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# GENERALIZATION OF THE RCGM AND LSLR PAIRWISE COMPARISON METHODS

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Pairwise comparison methods are convenient procedures for predicting a sound weight vector from a set of relative comparisons between elements to be weighted. Several pairwise comparison methods exist. After a brief presentation of the Least Squares Logarithmic Regression (LSLR) method of de Graan [1] and Lootsma [2] and the recent Row and Column Geometric Mean (RCGM) of Koczkodaj and Orłowski [3], this paper proposes a common mathematical formulation for these two approaches. This common formulation leads to two generalized methods: The GLSLR is now able to process non-reciprocal comparison matrices, and the GRCGM is extended to several decision makers expressing different opinions per pairwise comparison. It also results in an explicit formulation of the weights that generalizes Koczkodaj and Orłowski's formulation of the closest consistent comparison matrix.

*Keywords:* pairwise comparison, decision making, logarithmic least squares regression, row column geometric mean

## 1. Introduction

Rating a set of  $n$  elements  $(e_1, \dots, e_n)$  under the consideration of one criterion is not readily achieved in the presence of  $d$  experts or decision makers. A convenient class of methods called “pairwise comparison” notably simplifies the problem by focusing the attention of decision makers on pairs of elements to be compared. The so-called comparison matrix (see figure 1) represents all possible combinations.

	$e_1$	$e_2$	$\dots$	$e_n$
$e_1$	$(e_1, e_1)$	$(e_1, e_2)$	$\dots$	$(e_1, e_n)$
$e_2$	$(e_2, e_1)$	$(e_2, e_2)$	$\dots$	$(e_2, e_n)$
$\vdots$	$\vdots$	$\vdots$	$\dots$	$\vdots$
$e_n$	$(e_n, e_1)$	$(e_n, e_2)$	$\dots$	$(e_n, e_n)$

Fig. 1. The comparison matrix

Each pairwise comparison leads to a quantified value  $c_{ij}$  which is an estimate of the ratio of element weights  $w_i/w_j$ . In a general case, each decision maker may be allowed to express his/her own assessment of comparison  $c_{ij}$ . Let  $c_{ijk}$  denote the opinion or the vote of the decision maker  $k$  (among  $d$ ) regarding elements  $e_i$  and  $e_j$ .

When considering all the comparison matrix the votes collected for several decision makers hold in a cube. Starting from the pairwise vote cube  $C=(c_{ijk})$ , pairwise comparison methods consist in mapping functions that predict a suitable set of weights  $W=(w_i)$ .

For this problem, the answer provided by the literature is not unique and the coexistence of different methods can be justified by the following reasons.

- Each of the estimated ratios  $c_{ijk}$  leads to a specific equation linking the weights variables. Since there are  $n$  unknown weights and up to  $d \times n^2$  different equations (if each decision maker expresses  $n^2$  comparisons), the system has great chances of being over-constrained. Errors, ambiguities and vagueness are expectable in personal judgments [4] and they result in inconsistencies. In some circumstances, inconsistencies may be explained and considered as natural for human beings [5]. They are less accepted in their ordinal and more noticeable form where they can result in cyclic preferences i.e., for a triple of elements  $(i,j,k)$ , preference of  $e_i$  over  $e_j$  and  $e_j$  over  $e_k$  coexist with preference of  $e_k$  over  $e_i$ . In case of multiple decision

makers, inconsistencies also occur when different opinions are expressed for the same binary comparison. In such a case, they characterize the group as a whole and must be interpreted as the divergence of decision makers' opinions. More generally, there is consistency if and only if the following cardinal transitivity relation holds:  $c_{ihx} \cdot c_{hzy} = c_{izy}$ ;  $i, j, h = 1, 2, \dots, n$ ;  $x, y, z = 1, 2, \dots, d$ . In case of non respect of this generalized transitivity relation there is no a priori best set of weights. This is why, according to the decision strategy, different optimization logics can be considered to yield a sound set of weights [6; 7]<sup>1</sup>.

- Some simplifying hypotheses related to specific configurations of decision making allow the use of specific methods. Some examples, concerning the simplification of the vote cube are listed hereafter:
  - Only precise opinions (crisp values) are considered without taking the possible imprecision of judgments into account. The corresponding pairwise comparison approaches are considered as deterministic.
  - The vote cube can be assumed to be reciprocal, i.e. ( $c_{ijx} = 1/c_{jix}$ ;  $i, j = 1, 2, \dots, n$ ;  $x, y = 1, 2, \dots, d$ ), leading to  $d \times n \times (n-1)/2$  independent votes at most.
  - The number of opinions taken into account for each pairwise comparison can be fixed to exactly one (ex: common decision). In this case, the vote cube consists in a comparison matrix.

This work addresses the research issue of extending deterministic pairwise comparison methods. Such generalization increases the methods' aptitude to tackle the

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<sup>1</sup> For example, minimizing the sum of absolute errors is known to be resistant to the presence of outliers [6 ; 7]. Such outliers can represent locally erroneous judgments or isolate opinions in a decision group. Conversely, when it is legitimate to have a solution that is representative of all the opinions (even outliers), optimization criteria of the type least squares of errors are more adequate. For example, in decision groups with mainly non experts, the experts themselves may be outliers!

variability of decision making contexts. They can also provide generalized straightforward computational formulas. This can be useful for further extensions such as, for example, extending a deterministic pairwise comparison method to take into account the possible imprecision of judgments [8-10].

More precisely, we will extend two methods: the Least Squares Logarithmic Regression (LSLR) method of de Graan [1] and Lootsma [2] and the recent Row and Column Geometric Mean (RCGM) of Koczkodaj and Orłowski [3], by respectively releasing the simplifying hypotheses: reciprocity and one opinion per comparison. Although based on different assumptions and different computational processes, these two popular pairwise comparison methods have very close optimization criteria (based on the logarithmic least squares) and can be considered as two different generalizations of the Row Geometric Mean approach (section 2).

In the following section, we will briefly present those two methods within a brief literature review. In sections 3 and 4, a common formulation is proposed by releasing some restrictive assumptions. This formulation results in two generalized approaches, respectively the GLSLR in section 3 and the GRCGM in section 4. It also yields an explicit formulation of the weights which generalizes the Koczkodaj and Orłowski's formulation of the closest consistent comparison matrix [3]. This new formulation is presented in section 5 before concluding in section 6.

## **2. Deterministic pairwise comparison methods**

Each pairwise comparison method provides a mapping function which minimizes the distance between the input pairwise comparisons and the ones derived from the resulting set of weights (unknowns). Most of the pairwise comparison methods are defined by a straightforward computational formula when proposing a set of weights. They refer to built-in optimization criteria more or less easy to express and assume

simplification hypothesis. Some recent approaches [11; 6; 7] formulate and solve the pairwise comparison problem in a more flexible but less straightforward mathematical programming way.

This literature review is restricted to few deterministic approaches. It briefly presents methods with built-in optimization criteria such as the fundamental eigenvector based method [12] and the two methods to be generalized in this paper: the geometric mean based approach of Koczkodaj and Orłowski [3] and the logarithmic least squares regression method of de Graan [1] and Lootsma [2]. It also presents Bryson and Joseph's goal programming approach [6; 7] which has, in contrast to the previous ones, the potential for a more flexible formulation.

### *2.1. Eigenvector method*

This method assumes that each pairwise comparison is associated to exactly one opinion. As mentioned in the introduction, the vote cube is equivalent to a comparison matrix under this condition.

Since the comparison matrix  $C$  has positive elements, Saaty [13; 12] recalls that, in such a case, the theorem of Perron and Frobenius guarantees that the largest eigenvalue  $\lambda_{max}$  is unique, real and positive. Saaty shows that given a consistent  $C$  matrix, the eigenvector is the weight vector once normalized (its components sum to one). In case of reasonable (not too severe) inconsistencies, Saaty proposes to adopt this normalized eigenvector as an acceptable weight vector. This is the base of his priority theory and Analytic Hierarchy Process (A.H.P.). Unlike the methods presented hereafter, there is no clearly identified optimization criteria associated to the eigenvector method.

### *2.2. Row Geometric Mean (RGM) or Column Geometric Mean (CGM)*

Other formulas often used to solve a comparison matrix are those of the Row Geometric Mean (1) [8; 3] and the Column Geometric Mean (2) [3]. These methods

require the reciprocity of the comparison matrix in order to have the least logarithmic squares as optimization criteria (section 2.3).

$$w_i \approx \frac{r_i}{\sum_{s=1}^n r_s}, \quad i = 1, 2, \dots, n; \quad \text{with } r_i = \left( \prod_{j=1}^n c_{ij} \right)^{1/n} \quad (1)$$

$$w_i \approx \frac{r_j}{\sum_{s=1}^n r_s}, \quad i = 1, 2, \dots, n; \quad \text{with } r_j = \left( \prod_{i=1}^n c_{ij} \right)^{-1/n} \quad (2)$$

### 2.3. Row and Column Geometric Mean (RCGM)

Koczkodaj and Orłowski [3] proposed recently a generalization of the RGM and CGM methods to non reciprocal comparison matrices. Starting from a non necessarily consistent matrix  $C$ , they provide the closest consistent  $C^*$  matrix from a least logarithmic squares point of view (see note 1), i.e. minimizing  $\sum (\log(c_{ij}^*) - \log(c_{ij}))^2$  with the following formulas:

$$c_{ij}^* = \left( \frac{R_i^*}{R_j^*} \cdot \frac{G_j^*}{G_i^*} \right)^{1/2}, \quad i, j = 1, 2, \dots, n; \quad \text{with } R_i^* = \left( \prod_{j=1}^n c_{ij} \right)^{1/n} \quad \text{and } G_i^* = \left( \prod_{j=1}^n c_{ij} \right)^{1/n} \quad (3)$$

When applied to the consistent matrix  $C^*$ , any of the previous methods yields the weight vector.

### 2.4. Least Squares Logarithmic Regression (LSLR)

For a consistent matrix  $C$ , all the methods listed above: EV, RGM, CGM, RCGM coincide. But they all require exactly one opinion per comparison. For dealing with

multiple opinions or with no opinion per comparison, de Graan [1] and Lootsma [2] proposed a generalization of RGM through a least squares logarithmic regression approach (denoted LSLR). It consists in minimizing the distance between the logarithmic terms of the vote cubes  $C$  and  $C^*$ . This can be formulated as follows:

$$\sum_{i=1}^n \sum_{j=i+1}^n \sum_{k=1}^{d_{ij}} \alpha_{ijk} \left( \log(c_{ijk}) - (\log(w_i) - \log(w_j)) \right)^2 \quad (4)$$

with  $c_{ijk}$ ,  $i=1,2,\dots,n$ ,  $j=1,2,\dots,n$ ,  $k=1,2,\dots,d$  the opinion of the decision maker  $k$  for the  $(e_i, e_j)$  comparison,  $d$  the number of decision makers and  $\alpha_{ijk}$  ( $i,j=1,2,\dots,n$ ,  $k=1,2,\dots,d$ ) a parameter equal to 1 when the decision maker  $k$  decides to express a personal opinion ( $c_{ijk} \in ]0 ; +\infty[$ ) and equal to 0 otherwise. When  $\alpha_{ijk}$  equals 0,  $c_{ijk}$  is set to an arbitrary positive non zero value. This allows the algebraic representation of non expressed opinions.

The minimization of the least squares objective function (see note 1) given by (4) leads to the resolution of the so-called normal equations:

$$\theta_i \sum_{j \neq i}^n d_{ij} - \sum_{j \neq i}^{n-1} d_{ij} \theta_j = \sum_{j \neq i}^n \sum_{k=1}^d \alpha_{ijk} b_{ijk}, \quad i = 1, 2, \dots, n-1 ;$$

$$\left. \begin{array}{l} \theta_i \approx \log(w_i), \quad i = 1, 2, \dots, n, \\ \theta_n = 0, \quad (\text{weight fixed to 1}) \\ \text{with } b_{ijk} = \log(c_{ijk}), \quad i, j = 1, 2, \dots, n; \quad k = 1, 2, \dots, d \\ d_{ij} = \sum_{k=1}^d \alpha_{ijk}^2 = \sum_{k=1}^d \alpha_{ijk}, \quad i, j = 1, 2, \dots, n \text{ and } i \neq j \\ d_{ij} : \text{number of opinions for comparison } (i, j) \end{array} \right\} \quad (5)$$



Since the weights are defined up to a multiplicative constant, the normal equations are under-constrained. Solving the system requires to set one of the weights to an arbitrary value ( $w_n=1$ ).

Moreover, the possible missing opinions must not diminish the rank ( $n-1$ ) of the system of normal equations. This condition is satisfied when each of the  $n$  elements to be compared ( $e_1, \dots, e_n$ ) is involved in at least one opinion and when no pair of elements is disjoint by transitivity (elements  $e_i$  and  $e_j$  are disjoint by transitivity when  $\alpha_{ihk} \times \alpha_{hjk} = 0 \forall k=1,2,\dots,d, \forall h=1,2,\dots,n$ ).

The last stage consists in the normalization procedure described by the following formula:

$$w_i = \frac{\exp(\theta_i)}{\sum_{j=1}^n \exp(\theta_j)}, \quad i = 1, 2, \dots, n \quad (6)$$

Under this form (formulas 4,5), the symmetrical comparisons are assumed reciprocal ( $\alpha_{ijk} c_{ijk} = \alpha_{jik} 1/c_{jik}$ ;  $i, j = 1, 2, \dots, n$ ;  $k=1, 2, \dots, d$ ). The previous methods EV and RCGM do not suffer from this restrictive hypothesis.

### 2.5. Bryson and Joseph's goal programming approach

Bryson and Joseph's method [6; 7] represents the mapping from the vote cube  $C$  to a suitable set of weights in the form of a flexible and always feasible logarithmic goal programming model<sup>2</sup> (GPM). In their formulation, they assume that each decision

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<sup>2</sup> Assuming that the evaluator can provide, a priori, interval estimates for the weights and assuming particular behavioral tendencies in the extraction of ratio estimates from these intervals, Bryson et al. [4] derive validity conditions for the computed weight vector. In this particular context, they demonstrate the non validity of methods where the ratio estimates provided by the evaluator are treated with an averaging logic. All the methods previously presented in this section are based on such an averaging logic.



variables assumed not to be random. The model is built on a set of observations of the dependent variable for different sets of values of the prediction variables. For example, if we assume that the size of an individual is related to his/her weight, a regression approach consists in finding the straight line modeling at best a set of (weight, size) measurements performed on a representative sample of individuals.

In the case of a linear regression model [14], an observation  $Y_i$  of the dependent variable  $y$  is related to values taken by the prediction variables  $x_1, x_2, \dots, x_n$  by the way of equations of the form  $Y_i = \eta_0 + \eta_1 X_{1,i} + \dots + \eta_n X_{n,i} + \varepsilon_i$ . The constant coefficients  $\eta_0, \eta_1, \dots, \eta_n$  are parameters which have to be estimated in order to complete the model. Coefficient  $\varepsilon_i$  is a random coefficient of error representing the difference between the linear model prediction and the observation  $i$ . In matricial notation, the equation set may be expressed as:  $Y = XH + E$ . A least squares linear regression consists in a linear estimation model  $\hat{Y} = X\Theta$ . The vector  $\Theta$  corresponds to the minimal value of the sum of the error squares:  $\sum_i (Y_i - \hat{Y}_i)^2$  between the measured values of the dependent variable ( $Y$ ) and the estimated ones ( $\hat{Y}$ ). When  $\Theta$  exists it is solution of the normal equation set:  $X^t Y = X^t X \Theta$ , i.e.:

$$\Theta = (X^t X)^{-1} X^t Y \quad (8)$$

In the pairwise comparison context, if we consider  $Y_{ijk} = \alpha_{ijk} \log(c_{ijk})$   $i, j = 1, 2, \dots, n, i \neq j$  as the dependent variable observations, the equation  $\alpha_{ijk} \log(c_{ijk}) = \alpha_{ijk} (\log(w_i) - \log(w_j) + \varepsilon_{ijk})$  relates in a linear manner an observation  $Y_{ijk}$  to the set of prediction variables  $(X_1 = 0, \dots, X_i = \alpha_{ijk}, X_{i+1} = 0, \dots, X_j = -\alpha_{ijk}, X_{j+1} = 0, \dots, X_n = 0)$  by the way of intermediary parameters  $(\eta_0 = 0, \eta_1 = \log(w_1), \dots, \eta_i = \log(w_i), \dots, \eta_j = \log(w_j), \dots, \eta_n = \log(w_n))$ . Let us recall that  $\alpha_{ijk} = 1$  if the decision maker  $k$  expresses an opinion on comparison  $c_{ij}$  and  $\alpha_{ijk} = 0$  otherwise ( $c_{ijk}$  is then set to  $c_0 > 0$ ). With this convention it is straightforward to extend

the formulas presented in section 2.4 in order to handle non necessarily reciprocal cubes. The observation vector which was restricted to the upper triangular part of the vote cube ( $j>i$ ) must now include all binary combinations except the reflexive ones ( $i=j$ ).

The function to be minimized is given by:

$$f = \sum_{\substack{i,j=1 \\ i \neq j}}^n \sum_{k=1}^d \alpha_{ijk} \left( \log(c_{ijk}) - (\log(w_i) - \log(w_j)) \right)^2 \quad (9)$$

This formula differs from formula 4 by the fact that now  $i \neq j$  instead of  $j>i$ . In the same way, a generalization of formula 5 is given by:

$$\begin{aligned} \theta_i \sum_{j \neq i}^n (d_{ij} + d_{ji}) - \sum_{j \neq i}^{n-1} (d_{ij} + d_{ji}) \theta_j &= \sum_{j \neq i}^n \sum_{k=1}^d (\alpha_{ijk} b_{ijk} - \alpha_{jik} b_{jik}), \quad i = 1, 2, \dots, n-1 \\ \theta_i &\approx \log(w_i), \quad i = 1, 2, \dots, n, \\ \theta_n &= 0, \quad (\text{weight } w_n \text{ arbitrarily fixed to 1}) \\ \text{with } b_{ijk} &= \log(c_{ijk}), \quad i, j = 1, 2, \dots, n; \quad k = 1, 2, \dots, d, \\ d_{ij} &= \sum_{k=1}^d \alpha_{ijk}, \quad i, j = 1, 2, \dots, n \text{ and } i \neq j. \end{aligned} \quad (10)$$

We denote this pairwise comparison approach GLSLR for Generalized Least Squares Logarithmic Regression. As for the LSLR approach, the rank of the system of normal equations must be equal to  $n-1$ .

If we refer to the formula, the opinions which can concern reflexive ( $i=j$ ) binary comparisons (as required for example in some blind tests) will not influence the estimated weights. This invariance does not depend on the pairwise comparison method that is used. Setting the reflexive votes to 1 will always improve the quality of the starting vote cube whatever the optimization logic adopted is.

#### 4. Generalization of the RCGM approach

In this section, we propose a generalization of the RCGM approach of Koczkodaj and Orłowski [3] to authorize several opinions per pairwise comparison. This extension yields a more flexible and practical method. Furthermore it opens the scope to a straightforward analytic weight formula that generalizes the formula Koczkodaj and Orłowski obtain for the closest consistent comparison matrix under the mono-opinion hypothesis. Such formulas could also be useful for further extensions to handle imprecision of judgments [8-10].

In their paper, Koczkodaj and Orłowski [3] propose to find the consistent comparison matrix  $C^*$  that is the closest to the initial  $C$  matrix containing the decision group opinions, in a logarithmic least squares sense. The problem is equivalent to minimizing the quadratic function  $f$  given by:

$$f = \sum_{i,j=1}^n (\log(c_{ij}) - (\log(w_i) - \log(w_j)))^2 \quad (11)$$

When extending this function to multiple (or no) opinions per comparison, it leads exactly to formula 9. As noticed in the end of the previous section, it does not matter if the reflexive binary comparisons are represented or not in the objective function. The resulting set of weights will always respect the equality:  $c_{ii}=w_i/w_i=1, i=1,2,\dots,n$ .

Let us denote by GRCGM (Generalized Row and Column Geometric Mean approach) the RCGM method extended to multiple opinions. We are already allowed to state that the GLSLR and the GRCGM approaches correspond to the same optimization criterion.

The weights being defined up to a multiplicative constant, Koczkodaj and Orłowski chose to minimize the Euclidean distance between matrices  $B$  and  $B^*$ , respectively the logarithmic images of  $C$  and  $C^*$ , under the constraint  $\log(w_n)=0$  ( $w_n=1$ ). They used the

Lagrange multipliers approach by formulating the problem as the minimization of the function  $u=f+\lambda\eta_n$  relatively to the variables  $\eta_1=\log(w_1)$ ,  $\eta_2=\log(w_2),\dots,\eta_n=\log(w_n)$  and  $\lambda$ .

By applying Koczkodaj and Orłowski's approach to a variable number of opinions per comparison and setting to 0 the partial derivatives of function  $u$  relatively to  $\eta_i$ ,  $i=1,2,\dots,n$ , it leads to the equations:

$$\left\{ \begin{array}{l} \theta_i \sum_{j=1}^n Q_{ij} - \sum_{j=1}^n \theta_j Q_{ij} = R_i - G_i, \quad i = 1, 2, \dots, n \\ \theta_n = 0 \end{array} \right. \quad (12)$$

$$\left. \begin{array}{l} \theta_i \approx \log(w_i), \quad i = 1, 2, \dots, n, \\ R_i = \sum_{j=1}^n \sum_{k=1}^d \alpha_{ijk} b_{ijk}, \\ \text{with } G_i = \sum_{j=1}^n \sum_{k=1}^d \alpha_{jik} b_{jik}, \\ Q_{ij} = Q_{ji} = \sum_{k=1}^d (\alpha_{ijk} + \alpha_{jik}), \\ b_{ijk} = \log(c_{ijk}), \quad i, j = 1, 2, \dots, n; \quad k = 1, 2, \dots, d. \end{array} \right.$$

These equations are similar to those of formula 10 even if there are presented in a different way. By shifting to matrix notations we can easily retrieve the normal equations introduced in section 3. The quantities  $R_i$  and  $G_i$  represent summations involving opinions where element  $i$  appears in the first position (i.e.  $c_{ihk}$ ) for  $R_i$  and in the second position (i.e.  $c_{hik}$ ) for  $G_i$ . The quantity  $Q_{ij}$  represents the number of opinions expressed to compare the elements  $e_i$  and  $e_j$ , whatever the order is, i.e. it concerns the  $c_{ijk}$  and  $c_{jik}$  comparisons, for  $k=1,2,\dots,d$ .

## 5. Explicit weight formulation under a restrictive hypothesis

Let us assume  $Q_{ij}$  (see section 4) to be constant for all combinations of two elements.  $Q_{ij}$  is then an even integer, i.e.  $Q_{ij}=2q$ , with  $q$  a constant integer. This is due to the symmetry of the comparison matrix. In particular, the reflexive opinions (for  $i=j$ )

are naturally counted twice :  $Q_{ii} = \sum_{k=1}^d (\alpha_{iik} + \alpha_{iik}) = 2 \sum_{k=1}^d \alpha_{iik}$  .

For example figure 1 illustrates the case where  $q=2$  for  $n=3$  (number of elements). Each point symbolizes one opinion.

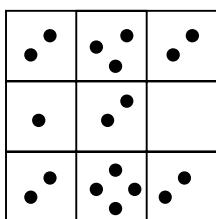


Fig. 2. Example of opinion distribution in a comparison matrix for the GRCGM approach, with  $n=3$  and  $q=2$ .

Even if setting  $Q_{ij}$  to a constant is a restrictive assumption it is still of interest in practice. It covers the case where exactly one opinion is available per comparison. More generally it corresponds to an equilibrated vote where a same number of opinions is attributed to each combination of two elements, i.e. to the  $c_{ij}$  and  $c_{ji}$  comparisons (including reflexive comparisons  $c_{ii}$  counted twice). When the vote cube is partially filled, it is possible to complete some of the missing entries. For instance, it is always possible to assume the missing reflexive comparisons to be equal to 1 or to consider several reflexive opinions equal to 1 so as to equilibrate the vote entries. The decision group can also duplicate (increase the importance of) some of the opinions for the comparisons  $\{(e_i, e_j), (e_j, e_i)\}$  that received less votes than others.

Our assumption allows us to transform formula 12 into:

$$\theta_i \sum_{j=1}^n 2q - \sum_{j=1}^n 2q\theta_j = R_i - G_i, \quad i = 1, 2, \dots, n \Leftrightarrow \theta_i = \frac{R_i - G_i}{2nq} + \frac{\sum_{j=1}^n \theta_j}{n}, \quad i = 1, 2, \dots, n. \quad (13)$$

The weight  $w_n$  being arbitrarily fixed to 1, this leads to:

$$\theta_n = \log(w_n) = 0 = \frac{R_n - G_n}{2nq} + \frac{\sum_{j=1}^n \theta_j}{n}, \quad \text{hence } \theta_i = \frac{R_i - G_i - (R_n - G_n)}{2nq}, \quad i = 1, 2, \dots, n \quad (14)$$

The non yet normalized weights may now be expressed as:

$$w_i \approx \exp(\theta_i), \quad i = 1, 2, \dots, n \Leftrightarrow w_i \approx \sqrt[2q]{\frac{R_i^*}{G_i^*} \times \frac{G_n^*}{R_n^*}}, \quad i = 1, 2, \dots, n. \quad (15)$$

The terms  $R_s^*$  et  $G_s^*$  are homogeneous with geometric means of opinions of row  $s$  and column  $s$ , respectively. They are given by:

$$\left| \begin{aligned} R_s^* &= \sqrt[n]{\exp(R_s)} = \sqrt[n]{\exp\left(\sum_{r=1}^n \sum_{k=1}^d \alpha_{srk} \log(c_{srk})\right)} = \sqrt[n]{\prod_{r=1}^n \prod_{k=1}^d c_{srk}^{\alpha_{srk}}} \\ G_s^* &= \sqrt[n]{\exp(G_s)} = \sqrt[n]{\exp\left(\sum_{r=1}^n \sum_{k=1}^d \alpha_{rsk} \log(c_{rsk})\right)} = \sqrt[n]{\prod_{r=1}^n \prod_{k=1}^d c_{rsk}^{\alpha_{rsk}}} \end{aligned} \right., \quad s = 1, 2, \dots, n. \quad (16)$$

The two constant terms  $R_n^*$  and  $G_n^*$  disappear when the weights are normalized. This normalization leads to the definitive weight expression:



$$w_{iN} \approx 2q \sqrt{\frac{R_i^*}{G_i^*}} / \sum_{i=1}^n 2q \sqrt{\frac{R_i^*}{G_i^*}}, \quad i = 1, 2, \dots, n,$$

$$\text{with } \begin{cases} R_s^* = \sqrt[n]{\prod_{r=1}^n \prod_{k=1}^d c_{srk}^{\alpha_{srk}}} \\ G_s^* = \sqrt[n]{\prod_{r=1}^n \prod_{k=1}^d c_{rsk}^{\alpha_{rsk}}} \end{cases}, \quad s = 1, 2, \dots, n. \quad (17)$$

Finally, it is possible to give an explicit formula for the comparisons  $c_{ij}^*$  composing the resulting consistent matrix  $C^*$  in the form:

$$c_{ij}^* = \frac{w_i}{w_j} \approx 2q \sqrt{\frac{R_i^*}{G_i^*}} \times \frac{G_j^*}{R_j^*}, \quad i, j = 1, 2, \dots, n, \quad \text{with } \begin{cases} R_s^* = \sqrt[n]{\prod_{r=1}^n \prod_{k=1}^d c_{srk}^{\alpha_{srk}}} \\ G_s^* = \sqrt[n]{\prod_{r=1}^n \prod_{k=1}^d c_{rsk}^{\alpha_{rsk}}} \end{cases}, \quad s = 1, 2, \dots, n. \quad (18)$$

Let us consider again our assumption  $Q_{ij}=2q$ . It means that the number of opinions expressed on two elements (i.e. on the comparisons  $c_{ij}$  and  $c_{ji}$ ) is constant and even. The case  $q=1$  corresponds to exactly one opinion per comparison. Formula 18 is then equivalent to the formula given hereafter which, in return, is identical to formula 3 proposed by Koczkodaj and Orłowski:

$$c_{ij}^* = \frac{w_i}{w_j} \approx \sqrt{\frac{R_i^*}{G_i^*}} \times \frac{G_j^*}{R_j^*} = \sqrt[n]{\prod_{r=1}^n \left( \frac{c_{ir}}{c_{ri}} \times \frac{c_{rj}}{c_{jr}} \right)}, \quad i, j = 1, 2, \dots, n, \quad \text{with } \begin{cases} R_s^* = \sqrt[n]{\prod_{r=1}^n c_{sr}} \\ G_s^* = \sqrt[n]{\prod_{r=1}^n c_{rs}} \end{cases} \quad (19)$$

## 6. Conclusion

Pairwise comparison methods are convenient procedures that decompose the weighting of  $n$  elements into pairwise relative comparisons so as to help decision makers in predicting the soundest weights.

Two popular approaches exist in the literature: the Least Squares Logarithmic Regression method (LSLR) by de Graan [1] and Lootsma [2] and the recent Row and Column Geometric Mean (RCGM) by Koczkodaj and Orłowski [3]. Both approaches are based on the minimization of logarithmic least squares. However, they consider different hypothesis: the LSLR approach assumes the reciprocity property for the vote cube while the RCGM approach requires the presence of exactly one opinion per comparison.

In this paper, each of these approaches has been extended by releasing the two corresponding restrictive assumptions. Both extensions lead to the same generalized objective function. With the assumption of a constant opinion number for all the pairwise comparisons, new algebraic expressions have been established for the predicted weights. We have verified that for one opinion per comparison, our formula matches that of Koczkodaj and Orłowski. Such an explicit formulation is particularly interesting for extending the deterministic pairwise comparison approach to a modeling of judgmental imprecision.

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