WCIT-2010

Fuzzy cognitive mapping in factor elimination: A case study for innovative power and risks

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Abstract

Factor or criteria prioritization is essential for decision making and planning. In most areas in decision making, integrating the related literature yields an exuberance of criteria which leads a robust decision. Yet, an excess number of criteria may handicap decision making or evaluations in terms of computational time and complexity. In these circumstances, decreasing the number of factors in exchange for a negligible amount of knowledge can emancipate the decision maker yet does not affect the quality of the decision. This elimination can be conducted through qualitative methods such as interviews or quantitative methods. However, quantitative methods are more trustworthy since qualitative methods can be deceptive due to the perceptions of the interviewee. Furthermore, working with larger groups is more prone to neutrality in terms of group thinking. On the subject of innovative power and risks, the literature offers 48 criteria depending on the industry, size or demographics of related companies. Prioritizing and working with these criteria for their decision making applications becomes computationally expensive, especially when embedded in more complex algorithms. In this study, 48 criteria will be reduced using Fuzzy Cognitive Maps and it is believed to provide a sufficient number of criteria with a negligible loss of information and comparisons will be conducted.

Keywords: Fuzzy Cognitive Maps, innovation, factor prioritization, factor elimination

1. Introduction

Factor prioritization is a broad term that ranks a number of factors according to the importance and effect on the output. The process supports all types of decision making strategies by providing more realistic and robust decisions. For prioritization, both qualitative and quantitative data can be used by quantifying all data [1]. Once the data is quantitative, various methods can be applied in order to rank valid factors for any decisions. Methods can be statistical such as Variance Based Factor Prioritization [2] or subjective such as Analytical Hierarchy Process [3].

However, there can be cases when decision variables may yield an abounding number of factors. The excess number of criteria results in computationally expensive calculations and comparisons especially in subjective factor prioritization methods [4]. In this respect, number of factors should be reduced for the sake of easy computation. Obviously, the reduction in the number of factors introduces deviations in calculations caused by the loss of knowledge. Hence, factor elimination should eliminate a negligible amount of knowledge without causing the decision to exceed the sensitivity borders of the problem [5]. Both qualitative and quantitative methods are valid for factor elimination yet quantitative methods are known to be more trustworthy and robust. Cognitive maps, also called causal maps or reasoning maps, are widely accepted as tools for factor evaluation, prioritizing and elimination.

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Fuzzy Cognitive Mapping is the method that will be used in the context of this study. Defined as the capability of persisting through time, sustainability has been a wide research area for over twenty years [7]. The term alludes to preservation of success, and the concept has been introduced as an abstract approach to academia. Hence, in order to manage the preservation successfully, the borders have been elucidated with the ongoing research [8,9]. Various methods and channels have been developed for achieving sustainability. Innovation has been one of the most successful methods for sustainability that assures the success and maintains the standards [10].

However, depending on the status of companies, the means of achieving innovation can vary. Depending on the size or budget of company, different criteria are revealed to be more important. In this study, factors are ranked by the perspective of large companies and results are compared with the perspectives of SMEs (Small and medium sized companies).

2. Literature Review

In literature, factor prioritization, also called criteria ranking, and elimination is widely exploited in many different areas from nuclear science to urban planning [11,12]. Other applications include Butler and McGlone’s [13] study for selecting a primary care physician in health care, Yalcin and Akyurek’s [14] study aiming to generate composite maps for flood avoidance. Factor prioritization both has qualitative and quantitative methods. Early studies include mainly qualitative methods such as group interviews. Nikolaidis et. al. [15] investigate consumer behavior in olive oil purchasing criteria with interviews. Aiming to generate concrete and more objective borders, statistical analyses and variance tests are conducted in case of reliable data existence. Ammarapala and Luxhoj [3] rank risk factors using pastime data or Fong et. al’s [11] study involve electronic reactor evaluation controlled with signal data. On the other hand, in reality, it is not very often that data are available. In these circumstances, subjective evaluations and pairwise comparisons construct the quantification borders of factor prioritization. Yalcin and Akyurek’s [14] study use pairwise comparisons between factors for flood control. Analytical Hierarchy and Analytical Network Models are also frequently used in factor prioritization [16].

When it comes to the methodology, studies focus on surveys and statistical analyses (mostly regression) [17-22]. In this paper, fuzzy cognitive mapping will be used as a new approach to factors influencing innovation in large firms. Cognitive maps are basic tools understanding relations and human perceptions within elements [23,24]. What makes fuzzy cognitive maps (FCMs) is that beneficial that they are applicable to many areas. Papageorgiou, Markinas & Gemptos apply FCMs to cotton growing behavior in agriculture [23] whereas Xirogiannis, Stefanou & Glykas apply FCMs to urban planning [25]. Another application by Banini & Bearman [24] involves slurry rheology in mines and measures the inter-dependency and importance of criteria such as shape, size, shear rate, etc... Other social studies involve planning how to manage water sources [26] and exploring the importance of human factors in working environments [27]. FCMs are also applied to technical subjects. Kang, Lee & Choi [28] apply FCMs to determine the relationship within airline service criteria such as quality control, market share, sales price, etc... whereas Lee, Kim, Chung & Kwon [29] apply FCMs to web-mining and modems.

The innovational risk factors used in this study are derived from literature review and interviews from industry experts. Taalika groups innovation affecting factors into four as organizational, managerial, environmental and communicational [30] She also points out that six criteria: size, centralization, functional differentiation, resources, organizational attitude and age are most important to large firms in Finland. Another Finnish study conducted by Vahtera [31] detect almost the same result although both studies are conducted in greatly different sectors, one being in education and the other being in websites. A Chinese study by Lin [32] in the logistics sector differs from Finnish cases and it is imposed on organizational encouragement, quality of human resources, environmental uncertainties and governmental support. Canadian manufacturing firms case designates three criteria: R&D investments, competencies and past innovation activities [33].

3. Innovation Factors

According to the literature review and industry expert interviews, the innovational risk factors are grouped under three groups: industry factors, internal factors and external factors. All factors are listed below [17-22]:
1. Industry
   a. Number of firms in the industry (F1)
   b. High tech or low tech? (High tech) (F2) [5]
   c. Inclining or declining in the area? (Inclining) (F3)
   d. Collaborative, cooperative? (Competitive) (F4)
   e. Speed of change (F5)
2. Enterprise Demographics
   a. Facility location (being in an industrial region) (F6)
   b. Age of the firm (F7)
   c. Facility size (F8)
   d. Workforce size (F9)
3. Financial Features
   a. Financial resources (F10)
   b. Annual profit (F11)
   c. Annual productivity (F12)
   d. Venturing activities (F13)
   e. Capital structure (F14)
4. Organizational Culture
   a. Shareholder structure (F15) [5]
   b. Leadership level (F16)
   c. How far is the organization to a learning organization? (distance to being a learning organization) (F17)
   d. Resource allocation policy (F18)
   e. Competitive relations (F19)
5. Customer relations
   a. Is the customer an industrial one or the end customer? (Having an industrial customer) (F20)
   b. Level of education of the customer (F21)
   c. Income level of the customer (F22)
   d. Level of collaboration with customers (F23)
   e. Do customers contribute to innovation? (F24)
6. Sales Channels
   a. Structure of the sales channels (mediary, direct sales, vb…) (Having an intermediary sales partner) (F25)
   b. Reaction to change (Having a traditional sales channel) (F26)
   c. Activity enforcement by sales channels (F27)
   d. Demand fluctuations and changes (F28) [8]
   e. Do sales channels contribute to innovation? (F29)
7. Supplier Channels
   a. Number of suppliers (F30)
   b. Activity enforcement by suppliers (F31)
   c. Do suppliers contribute to innovation? (F32)
8. Employee relations
   a. The rate of white collar employees. (F33)
   b. Reward systems? (Having prize based personnel system) (F34)
   c. Number of qualified workers (F35)
   d. Per employee efficiency – labor productivity (F36)
9. Intellectual properties
   a. Number of licenses that firm has obtained (F38)
   b. Number of patents that firm has applied for (F39)
   c. Number of patents that the firms has obtained (F40)
10. Innovation and R&D policy
    a. Open innovation – closed innovation (Closed innovation) (F41)
b. R&D structure (lab, department, outsourced, none? (F42) 
   c. Innovation level of the firm (F43) 
   d. Paradigm shifts in the history of the firm (F44) 

11. Government Regulations 
   a. Tax Policies (F45) 
   b. Governmental encourage and guarantee (F46) 

12. Relations with Institutions and Universities (F47) 
   a. Relations with universities (F47) 
   b. Relations with other institutes (F48) 

Once the affects of the criteria are defined, the criteria classes can be clustered into three categories: industry risks and innovation, risks and innovations derived from external relations of the company and risks and innovations derived from internal relations of the company. The first class of criteria, Industry Dynamics are grouped in the industry cluster, The classes Sales Channels, Supplier Channels, Customer Relations, Government Regulations and Relations with Other Institutions are grouped under external relations of the company. Lastly, the classes Enterprise Demographics, Financial Features, Organizational Culture, Intellectual Properties, Innovation and R&D Policies and Employee Relations are grouped into internal relations of the company.

4. Fuzzy Cognitive Maps

Cognitive maps are tools for analysis of the relations within the elements of a system. Cognitive maps are composed of variables and relationships within variables [34] Each variable is linked with each other with either a positive relationship which denotes a direct proportion or a negative relationship which denotes an inverse proportion. Cognitive mapping starts with defining the relationships between variables with arrows drawn from the affecting variable to the affected variable. 

The next step in cognitive map is the construction of the pairwise comparison matrix. Rows and columns of the pairwise comparison matrix are constructed by the variables and uses binary notation. For example, if the \( i^{th} \) variable positively affects the \( j^{th} \) variable, then \( i^{th} \) row and \( j^{th} \) column of the matrix is 1. If the relationship is negative, then the ith row and jth column of the matrix is -1 and lastly if there is no relationship, the \( i^{th} \) row and \( j^{th} \) column of the matrix is 0. Finally, it is assumed that any variable does not affect itself, therefore the diagonal of the pairwise comparison matrix is 0 [35].

There are three properties of variables: indegree, outdegree and centrality. Indegree of a variable is the sum of the related column of the matrix, that is, the sum of variables that affect the related variable. Outdegree of a variable is the sum of related row of the matrix, that is, the sum of variables that are affected by the related variable. Lastly, centrality is the sum of indegree and outdegree. This value is 0 for every variable in the basic cognitive maps which encourages the use of fuzzy cognitive maps.

Fuzzy cognitive maps differ from basic cognitive maps. Unlike basic cognitive maps, fuzzy cognitive maps measure the relation in the interval of [-1, 1] which means the relationships among two variables does not necessarily have to be at the same degree. Therefore, the centrality of a variable may not be 0 and centrality becomes a measure of dominance.

The pairwise comparison matrix has two properties: the index density and the hierarchy index. The index density (D) implies the density of relationships within a system. On the other hand, the hierarchy index (h) implies the democracy within the variables. If \( h = 0 \), then the map is fully democratic and if \( h = 1 \), then the map is fully hierarchical [34,35].

Formulae for all properties for a given pairwise comparison matrix \( E \).
Once the criteria and the two-ends are defined, a fuzzy cognitive map of criteria can be derived in order to determine weights of these criteria. For building the fuzzy cognitive map, the pairwise comparison of the criteria is made to observe the possibility and degree of the relations within them. The fuzzy cognitive matrix is a 48x48 matrix and the degrees of relations are determined by an industry expert. For a criterion given in a row, the industry expert is asked the degree of the relationships. The choices for the industry expert and their related triangular fuzzy numbers are:

- affects strongly in a negative way: [-1, -1, 0]
- affects moderately-strongly in a negative way: [-1, -0.8, -0.6]
- affects moderately in a negative way: [-0.8, -0.6, -0.4]
- affects weakly-moderately in a negative way: [-0.6, -0.4, -0.2]
- affects weakly in a negative way: [-0.4, -0.2, 0]
- does not affect at all: [-0.2, 0, 0.2]
- affects weakly in a positive way: [0, 0.2, 0.4]
- affects weakly-moderately in a positive way: [0.2, 0.4, 0.6]
- affects moderately in a positive way: [0.4, 0.6, 0.8]
- affects moderately-strongly in a positive way: [0.6, 0.8, 1]
- affects strongly in a positive way: [0.8, 1, 1]
The fuzzy numbers are also in Figure 1. With the pairwise comparisons, fuzzy cognitive matrix is constructed. The results of the fuzzy cognitive matrix (indegree, outdegree, centrality) are given in Table 2.

When it comes to matrix properties, there exist 948 connections within 48 variables. Then the index-density is 0.42. The outdegree variance is calculated as 25.1 and the hierarchy index is calculated as 0.1307. The hierarchy index is closer to 0 than 1, the cognitive map is close to being fully democratic.

![Fig. 1. Fuzzy Numbers for the Relationships between Variables](image)

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<th>od</th>
<th>id</th>
<th>ci</th>
<th>Normalized ci</th>
<th>Criterion</th>
<th>od</th>
<th>id</th>
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According to the results, three most important criteria are innovation level of the firm, resource allocation policy, annual profit and venturing activities. The least important three criteria are age of the firm, tax policies and governmental encouragement.

Last 10 criteria (from F27 to F7) have an approximate overall weight of 10% and can be quite negligible for system evaluation. On the other hand, a study is to be conducted, because of the excess in the number of criteria, a threshold for the centrality value can be assigned. An acceptable threshold value could be 20, carrying 24 criteria to the other step yet causing an information loss of 31.7%.

6. Comparison with SME Priorities

Same comparisons applied to SMEs yield to the most similar results with minor differences. Comparing the first three important factors, SMEs appraise resource allocation policy, shareholder structure and R&D structure. For large companies, resource allocation policy remains in the first three factors and the other two factors remain in the uneliminated factor list. Large companies’ first three criteria are innovation level of the firm, resource allocation policy, annual profit which are in the first five factors for SMEs.

When it comes to factors that are last favored, large companies are not widely affected by age of the firm, governmental encourage and tax policies. On the other hand, SMEs are not thoroughly affected by age of the firm, having traditional sales channels and turnover rate. All last three factors except turnover rate are eliminated by both large companies and SMEs. Turnover rate is considered important by large companies.

Considering the innovation factor groups, large companies and SMEs share the first three groups but their rank reversed: financial features, innovation and R&D policy and organizational culture (Table 2). As for the last three innovation factor groups both large companies and SMEs consider government regulations and supplier channels. However, large companies reckon with enterprise demographics whereas SMEs deal with sales channels in their last three innovation factor groups.

<table>
<thead>
<tr>
<th>FACTOR GROUP</th>
<th>Average Factor Score for Large Companies</th>
<th>Average Factor Score for SMEs</th>
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</table>

7. Conclusion

Factor prioritization plays an important role in realistic and robust decision making processes. Besides, the ability to be applied in any decision field causes the integration of qualitative and quantitative methods. As the number of factors increase, the decision making process becomes cumbersome. Especially in subjective methods, the decision may not reflect the real world based on long processing time and confusion caused for decision makers. Only when
these cases occur, the number of factors should be reduced. For this elimination, quantitative methods of factor prioritization are proper to be used.

In this study, factor prioritization is applied to large companies and the results are compared to the choices of SMEs. It is observed that SMEs and large companies are affected by similar factors during the innovation process. All companies favor resource allocation policy, shareholder structure, R&D structure, innovation level of the firm and annual profit. Firm age, governmental encouragement, tax policies, traditional sales channels and turnover rate are the least chosen factors. Financial features, innovation and R&D policy and organizational culture are the most important factor groups for all companies as well as government regulations and supplier channels being the least important.

Further studies may include decision making or other evaluation processes that can use the findings in this study. It is also possible to re-apply this study with no factor limit and the use of brainstorming for companies of different industries and different size.

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