# Modifications of Simple Additive Weighting and Weighted Product Models for Group Decision Making

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**Abstract**
Many real problems related with decision making involve different experts for different business decisions. The differences in experts' knowledge and experience can be overcome by using of corresponding weighted coefficients. The objective of this paper is to provide group decision making models taking into account the presence of group of experts with different knowledge and experience. For the goal, two modifications of simple additive weighting model and weighted product model are described. The proposed modifications of models for group decision making are numerically tested for selection of ERP system from 3 alternatives and 5 experts using 4 evaluations criteria. The obtained results show the applicability of the described modifications of both models for group decision making.

**Key words:** *Simple additive weighting model; weighted product model; group decision making; weighted coefficients; combinatorial optimization.*

## 1. Introduction

Many real problems can be overcome by using of multi-attribute decision making (MADM). Therefore, MADM is an important research field in the area of decision making due its application in different business applications [Borissova et al., 2016b]. The MADM concern the problems that involve a finite and discrete set of alternatives. The evaluation and selection of the single alternative define significant difficulties in making of trade-offs between evaluation criteria in order to get the best compromise solution. Many techniques are proposed to support selection decisions as multi-attribute utility theory (MAUT); outranking methods and

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interactive methods. The family of MAUT methods aggregate the different criteria into a function, which has to be maximized, while outranking methods rely on building a global outranking relation and exploring it by a recommendation, consistent with the problem in question [Nedjah & Macedo Mourelle, 2005]. Often interactive methods are used to present a proposal to the DM at each iteration consisting of one or several alternatives against which the DM reacts and provides preference information [Vanderpooten, 1989].

To improve decision making, many organizations rely on group decision forming by involving a group of experts with different field of expertise in the decision making process [Kerr & Tindale, 2004]. The larger number of group members has the potential to be more creative and to lead to a more reasonable decision. Today, many decisions in organizations are made by groups, teams, or committees considered as a group of decision makers rely on: knowledge and expertise of more experts; a greater number of alternatives to be examined; better understanding and accepting of the final decision by all group members [Lunenburg, 2011]. Many authors indicate that consensus decisions with five or more participants are superior to individual, majority vote, and leader decisions [Bonner et al., 2007; Wanous & Youtz, 1986; Watson et al., 1991]. Accordingly to Yetton and Botter, groups of 5 experts are the most effective in group decision making, followed by a group of 7 experts [Yetton & Botter, 1983].

The researchers focused on group decision making in case of MADM use different approaches. Some of them deal with linguistic preferences [Tan et al., 2011; Tao et al., 2015], fuzzy preferences [Meng et al., 2017; Peneva & Popchev, 2009; Wan et al., 2018] or aggregation of utility-based individual preferences [Huang et al., 2013]. Other researchers seek to propose new methods for group decision making or extend of existing methods [Chen & Yang, 2011; Wang & Chen, 2017; Dong et al., 2017; Gupta et al., 2016]. In contrast to the outranking methods that are related with building a global outranking relation to explore each alternative, the MAUT methods rely on aggregation of different criteria into a function, which has to be maximized. Due this fact, the investigations in this article concern more effective modifications of the most used models based on MAUT. The family of MAUT methods require definition of quantitative weights for the criteria, in order to assess the relative importance of the each criterion [Fulop, 2005]. Two of the best known and widely used methods – namely simple additive weighting (SAW) and weighted product model (WPM) are considered in the paper toward their effective modifications for group decisions. The utility function of SAW for selection of the best alternative is derived by the following equation [Triantaphyllou, 2000]:

(1) $$A^*_{WSM} = \max \sum_{j=1}^{n} w_j a_{ij}, \text{ for } i = 1,2,...,m$$

where $A^*_{WSM}$ express the score of the best alternative, $n$ is number of decision criteria, $a_{ij}$ express the value of $i$-th alternative toward the $j$-th criterion, $w_j$ express the weight of relative importance of the $j$-th criterion where $\sum_{j=1}^{n} w_j = 1$.

The WSM differs from WPM by multiplication of the value ($a_{ij}$) of alternative to the power equivalent of the relative weight of the corresponding criterion $w_j$ [Webster, 1998]:

$$R(A^*_{WPM}) = \max \prod_{j=1}^{n} (a_{ij})^{w_j}, \ i = 1,...,m \tag{2}$$

Using the classic of simple additive weighting and weighted product models, in the paper they are modified to be able to be more effective for group decision making. These two models are considered here, as they are the best known and widely used to problems of MADAM, due the using of simple additive/multiplicative function that represent the preferences of decision makers.

The main contribution of the article is focused on taking into account of the fact that different experts have different knowledge and experience. That is considered by modification of simple additive weighting and weighted product models via assigning of proper weighted coefficient for each expert. Another contribution is the usage of combinatorial optimization for determination of the best alternative/s for group decision making. For the goal, an extended decision matrix is proposed including the needed parameters for group decision making.

The rest of the article is structured as follows: Section 2 describes in details the proposed modifications of simple additive weighting and weighted product models for group decision making. Section 3 describes an illustrative application of the proposed models for group decision making together with analysis of the numerical testing results and conclusions are given in Section 4.

## 2. Modifications of Simple Additive Weighting and Weighted Product Models for Group Decision Making Using of Combinatorial Optimization

In the case for group decision making, an extended weighted decision matrix is proposed, which takes into account the needed parameters for multi-attribute group decision making – alternatives, evaluation criteria and group of experts as shown in Table 1.

The following indexes are used: $m$ – number of alternatives, $n$ – number of criteria (attributes), $k$ – number of experts in the group. The set of alternatives is denoted by $A = \{A_1, A_2, \ldots, A_m\}$, where $A_i$ ($i$ = 1, 2, 3, …, $M$) express $i$-th alternative. The set of criteria is denoted by $C = \{C_1, C_2, \ldots, C_n\}$, where $C_j$ ($j$ = 1, 2, 3, …, $N$) express $j$-th criterion. The group of experts involved in the evaluation process is denoted by the set $E = \{E^1, E^2, \ldots, E^k\}$, where $E^q$ ($q$ = 1, 2, 3, …, $K$) express $q$-th expert. The weighted coefficients for each expert in the group are denoted by the set $\{\lambda^q\}$ for $q$ = 1, 2, 3, …, $K$. The evaluations of the corresponding alternatives $A_i$ on the given criteria $C_j$ by the $q$-th expert are expressed by $e^q_{ij}$. The weighted coefficients for the relative importance of the $j$-th criterion, according to the $q$-th expert' point of view, are denoted by $w^q_j$. In this matrix a set of decision variables $\{x_i\}$ (for $i$ = 1, 2, 3, …, $M$) is used and are assigned to each of the alternative.

*Table 1. Modified structure of the weighted decision matrix for group decision making*

| **Group of experts** | **Weighted coefficients for experts** | **Alterna-tives, $A_i$** | **Decision variables, $x_i$** | **Criteria/Attributes** | | | |
|---|---|---|---|---|---|---|---|
| | | | | **$C_1$** weight/ evaluation | **$C_2$** weight/ evaluation | … … | **$C_n$** weight/ evaluation |
| $E^1$ | $\lambda^1$ | | | $w_1^1$ | $w_2^1$ | | $w_n^1$ |
| | | $A_1$ | $x_1$ | $e_{11}^1$ | $e_{12}^1$ | | $e_{1n}^1$ |
| | | $A_2$ | $x_2$ | $e_{21}^1$ | $e_{22}^1$ | | $e_{2n}^1$ |
| | | $A_3$ | $x_3$ | $e_{31}^1$ | $e_{32}^1$ | | $e_{3n}^1$ |
| | | …. | | … | … | … | … |
| | | $A_m$ | $x_m$ | $e_{m1}^1$ | $e_{m1}^1$ | | $e_{mn}^1$ |
| $E^2$ | $\lambda^2$ | | | $w_1^2$ | $w_2^2$ | | $w_n^2$ |
| | | $A_1$ | $x_1$ | $e_{11}^2$ | $e_{21}^2$ | | $e_{1n}^2$ |
| | | $A_2$ | $x_2$ | $e_{21}^2$ | $e_{22}^2$ | | $e_{2n}^2$ |
| | | $A_3$ | $x_3$ | $e_{31}^2$ | $e_{32}^2$ | | $e_{3n}^2$ |
| | | …. | | … | … | … | … |
| | | $A_m$ | $x_m$ | $e_{m1}^2$ | $e_{m2}^2$ | | $e_{mn}^2$ |
| …. | | …. | | … | … | … | … |
| $E^k$ | $\lambda^k$ | | | $w_1^k$ | $w_2^k$ | | $w_n^k$ |
| | | $A_1$ | $x_1$ | $e_{11}^k$ | $e_{12}^k$ | | $e_{1n}^k$ |
| | | $A_2$ | $x_2$ | $e_{21}^k$ | $e_{22}^k$ | | $e_{2n}^k$ |
| | | $A_3$ | $x_3$ | $e_{31}^k$ | $e_{32}^k$ | | $e_{3n}^k$ |
| | | …. | | … | … | … | … |
| | | $A_m$ | $x_m$ | $e_{m1}^k$ | $e_{m2}^k$ | | $e_{mn}^k$ |

Using these notations, the modifications of simple additive weighting and weighted product models are formulated for the case of group decision making.

## 2.1. Modified Simple Additive Weighting for Group Decision Making

The proposed modification of the Simple Additive Weighting method includes the ability to assign different weights for experts in the group, expressing their competencies and experience, of group members. Based on the modified weighted decision matrix in Table 1 and the standard form of simple additive weighting model (1), the simple additive weighting method for group decision-making is transformed as following combinatorial optimization model:

(3)
$$maximize\left(\sum_{i=1}^{M} x_i \sum_{k=1}^{K} \lambda^k A_i^k\right)$$

subject to

(4)
$$\forall i = 1, 2, \dots, M : (\forall k = 1, 2, \dots, K : A_i^k = \sum_{j=1}^{N} w_j^k e_{i,j}^k\ )$$

(5) $$\sum_{j=1}^{N} w_j^k = 1, \forall k = 1, 2, \dots, K$$

(6) $$\sum_{i=1}^{M} x_i = 1,\ x_i \in \{0, 1\}$$

(7) $$\sum_{k=1}^{K} \lambda^k = 1,\ \lambda^k \in [0,1]$$

where $A_i^k$ express the aggregate assessment of the *i*-th alternative against all criteria, according to the point of view of the *k*-th expert in the group. The relative importance between criteria, according to the various experts, is expressed by corresponding weighted coefficient $w_j^k$ determined by each expert. The evaluation of the *i*-th alternative versus the *j*-th criterion by *k*-expert is expressed by $e_{ij}^k$. The decision variables used to select a single alternative are introduced as binary integer variables $x_i$ ($i$ = 1,2, .., M), assigned to each of the alternatives. A specific feature of the proposed model (3) – (7) is introducing of coefficients $\lambda^k$ and decision variable $x_i$. The coefficients $\lambda^k$ express the expertise of the members in group involved in the group decision-making process. If the knowledge of the different experts is considered equally important, then the corresponding coefficients $\lambda^k$ are equal to 1.

In order to obtain comparable scales and to eliminate the problems associated with the use of different units of measurement, it is necessary to use some normalization. Normalized estimation has dimensionless units, and larger values correspond to a better performance of the alternative toward the relevant criterion. For this purpose, the estimations $e_{ij}$ of the criteria, which are to be maximized, can be normalized according to the following scheme [Yoon & Hwang, 1995; Borissova et al., 2016a]:

(8a) $$e_{ij}^* = \frac{e_{ij}}{e_{ij}^{\max}}$$

For criteria that require minimization, the normalization scheme is:

(8b) $$e_{ij}^* = \frac{e_{ij}^{\min}}{e_{ij}}$$

The most preferable alternative is obtained as a result of solving the optimization problem (3) – (7), which determines the values of binary integer decision variables $x_i$.

The formulated above Simple Additive Weighting for group decision making (3) – (7) can be modified to select more than one alternative. This can be done by changing the equation (6) to select $z$ number of alternatives and the single choice problem is transformed to multiple-choice problem [Mustakerov et al., 2012]:

(6*) $$\sum_{i=1}^{M} x_i = z,\ x_i \in \{0, 1\},\quad 1 < z < M$$

The solution of the optimization problem (3) – (7) using (6*) will determine simultaneously $z$ number good alternatives without supplying information which of the alternatives is the better.

## 2.2. Modified Weighted Product Model for Group Decision Making

The weighted product model for group decision-making [Webster, 1998] is modified as combinatorial optimization model. This modification allows evaluating the effectiveness of individual alternatives instead of the relationship between each two alternatives. Based on the modified weighted decision matrix in Table 1, the weighted product model is transformed as follow:

(9) $$maximize \sum_{i=1}^{M} x_i \sum_{k=1}^{K} \lambda^k R(A_i)^k$$

subject to

(10) $$\forall i = 1, 2, \dots, M : (\forall k = 1, 2, \dots, K : R(A_i)^k = \prod_{j=1}^{N} (e_{ij}^k)^{w_j^k}$$

(11) $$\sum_{j=1}^{N} w_j^k = 1, \forall k = 1, 2, \dots, K$$

(12) $$\sum_{i=1}^{M} x_i = 1,\ \ x_i \in \{0, 1\}$$

(13) $$\sum_{k=1}^{K} \lambda^k = 1,\ \ \lambda^k \in [0,1]$$

where $R(A_i)^k$ express the aggregate assessment of the $i$-th alternative against all criteria, according to the point of view of the $k$-th expert in the group. If necessary, normalization can be also applied in this model in order to obtain comparable scales and to overcome the problems associated with the use of different units of measurement.

The formulated weighted product model for group decision making (9) – (13) can be also modified by changing the relation (12) with (6*) to select more than one good alternatives.

In the described way, the structured information from Table 1 can be used to formulate and solve the corresponding combinatorial optimization tasks (3) – (7) and (9) – (13) to determine the most preferred alternative by group of decision makers.

# 3. Illustrative Application

This section provides an illustrative application of the proposed models for group decision making described in Section 2. The Enterprise Resources Planning (ERP) systems are good example for group decision making application. The ERP enhance business operations and the companies should carefully determine the factors that influence the success of resources implementation to prevent future failures [Tsai et al., 2012]. The selection of ERP software is a typical MADM problem. The proposed modifications of simple additive weighting and weighted product models are used for this type of problems. The input data for numerical testing are adapted from [Efe, 2016]. To evaluate the ERP software, four performance criteria are used: 1) cost; 2) vendor specifications; 3) technical specifications; 4) ease of use. The cost criterion incorporates the price for acquisition of software and following updating fees to get the latest version. Criterion for vendor's specifications includes training and consultant services, reputation and references of vendor. Criterion for technical specifications emphasizes on software interface, functionality, compatibility with other existing platforms, reliability and supporting data files. The criterion for ease of use combines software ergonomics, satisfaction of software utilization and learnability, and reporting of the requested reports. A group of 5 authorized experts are formed to get the group decision: one financial consultant (E-1), two business analysts (E-2 and E-3), and two database administrators (E-4 and E-5). The normalized evaluation of alternatives performance toward the described above criteria together with the weighted coefficients for the relative importance of criteria are shown in Table 2. The weighted coefficients that express the expertise of the members of group accordingly their competencies of knowledge, experience and importance are also given in Table 2.

*Table 2. The normalized weighted decision matrix for group decision making*

| **Group of experts** | **Weighted coefficients for experts** | **Alterna-tives** | **Decision variables** $x_i$ | **Criteria** | | | |
|---|---|---|---|---|---|---|---|
| | | | | Cost C1 | Vendor specifica-tions, C2 | Technical specifica-tions, C3 | Ease of use, C4 |
| E-1 | **0.10** | | | **$w_1$= 0.30** | **$w_2$=0.20** | **$w_3$=0.25** | **$w_4$=0.25** |
| | | A-1 | $x_1$ | 0.806 | 0.85 | 0.777 | 0.823 |
| | | A-2 | $x_2$ | 0.762 | 0.894 | 0.765 | 0.841 |
| | | A-3 | $x_3$ | 0.818 | 0.813 | 0.785 | 0.877 |
| E-2 | **0.27** | | | **$w_1$=0.21** | **$w_2$=0.26** | **$w_3$=0.26** | **$w_4$=0.27** |
| | | A-1 | $x_1$ | 0.792 | 0.865 | 0.767 | 0.843 |
| | | A-2 | $x_2$ | 0.785 | 0.904 | 0.775 | 0.905 |
| | | A-3 | $x_3$ | 0.763 | 0.893 | 0.792 | 0.89 |
| E-3 | **0.21** | | | **$w_1$=0.16** | **$w_2$=0.28** | **$w_3$=0.28** | **$w_4$=0.28** |
| | | A-1 | $x_1$ | 0.822 | 0.876 | 0.815 | 0.915 |
| | | A-2 | $x_2$ | 0.793 | 0.884 | 0.838 | 0.885 |
| | | A-3 | $x_3$ | 0.808 | 0.831 | 0.808 | 0.897 |
| E-4 | **0.25** | | | **$w_1$=0.18** | **0.22** | **$w_3$=0.28** | **$w_4$=0.33** |
| | | A-1 | $x_1$ | 0.788 | 0.798 | 0.807 | 0.873 |
| | | A-2 | $x_2$ | 0.764 | 0.815 | 0.868 | 0.916 |
| | | A-3 | $x_3$ | 0.749 | 0.855 | 0.835 | 0.905 |
| E-5 | **0.17** | | | **$w_1$=0.20** | **$w_2$=0.25** | **$w_3$=0.25** | **$w_4$=0.30** |
| | | A-1 | $x_1$ | 0.797 | 0.877 | 0.786 | 0.865 |
| | | A-2 | $x_2$ | 0.811 | 0.897 | 0.798 | 0.897 |
| | | A-3 | $x_3$ | 0.823 | 0.854 | 0.812 | 0.925 |

### 3.1. Application of Modified Simple Additive Weighting for Group Decision Making

Based on the normalized data shown in Table 2, the following optimization task is formulated:

(14) $$maximize\left(\sum_{i=1}^{3} x_i \sum_{k=1}^{5} \lambda^k A_i^k\right)$$

subject to

(15) $$\forall i = 1, 2, \dots, 3 : (\forall k = 1, 2, \dots, 5 : A_i^k = \sum_{j=1}^{4} w_j^k e_{i,j}^k\ )$$

(16) $$\sum_{j=1}^{4} w_j^k = 1, \forall k = 1, 2, \dots, 5$$

(17a) $$x_1 + x_2 + x_3 = 1,\ x_i \in \{0,1\}$$

(17b) $$x_1 + x_2 + x_3 = 2,\ x_i \in \{0,1\}$$

(18) $$\lambda^1 = 0.10;\ \lambda^2 = 0.27;\ \lambda^3 = 0.21;\ \lambda^4 = 0.25;\ \lambda^5 = 0.17$$

The optimization task (14) – (18) is solving using one of the restrictions (17a) or (17b). The restriction (17a) expresses the case for a single selection of alternative, while (17b) is used to select two good alternatives simultaneously.

### 3.2. Application of Modified Weighted Product Model for Group Decision Making

Considering the input data from Table 2 for normalized weighted decision matrix for group decision making, the following optimization task is formulated:

(19) $$maximize \sum_{i=1}^{3} x_i \sum_{k=1}^{5} \lambda^k R(A_i)^k$$

subject to

(20) $$\forall i = 1, 2, \dots, 3 : (\forall k = 1, 2, \dots, 5 : R(A_i)^k = \prod_{j=1}^{4} (e_{ij}^k)^{w_j^k}$$

(21) $$\sum_{j=1}^{4} w_j^k = 1, \forall k = 1, 2, \dots, 5$$

(22a) $$x_1 + x_2 + x_3 = 1,\ x_i \in \{0,1\}$$

(22b) $$x_1 + x_2 + x_3 = 2,\ x_i \in \{0,1\}$$

(23) $$\lambda^1 = 0.10;\ \lambda^2 = 0.27;\ \lambda^3 = 0.21;\ \lambda^4 = 0.25;\ \lambda^5 = 0.17$$

The restriction (22a) expresses the situation where of a single alternative is to be selected, while restriction (22b) is used for determination of two good alternatives simultaneously.

### 3.3. Results Analysis and Discussion

The solutions of formulated optimization tasks in Section 3.1 and 3.2 representing the usage of modifications of simple additive weighting and weighted product models for group decision making are obtained by means of software system LINGO v. 12. The solution times took a few seconds on PC with Intel Core i3 CPU at 2.93 GHz, 3.37 GB RAM under MS Windows OS.

The results of formulated optimization task (14) – (18) based on modified simple additive weighting for group decision making are shown in Table 3.

*Table 3. Results from usage of modified simple additive weighting model*

| Case | Weighted coefficients for expertise of the members of group | | | | | Selected single alternative | Selected 2 good alternatives |
|---|---|---|---|---|---|---|---|
| | E-1 | E-2 | E-3 | E-4 | E-5 | | |
| (1) | 0.10 | 0.27 | 0.21 | 0.25 | 0.17 | A-2 | A-2 & A-3 |
| (2) | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | A-2 | A-2 & A-3 |
| (3) | 0.35 | 0.13 | 0.12 | 0.20 | 0.20 | A-3 | A-2 & A-3 |

Six different situations are investigated – case (1), case (2) and case (3) for determination of a single alternative and determination of two alternatives. The used three cases are based on three different sets of weighted coefficients for experts in accordance to their knowledge and experience. For case (1) and case (2) when a single group alternative is to be selected, the solution determines alternative A-2 as the most preferable one, while in case (3) the most preferable alternative is A-3. The second scenarios express the situation when two good alternatives are to be selected simultaneously. All three cases for second scenario determine A-2 and A-3 as good alternatives to chose from.

The results of formulated optimization task (19) – (23) based on modified weighted product model for group decision making are shown in Table 4.

*Table 4. Results from usage of modified weighted product model*

| Case | Weighted coefficients for expertise of the members of group | | | | | Selected single alternative | Selected 2 good alternatives |
|---|---|---|---|---|---|---|---|
| | E-1 | E-2 | E-3 | E-4 | E-5 | | |
| (1) | 0.10 | 0.27 | 0.21 | 0.25 | 0.17 | A-2 | A-2 & A-3 |
| (2) | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | A-2 | A-2 & A-3 |
| (3) | 0.35 | 0.13 | 0.12 | 0.20 | 0.20 | A-3 | A-2 & A-3 |

The modified weighted product model for group decision making uses the same scenarios for estimation of experts – case (1), case (2) and case (3) for determination of a single alternative and determination of two good alternatives. As can be seen form Table 4, the usage of modified weighted product model for group decision making for case (1) and case (2) the most preferable alternative is A-2 and for case (3) the most preferable alternative is A-3. For situation when two good alternatives are to be selected, in all three cases alternatives A-2 and A-3 are determined.

The analysis of obtained results in Table 3 and Table 4 for the particular example for ERP systems selection shows identical results regardless of the used modification of the considered models for group decision making.

## 4. Conclusion

The proposed modifications of simple additive weighting and weighted product models can be applied for group decision making while considering the differences in experts' knowledge and experience. These differences are taken into account by introducing of weighted coefficients for each expert of the group. The proposed modifications of simple additive weighting and weighted product models for group decision can be used for selection of more than one preferable alternative. The modifications of both models allow formulation and solution of combinatorial optimization tasks go get the best alternative/s. The numerical testing shows the practical applicability of the both proposed modifications of the models for group decision making.

Having in mind that the popular MS Excel provides optimization solver, the described combinatorial optimization modeling approach can be applied directly without need of additional training of users.

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