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Selection Procedure of the Approximation Methods for Deriving Priorities: A Case of Inconsistent Pairwise Comparisons

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Abstract

Background: When pairwise comparisons are used to express preferences for alternatives or judgments on criteria's importance, several methods can be used to derive priorities in multi-criteria decision-making. In the case of inconsistency, different methods give different results. **Objectives:** The main goal of this paper is to present the procedure of measuring the accuracy of the selected approximation methods based on pairwise comparisons compared to the priorities obtained by the eigenvalue method. It also aims to illustrate the procedure on the numerical example characterised by acceptable inconsistency. **Methods/Approach:** The presented procedure is based on a prescriptive approach, the fixed ratio scale, reciprocal pairwise comparison matrices, and consistency ratio. Mean absolute deviation and mean absolute percentage deviation are used to measure accuracy. **Results:** The first result is the theoretical statement of the priorities' accuracy measurement procedure. The results of the numerical example characterised by the preferences of strength slight to strong plus show that, on average, the most accurate approximation method is the geometric mean method. **Conclusions:** The research contributes to the literature on prescriptive approaches to decision-making. The results can show potential users which approximation method to use and lecturers which of them to include in the curriculum portfolio.

Keywords: accuracy; analytic hierarchy process; approximation method; pairwise comparisons; priority; simulation

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Introduction

In multi-criteria decision-making, pairwise comparisons (Kuske et al., 2019) are recognised as a useful indirect way of expressing preferences for alternatives and judgments of criteria's importance whose advantages are reflected in a growing number of applications in solving complex problems (e.g., Chakrabortty, Abdel-Basset, & Ali, 2023; Čančer et al., 2023; Koczkodaj et al, 2016; Promentilla et al., 2018). According to Koczkodaj et al. (2016), pairwise comparison method is one of a few valid methods for processing subjective data. Based on pairwise comparisons of preferences to various alternatives and the importance of various criteria performed by the decision-maker, the pairwise comparison matrices are built. Grzybowski (2012) identifies the right eigenvalue method, which is later in this paper called the eigenvalue method, as one of the most popular, commonly used, and recommended for deriving priorities. According to Choo and Wedley (2004), the eigenvalue method also satisfies the condition of correctness in error-free cases. However, quality and purpose-developed computer programs that support decision-making procedures, including this method, are often inaccessible to users due to several factors such as price, incompatibility of computer programs with the operating system, etc. Users can, and in these cases, also use approximation methods for creating appropriate spreadsheets with available programs, such as Excel. The question of how to choose the method to calculate the priorities (Ishizaka, 2019) arises.

Kazibudzki (2019) pointed out that when judgments or preferences are perfectly consistent, i.e., cardinally transitive, all approximation procedures coincide, and the quality of the prioritization process is exemplary. According to Koczkodaj et al (2016), the lack of consistency in the pairwise comparison matrices is the main challenge in terms of realistic inputs. As the human judgments and preferences are rarely perfectly consistent (Kazibudzki, 2019), the results are often subject to considerable inaccuracy and the quality of the priorities derived from pairwise comparison matrices with different approximation methods may vary. By adapting Chen's (2020) definition of inaccuracy to our problem it can be concluded that inaccuracy means that priorities do not reflect the real relative importance levels of criteria or preference levels of alternatives. This is a critical issue since approximation methods are often used in practice to approximate priorities. If the matrix of expressed judgments or preferences is inconsistent, different approximating methods give different priorities, i.e., weights and local alternatives' values. When selecting approximation methods, it is, therefore, appropriate to assess the accuracy of the obtained priorities.

The purpose of this paper is, therefore, to develop the procedure for measuring the accuracy of the approximation methods for priorities derivation based on inconsistent pairwise comparisons (see, e.g., Choo & Wedley, 2004; Saaty, 2012) compared to the priorities obtained by the eigenvalue method. This paper aims also to compare the accuracy of the approximation methods on the numerical example of the inconsistent pairwise comparisons matrix with the elements expressing slight to strong plus preferences to alternatives.

For this purpose, mean absolute deviation (*MAD*) and mean absolute percentage deviation (*MAPD*) (Bastič, 2003; Render et al., 2021) were adjusted and used as the measures of accuracy. For example, Grzybowski (2012) already used *MAD* when comparing simulation results of several prioritization techniques, but for the analysis of the rounding impact and the errors of human nature. The eigenvalue method, on the other hand, is used in the analytic hierarchy process (AHP) method. Many scientists, practitioners, and students from various scientific and professional fields agree that AHP is a simple and versatile multicriteria method (e.g., Čančer et al., 2023; Ishizaka, 2019; Promentilla et al., 2018) that helps individuals and groups solve important comprehensive decision problems. It provides a systematic decision-making procedure (Promentilla et al., 2018). Koczkodaj et al (2016) pointed out that AHP is not the only representation of pairwise comparisons. However, the AHP method had a significant impact on the pairwise comparisons research (Koczkodaj et al, 2016; Ágoston & Csató, 2022), which also applies to the research presented in this paper.

This paper aims to answer the following research questions:

- RQ1: How can we combine the simulation of inconsistent pairwise comparison matrices and customized accuracy measures to the procedure of selecting the most accurate approximation method for deriving priorities? and
- RQ2: Which approximation method considered in case of inconsistencies and slight to strong plus judgments or preferences gives the most accurate priorities?

The rest of the paper is structured as follows. The methodological section presents the basics of the eigenvalue method of the AHP and the selected approximation methods for priorities derivation. It also presents the selected accuracy measures and a description of the procedure for assessing the accuracy of the approximation methods for priorities derivation. The next section illustrates the developed procedure with a numerical example. The paper concludes with the main findings, limitations, and further research possibilities.

Methodology

Under the term priority, we understand the weights of criteria and local values of alternatives. When decision-makers cannot determine criteria weights and local alternatives' values directly they can use indirect methods based on ordinal, interval, and ratio scales (Belton & Stewart, 2002; Čančer, 2012). Judgments on the importance of the criteria and preferences for alternatives concerning a single criterion can be expressed by pairwise comparisons based on a ratio scale (Saaty, 2008, 2012). The linguistic equivalents to numerical values of the fundamental AHP scale (Saaty, 2008) were used in this research: 1 means that none of the two criteria compared is more important or none of the two alternatives compared is favoured; 2 means that the criterion is slightly more important than the compared one or the alternative is slightly more preferred than the compared one; the linguistic explanation of judgment or preference strength 3 is moderate, of 4 moderate plus, of 5 strong, of 6 strong plus, of 7 very strong, of 8 very, very strong, and of 9 extreme. Reciprocal values should be used when the criterion is less important or the alternative is less preferred than the compared one.

Eigenvalue method for priorities derivation

Let us summarize the basics of the eigenvalue method for the priorities' derivation (Saaty & Sodenkamp, 2010). Judgments on criteria's importance, expressed by pairwise comparisons, are the ratios of the criteria weights that indicate that criterion *i* is a_{ij} times more important than criterion *j*. Similarly, preferences for alternatives concerning each criterion, expressed by pairwise comparisons, are the ratios of the local values that indicate that the alternative A_i is a_{ij} times more preferred than alternative A_j:

$$a_{ij} = \frac{p_i}{p_j}, \qquad (1)$$

where p_i is the weight of the *i*th criterion or the local value of the *i*th alternative, and p_j is the weight of the *j*th criterion or the local value of the *j*th alternative, *i* = 1, 2, …, *k*,

j = 1, 2, …, k. Based on pairwise comparisons, we can write a square matrix A. Let A be the matrix of expressed judgments on the criteria's importance as well as the matrix of expressed preferences to alternatives with the following characteristics: $a_{ij} > 0$, $a_{ij} = 1/a_{ji}$, $a_{ii} = 1$, and $a_{im} \times a_{mj} = a_{ij}$. The latter characteristic, the so-called transitivity, applies only in the case of complete consistency. In this case, $Ap = kp$, or $(A – kE)p = 0$, which is a homogenous system of k linear equations with k unknown variables. It has infinitely many solutions because the rows in matrix A are proportional. In practice, the consistency is usually incomplete, so we get the system:

$$Ap = \lambda p, \qquad (2)$$

where λ is the eigenvalue of matrix A and p is the eigenvector of matrix A. If and only if $k = \lambda$, the consistency is complete. λ is determined so that (2) has infinitely many solutions. We obtain a polynomial of the k^{th} level. At λ_{max}, we calculate a particular solution so that $\sum_{m=1}^{k} p_m = 1$. The smaller the difference $|\lambda_{max} - k|$, the more consistent a decision-maker. Consistency index $CI = \frac{\lambda_{max}-k}{k-1}$ can be used as a measure of inconsistency. However, in this paper, the consistency ratio

$$CR = \frac{CI}{R}, \qquad (3)$$

where R is the random index of inconsistency, obtained experimentally considering k (Ishizaka, 2019; Saaty & Sodenkamp, 2010), is used as a measure of inconsistency. A decision-maker is reasonably consistent if $CR \leq 0.1$.

Approximation methods for priorities derivation

Priorities can be derived using several approximation methods (Choo & Wedley, 2004). Ease of use was a fundamental criterion for including the assessment of the accuracy of the following approximation methods in the paper:

I. Divide the sum of the values in each row with the sum of all values in matrix A.
II. Calculate the reciprocal value of the sum of the values in each column in matrix A.
III. Calculate priorities as the average of priorities calculated by I and II.
IV. First, add the values in each column in matrix A. Then divide each entry in each column by the total of that column to obtain the normalized matrix which permits meaningful comparison among elements. Finally, calculate the average over the rows by adding the values in each row of the normalized matrix and dividing the rows by the number of entries in each. This is the so-called approximative eigenvector method based on normalization (Saaty, 2012).
V. First, calculate the geometric mean of a row in the pairwise comparison matrix A. That geometric mean is the priority value of the factor indicated by the row. Normalize the priorities by dividing each priority value by the sum of all priorities that is obtained from the geometric mean. This is the so-called geometric mean method (Choo & Wedley, 2004; SpiceLogic Inc, 2022).

Measures of accuracy

We adjusted the selected measures of forecast accuracy (Bastič, 2003; Render et al, 2021) to the measures of the accuracy of priorities derived by approximation methods based on pairwise comparisons. To see how accurate the priorities were, the priorities obtained with approximation methods were compared to the priorities obtained with the eigenvalue method, which in this paper is assumed as an exact method. The error is defined as the difference between the priority obtained with the exact method and the priority obtained with an approximation method. The adjusted measures are as follows.

Mean absolute deviation (*MAD*) is computed by taking the sum of the absolute values of the individual errors and dividing it by the number of errors:

$$MAD = \frac{1}{r}\sum_{l=1}^{r}|p_l^e - p_l^a|, \qquad (4)$$

where p_l^e is the exact l^{th} priority and p_l^a is the approximate l^{th} priority, and r is the number of simulations regarding *CR* (3).

Mean absolute percentage deviation (*MAPD*) is calculated by taking the sum of the absolute values of the individual errors, dividing it by the sum of exact priorities, and multiplying by 100:

$$MAPD = \frac{\sum_{l=1}^{r}|p_l^e - p_l^a|}{\sum_{l=1}^{r} p_l^e} \times 100. \qquad (5)$$

According to exact priorities, it reflects the mean percentage of absolute individual errors.

The procedure of measuring the accuracy of the approximation methods for deriving priorities

The procedure of measuring the accuracy of the approximation methods for priorities derivation is based on the simulation:

- Initiate from the perfectly consistent pairwise comparisons matrix with expressed judgments on the criteria's importance or preferences for alternatives. Then change a particular element in matrix *A* so that the inconsistency increases. In this procedure, *CR* is used as a discrete variable. As we want to measure the priorities' accuracy when a decision-maker is acceptably consistent ($CR \leq 0.1$), the *CR*'s values from 0.01 to 0.1 are considered.
- Obtain the priorities' values with the exact method and with the approximation methods considered.
- Calculate the accuracy measures *MAD* (4) and *MAPD* (5) for each priority and approximation method. For each approximation method, the average of the *MAD* values is calculated, as well as the average of the *MAPD* values. The approximation method where the mean *MAD* and *MAPD* values are the lowest should be used to prepare the multi-criteria decision-making basis.

The computer program Expert Choice can be used to obtain the priorities' values with the exact method, and the computer program Excel can be used to obtain the priorities' values with approximation methods.

Results

Let us illustrate the procedure of measuring the accuracy of the approximation methods for priorities derivation with a numerical example based on an extensive real-life problem of selecting the most appropriate video-conferencing system. The following video-conferencing systems for medium room were included as alternatives: MeetingBar A30 (Yealink, 2023) – Alternative 1, Panacast 50 (Jabra[GN], 2023) –

Alternative 2, and Poly Studio X50 (Plantronics Inc, 2024) – Alternative 3. Based on the IT expert help that considered the characteristics of alternatives, preferences for alternatives concerning 'camera' are as follows: Alternative 1 is 3 times – moderately more preferred than Alternative 2 and 6 times – strongly plus more preferred than Alternative 3, and Alternative 2 is twice – slightly more preferred than Alternative 3.

The initial matrix A is given as follows:

$$\begin{bmatrix} 1 & 3 & 6 \\ 1/3 & 1 & 2 \\ 1/6 & 1/2 & 1 \end{bmatrix}. \qquad (6)$$

CR = 0 shows that (6) is a perfectly consistent matrix. Then we changed the element a_{23} so that the inconsistency increased: 2.5 (CR = 0.01), 3 (CR = 0.02), 3.5 (CR = 0.03), 3.75 (CR = 0.04), 4 (CR = 0.05), 4.25 (CR = 0.06), 4.51 (CR = 0.07), 4.74 (CR = 0.08), 5.02 (CR = 0.09), 5.26 (CR = 0.1). In (6), the reciprocal values of a_{23} must be calculated for a_{32}, as well.

Table 1 presents the values of priorities p_1, p_2, and p_3, obtained with the exact and five approximation methods described in the previous section and rounded to three decimal places.

Table 1
Values of Priorities Obtained with Exact and Approximation Methods

Method	Consistency Ratio										
	0	**0.01**	**0.02**	**0.03**	**0.04**	**0.05**	**0.06**	**0.07**	**0.08**	**0.09**	**0.1**
	p_1										
Exact	0.667	0.661	0.655	0.649	0.647	0.644	0.642	0.639	0.637	0.635	0.633
I	0.667	0.649	0.632	0.614	0.605	0.597	0.589	0.580	0.573	0.564	0.557
II	0.667	0.667	0.667	0.667	0.667	0.667	0.667	0.667	0.667	0.667	0.667
III	0.667	0.658	0.649	0.640	0.636	0.632	0.628	0.623	0.620	0.616	0.612
IV	0.667	0.660	0.653	0.646	0.643	0.639	0.636	0.633	0.630	0.627	0.624
V	0.667	0.661	0.655	0.649	0.647	0.644	0.642	0.639	0.637	0.635	0.633
	p_2										
Exact	0.222	0.237	0.250	0.261	0.266	0.271	0.275	0.279	0.283	0.288	0.291
I	0.222	0.249	0.274	0.297	0.308	0.318	0.329	0.339	0.348	0.359	0.367
II	0.222	0.227	0.231	0.233	0.234	0.235	0.236	0.237	0.237	0.238	0.239
III	0.222	0.238	0.252	0.265	0.271	0.277	0.282	0.288	0.293	0.298	0.303
IV	0.222	0.238	0.251	0.263	0.268	0.274	0.279	0.284	0.288	0.293	0.297
V	0.222	0.237	0.250	0.261	0.266	0.271	0.275	0.279	0.283	0.288	0.291
	p_3										
Exact	0.111	0.102	0.095	0.090	0.087	0.085	0.083	0.081	0.080	0.078	0.076
I	0.111	0.102	0.095	0.089	0.087	0.085	0.083	0.081	0.079	0.077	0.076
II	0.111	0.105	0.100	0.095	0.093	0.091	0.089	0.087	0.085	0.083	0.082
III	0.111	0.103	0.097	0.092	0.090	0.088	0.086	0.084	0.082	0.080	0.079
IV	0.111	0.102	0.096	0.091	0.089	0.087	0.085	0.084	0.082	0.081	0.079
V	0.111	0.102	0.095	0.090	0.087	0.085	0.083	0.081	0.080	0.078	0.076

Note: I, II, III, IV, V – approximation methods
Source: Author's calculations

It can be concluded that the higher the CR, the more the priorities obtained differ from those at CR = 0 (Table 1). This applies to all the methods used, except for II, when used for the calculation of p_1, as the first column in (6) does not change in simulations.

The values of *MAD* and *MAPD* were calculated by (4) and (5) so that the approximation values of priorities were considered at *CR* = 0.01 to *CR* = 0.1 (Table 1), *r* = 10. At *CR* = 0, the exact value is equal to the approximation value, regardless of the approximation method used. The values of accuracy measures *MAD* and *MAPD* of priorities obtained with approximation methods from I to V are given in Table 2.

Table 2
Values of Accuracy Measures for Priorities Obtained with Approximation Methods

Approximation method	Mean Absolute Deviation				Mean Absolute Percentage Deviation			
	p_1	p_2	p_3	Mean	p_1	p_2	p_3	Mean
I	0.0482	0.0487	0.0003	0.0324	7.482	18.030	0.350	8.62
II	0.0228	0.0354	0.0053	0.0212	3.539	13.106	6.184	7.61
III	0.0128	0.0066	0.0024	0.0073	1.987	2.444	2.801	2.41
IV	0.0051	0.0034	0.0019	0.0035	0.792	1.259	2.217	1.42
V	0	0	0.0010	0.0003	0	0	1.167	0.39

Source: Author's calculations

The results in Table 2 show that on average, approximation method V, i.e., the geometric mean method, gives the most accurate priorities' values: mean absolute deviation is 0.0003 (*MAD* = 0.0003), and the sum of the absolute values of individual errors present 0.39 % of the sum of the exact priorities (*MAPD* = 0.39). Moreover, this method gives perfectly accurate values of p_1 and p_2 (*MAD* = *MAPD* = 0), and among the considered approximation methods, the second most accurate value of p_3 (*MAD* = 0.001, *MAPD* = 1.167). The second most accurate approximation method is, on average, the approximative eigenvector method based on normalization (IV, *MAD* = 0.0035, *MAPD* = 1.42), followed by the approximation method based on the average of priorities obtained with approximation methods I and II (III, *MAD* = 0.0073, *MAPD* = 2.41), and the approximation method based on the reciprocal value of the sum of the values in each column of *A* (II, *MAD* = 0.212, *MAPD* = 7.61). The least accurate approximation method is I which is based on the ratio of the sum of the values in each row and the sum of all values in the matrix *A* (*MAD* = 0.0324, *MAPD* = 8.62). The same order of accuracy of the approximation methods also applies to p_1 and p_2. For calculating p_3 values, however, the approximation method I is the most accurate, followed by the approximation methods V, IV, III, and II.

Discussion and Conclusion

The research work presented in this paper resulted in the theoretical statement of the priorities' accuracy measurement scheme, based on pairwise comparisons. The methodological part answered the first research question. Beginning with a perfectly consistent pairwise comparison matrix with expressed judgments on the criteria's importance or preferences for alternatives, the procedure for selecting the most accurate approximation method for deriving priorities includes several sequential steps. Initially, a simulation is conducted to gradually increase the inconsistency until reaching the *CR* at which the pairwise comparison matrix is still acceptably consistent. Following this, priorities are derived using the eigenvalue method and selected approximation methods. Then, accuracy measures are calculated, and the approximation method with the minimal mean accuracy values is identified. The accuracy measures *MAD* and *MAPD* were adapted to this problem.

The procedure has been applied to a numerical example to illustrate its applicability. The results of the considered numerical example can help us answer the second research question. In case of inconsistencies and slight to strong plus judgments or preferences, on average, the geometric mean method gives the most accurate priorities among the selected approximation methods for deriving priorities. This is in line with the summarization (Ishizaka, 2019) that simulations did not identify significant differences between the geometric mean and eigenvalue method.

The procedure for measuring the accuracy of the approximation methods for deriving priorities is useful for advising on the determination of a portfolio of approximation methods to those users who express their judgments and preferences by pairwise comparisons but do not have access to computer programs in which the calculation of priorities is based on the eigenvalue method. The results can show potential users which approximation method to use, and lecturers which approximation methods to include in the curriculum portfolio.

In this research, the accuracy measures were limited to *MAD* and *MAPD*. A well-known accuracy measure is an average error, known as bias, which tells whether the priorities' values obtained with approximation methods tend to be too high or too low and by how much; it may be negative or positive (Render et al, 2021). Because the negative errors can cancel out the positive ones, it is not a good measure of the actual size of the errors (Render et al, 2021); for this reason, it has been omitted. This research is limited to AHP pairwise comparisons using a positive reciprocal matrix. Focused on the research problem considered in this paper we did not use accuracy measures in other research fields (e.g., Vrigazova, 2020, 2021) or efficiency measures (Abele-Nagy et al., 2018; Chen, 2020). The numerical example was limited to the matrix of order 3 x 3, i.e., the lowest order in which inconsistencies can arise, and to relatively large ratios between matrix *A* elements. This research does not deal with the fuzzy analytic hierarchy process where approximation methods have been extensively applied to determining the weights of criteria in MCDM problems (Chen, 2020).

Further research can be oriented toward matrices of higher order, with different, smaller, and larger ratios between matrix A elements in several simulations. Further research possibilities also arise in adapting the presented procedure to examine the accuracy of fuzzy analytic hierarchy process methods according to the consistency ratio.

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