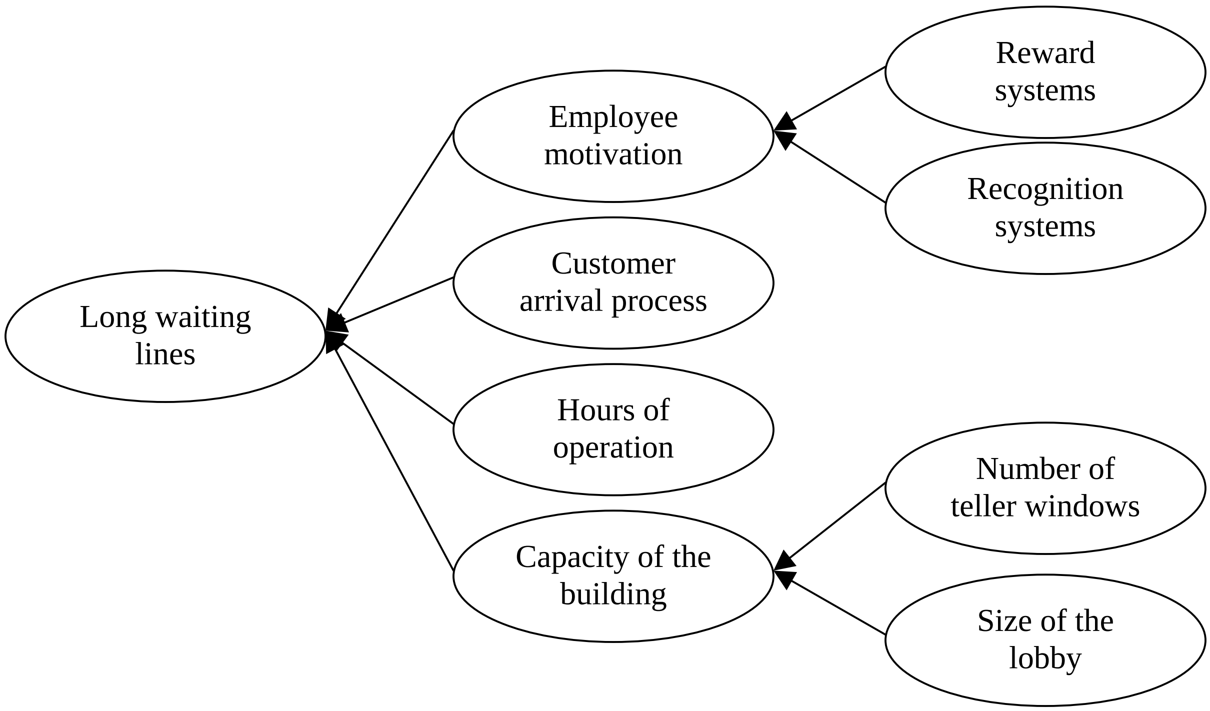
Figure 2.3 A simple example of an impact wheel



2.3. Issue trees

Consulting firms often apply a causal mapping tool called an issue tree analysis. The approach helps break down an issue (a problem) into its major components (causes) in order to create the project workplan (Miller, 2004). The approach usually puts the main issue on the left and then disaggregates the issue into smaller issues on the right. Figure 2.4 shows a simple issue tree example that "explodes" the bank waiting line problem into a set of sub-issues that might form the structure for a consulting project or at least enumerate the issues that the consulting project should consider.

Figure 2.4 A simple issue tree example.



2.4. Strategy maps

A strategy map is a causal mapping tool for developing and communicating strategy (Kaplan & Norton, 2000; Day, DeSarbo & Oliva, 1987; Kaplan & Norton, 2000; Oliva, Day & DeSarbo, 1987). Kaplan and Norton (1996) argue that a "strategy map" is a powerful tool for communicating the critical relationships needed to understand and implement a strategy. Strategy maps can also highlight the key metrics required to align the organization and monitor the execution of the strategy. Kaplan and Norton argue that the strategy map should focus on the few "balanced scorecard" metrics that drive the strategy to success. These metrics should be reported at a very high level in the firm.

2.5. Risk assessment mapping tools (FMEA)

Causal mapping is also a key tool for risk assessment and management (Hodgkinson, Tomes & Padmore, 1996; White, 1995), and is known by several names such as fault tree analysis (Fadier, De La Garza & Didelot, 2003; Jetter, Forte & Rubenstein, 2001), event tree analysis (Kumar, 2000), and Failure Mode and Effects Analysis (FMEA) (Davidson & Labib, 2003; Franceschini & Galetto, 2001). These maps are used to provide a systematic method for identifying all types of potential failures, their potential causes, and their consequences. These methods are beneficial in the design of a product and a process, in improving understanding of the system, focusing risk mitigation efforts, and identifying root causes of failures.

The most popular of these methods in practice is Failure Modes and Effects Analysis (FMEA), which is a systematic way of looking at process and product failure modes. The analysis begins with subjective estimates of Severity, Occurrence, and Detection, scored on a 1-10 scale. Severity is defined as the impact of the failure. (What is the impact in terms of cost, time, and quality of a failure?) Occurrence is defined as the frequency of occurrence. (What is the probability that this failure will occur?) Detection is defined as the organization's ability to detect the problem, chance of detection. (How good is the organization at detecting the failure so that if it does occur, it does not impact the customer?) Finally, the Risk Priority Number (RPN) is defined as the product of Severity, Occurrence, and Detection. Modes with high RPN indices are candidates for improvement and risk mitigation actions.

The risk assessment mapping tools listed above are related to decision trees, which are a special type of causal map that includes "chance nodes" to model random events. Influence diagrams take decision trees one step further by allowing for both decision and chance nodes to be continuous (rather than discrete) variables.

2.6. The cause and effect diagram

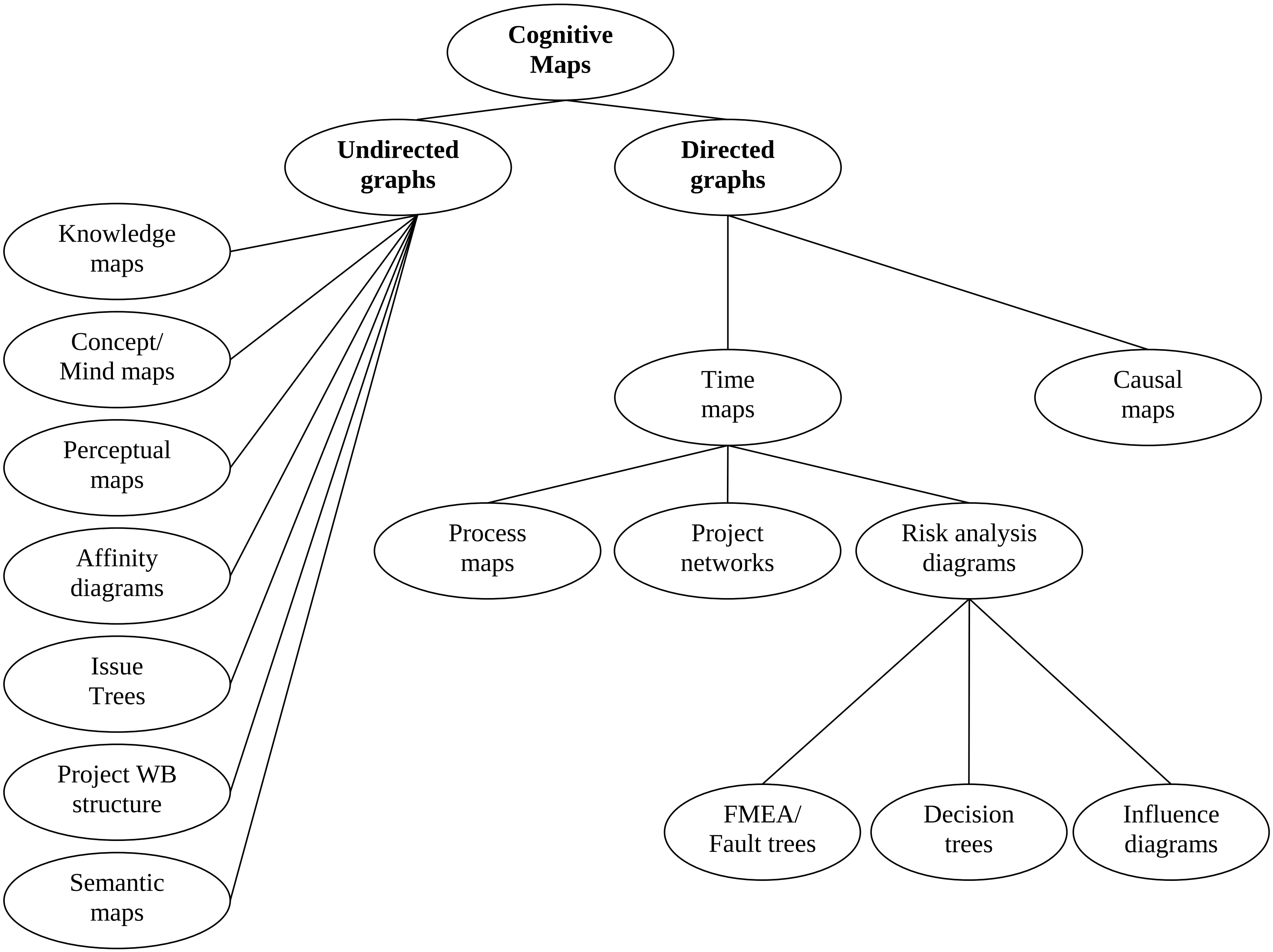
A cause and effect diagram is a causal mapping tool for quality improvement and plays a prominent role in quality management programs such as the Six Sigma program (Pande & Holpp, 2001). A cause and effect diagram is an extension of the Ishikawa diagram and is not constrained to the "fish" diagram (e.g., does not require any pre-defined structure and does not use the "M" alliteration to identify potential causes) and uses ovals to represent variables. Many popular books (Pande & Holpp, 2001) suggest asking the "five whys," which ask "why" five times in order to uncover the root causes of a problem. Goldratt's "current reality tree" (Goldratt, 1994) is a cause and effect diagramming technique that helps identify root causes. The diagram is unique in that allows for the creation of logical "and" between relationships leading into a cause. Most quality management authors recommend using brainstorming methods to generate cause and effect diagrams (Pande & Holpp, 2001). While brainstorming methods often create a hierarchical map, the methodology allows for any type of network diagram.

3. A review of the cognitive mapping practice and research literature

Our understanding of the causal mapping methods reviewed in the last section can be informed by the rich practice and research literature on the subject of "cognitive maps." A cognitive map is a representation of an individual's perception of a particular topic. A cognitive map can help an individual better organize, structure, and understand a topic. When multiple cognitive maps are combined into a collective cognitive map, the entire group can use the collective map to find differences and build a shared understanding of the topic. The act of building and debating the causal maps can help groups to convert tacit knowledge into explicit knowledge.

All cognitive maps have nodes and arcs, also known as "causal concept" and "causal connection," elements and beliefs, nodes and links, nodes and edges, and points and arrows. The nodes can represent a concept, variable, issue, entity, or attribute and can be represented by a single word, phrase, or paragraph. Nodes can include hyperlinks to additional information such as web pages or to other nodes. The arcs represent the relationships between the nodes. In mind mapping and concept mapping, arcs have a semantic label, which defines the nature of the relationship. Typical semantic arc labels include "belongs to," "when," and "because." Cognitive maps can be represented by either undirected or directed graphs (maps). Arcs for undirected maps do not have a direction and are represented by lines without an arrow; arcs for directed maps have a direction and are represented by arrows. For both undirected and directed maps, a value can be associated with an arc to represent the strength of the relationship between the nodes. Figure 3.1 presents a taxonomy of different types of cognitive maps.

Figure 3.1 A taxonomy of cognitive maps



3.1. Undirected cognitive maps

Undirected maps represent the degree of "connectedness with" or "belonging to" between the nodes. A good analogy here is a thesaurus, which shows the cross-reference structure for a particular topic. A thesaurus lists a word or a phrase along with other suggested terms, which can include synonyms, broader terms, narrower terms, related terms on the same level of the hierarchy (e.g., orangutans and monkeys), and antonyms.

Knowledge maps (Howard, 1989) are popular in library science and knowledge management. Mind maps are for individuals. Affinity diagrams are undirected maps that show the structure of the basic sub-topics within a larger topic and can be helpful in organizing a large number of ideas into natural groups. Affinity diagrams have contributed to knowledge representation of complex structures and are widely used in the social sciences and management practice and research literature as a method for organizing and describing data, determining boundaries, and categorizing issues. Issue trees, like affinity diagrams, disaggregate a topic, and intended to break down the topic into issues for further study. Lastly, the work breakdown structure for a project disaggregates a project into its major components to help project managers generate the list of tasks that need to be accomplished to finish the project.

A relatively new approach to creating a cognitive map is called "Centering Resonance Analysis" (CRA). The method begins with large amounts of texts (possibly from experts) and develops a semantic network of words based on how nouns and adjectives are embedded in noun phrases. Resonance is a measure of the similarity between two CRA networks. The measure of influence is based on the word/node's "betweeness centrality," a measure of how much discursive coherence it creates (Corman, Kuhn, McPhee & Dooley, 2002; McPhee, Corman & Dooley, 2002).

Marketing researchers often employ a mapping approach called "perceptual mapping," which is a form of an undirected graph that shows the relationships between products on a two-dimension plane (Hauster & Koppelman, 1979). Unlike other cognitive mapping methods, perceptual maps do not show any arcs. Perceptual maps attempt to display the nodes on a two-dimension plane so that the Euclidean distance is proportional to the psychological distance (similarity) between the concepts the nodes represent. Perceptual mapping techniques are used primarily in new product design, advertising, and marketing strategy to help marketing managers to better understand the cognitive dimensions that consumers use to evaluate products and their positions in the market relative to each other.

The term "Concept Maps" has been popularized by the Decision Explorer software (Chmeilewski, Dansereau, & Moreland, 1998; Chmeilewski & Dansereau, 1998; Cossette, 2001; Nicholson, 2000; Novak & Gowin, 1984). Concept maps can have either undirected or directed arcs and often have semantic labels associated with each arc.

3.2. Directed cognitive maps

Directed cognitive maps have arcs that measure the causal or influential relationships between the nodes. Directed cognitive maps can be of two basic types: time maps and causal maps. Time maps are ordered by time and include risk analysis tools (decision trees, influence diagrams, which allow for decision and chance nodes), process maps (which show the sequence of steps for a process with logical if-then conditions), and project networks (which show the sequences of tasks required to complete a project).

The focus for this paper is on causal maps. Eden, Ackermann, and Cropper (1992) suggested the word "cause" instead of cognitive to emphasize the difference in how the arcs are defined. Eden (1994) investigated the role of these maps in problem definition and highlighted the importance of feedback when many perspectives exist on a particular managerial problem.

Causal connections represent the experts' beliefs about causal relationships between the nodes. They show the antecedent-consequence relationships between two nodes by linking them with a unidirectional arrow from the antecedent (the one that causes) to the consequence (the one that is caused).

In most causal maps, the causal value for the arc is defined as $w_{jk} \in \{0,1\}$, indicating the non-existence or existence of an arc between nodes *j* and *k*. It is possible for cognitive maps to be cyclic graphs, with arcs that create a circuit, even between two nodes (e.g., $w_{jk} = 1$ and $w_{kj} = 1$), implying a feedback relationship. In some causal maps the causal value is some measure of the relationship (such as correlation) between the nodes (Nadkarni & Shenoy, 2003; New, 1992).

As any cognitive map, causal maps can also enable better understanding of a topic, but because they identify the causal relationships, they can also help to manage the system and investigate the consequences of actions. Obviously when working with groups, this understanding helps build a common language and shared meaning upon which negotiation and consensus can take place.

Causal mapping has been used extensively in strategy (Day, DeSarbo & Oliva, 1987; Eden & Spender, 1998; Kaplan & Norton, 2000; Oliva, Day & DeSarbo, 1987) and management science (Bouzdine-Chameeva, Durrieu & Mandajk, 2001; Clarke & Mackaness, 2001; Jenkins & Johnson, 1997b; Williams, Ackermann & Eden, 1997).

Words such as "if–then," "because," "so," "as," and "therefore" are used as causal connections. The causal map can be represented as either a diagram or as an association matrix.

For N nodes, the association matrix is the set of causal values for all "from-to" pairs of arcs $\{w_{ij} \mid i = 1, 2, \ldots, N;\ j = 1, 2, \ldots, N\}$.

3.3. Eliciting data for causal maps

Like other types of cognitive maps, causal maps are "extracted" from expert opinion. Two different approaches are commonly used to capture the data for a collective (group) causal map – group brainstorming (structured or unstructured) and interviews.

Group brainstorming can be accomplished through a structured group workshop using methods such as the nominal group technique (Delbecq, Van de Ven & Gustafson, 1975; Hegedus & Rasmussen, 1986). In some cases, visual interactive modeling is used to help each individual in the group to explore his or her own thinking and how it relates to other group individuals' thinking, gain a better understanding of how other group individuals' perceive the world/situation, and from this position begin to negotiate a way forward. The maps are transparent to the group working with all of them and allow the group/individual to be able to manage complexity.

Another approach for capturing cognitive data for causal maps is to use one-on-one interviews (Jenkins & Johnson, 1997a). In-depth qualitative and open-ended questions are posed to the experts to obtain raw data in the form of narratives. The interview process follows either a deductive (Newstead, Handley, Harley, Wright & Farrelly, 2004) or an inductive approach (Daniel, Wilson & McDonald, 2003). In the deductive approach experts use a highly elaborate hierarchical top-down structure to approach and solve problems, while in the inductive approach experts use a bottom-up structure and have precise exemplars for many problems likely to be encountered (Fischer, 1998). Specifically, a deductive or top-down approach is best used when the type of data sought is highly structured with a clear pattern of relationships among concepts or items. In contrast, an inductive or bottom-up approach should be used in instances in which unstructured data is elicited. The unstructured data are subsequently revised to create a final causal map based on expertise and consensus among the experts. In the inductive or unstructured technique, the concepts emerge from the data or the narrative of the expert. This method is more exploratory in nature and is a less intrusive approach.

Using the inductive approach, a causal statement provided by an expert is broken down into its components by the study team. The causal statement links two different causal concepts through a causal connection and it builds the causal map through its narrative. The process of analyzing the causal statement is labor-intensive and time-consuming. Aggregation or identification of the causal concepts is the process of determining which part of the text to code, and what words to use in the coding scheme. The study team goes through the causal statement and identifies concepts that may be extracted from the exact words of the text or from coding those words into generalized concepts (Nadkarni & Shenoy, 2001). No mathematical criterion is available for determining the appropriate level of aggregation, but at least two coders should analyze the subset of raw causal statements in order to establish intercoder reliability and independently suggest the level of aggregation that is appropriate (Neuendorf, 2001). Through the coding process it is possible to determine the adequacy of the sample size and the point of redundancy, the point at which data collection does not lead to additional concepts or coding categories.

Another approach for creating a group causal map supposes that a group is considered as a sum of individuals who form the group, and a collective map presents an aggregation of patterns of personal knowledge of individuals forming the group (Bouzdine & Michrafy, 2000).

Bouzdine-Chameeva, Durrieu and Mandajk (2001) explore methods for comparing and aggregating individual causal maps into one collective map of a group.

4. Conclusions

Causal maps are central to operations management practice and research. In the operations management literature, causal maps are known under many names, including Ishikawa (fishbone) diagrams, impact wheels, issues trees, strategy maps, risk assessment mapping tools (FMEA*)* and, cause and effect diagrams. Operations management researchers often use causal mapping as a key tool for building and communicating theory, particularly in support of empirical research.

However, the most commonly recommended approach in the operations management practice and research literature for building causal maps is to use brainstorming. Structured interviews are also recommended in the social science. However, in many situations, both of these methods are clearly inefficient and result in potentially ineffective causal maps.

Causal maps can provide an excellent teaching tool for both practitioners and academics. As suggested in the strategy mapping practice and research literature, causal maps can also be used to find critical control points where the system needs to be monitored and controlled with key metrics. As suggested in the risk management practice and research literature (e.g., FMEA practice and research literature) and the impact wheel practice and research literature, causal maps can also provide guidance for locating critical points for risk mitigation. Lastly, the authors would like to stimulate the use of causal maps for presenting an initial theory for how the system works (or at least how experts believe it works) that can be the first step in subsequent theory testing research.

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