Group Decision Making in Collaborative Modeling

Aggregating Individual Preferences with AHP

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Abstract. The need for negotiation and decision making among collaborative modelers stems from their desire to reconcile their different positions, priorities and preferences. This requires them to engage in an argumentative negotiation process so as to achieve consensus. A number of methods can be used to aggregate their judgements and priorities thus helping them to reach consensus. In this paper we show how the Analytic Hierarchy Process (AHP) can be used to help modelers reach consensus about the quality of the different modeling aspects in a collaborative modeling process. Insights derived from this approach could be used to aid modelers reach consensus about the quality of the different aspects in a collaborative modeling session through a decision making negotiation process.

Keywords: *Collaborative Modeling, Modeling Process Quality, Group Decision Making, Negotiation, Analytic Hierarchy Process*

1 Introduction

In collaborative modeling [13,19] or group modeling [21] a number of stakeholders (users or domain experts, systems analysts, etc.) with different skills, expertise and knowledge are brought together in a problem-solving modeling activity. These stakeholders jointly and collaboratively explore possible solutions during the modeling process so as to reach consensus. Whilst there are many ways of reaching consensus, negotiation has been found to be one of most effective ways of reaching agreement through a communicative and argumentative process in collaborative modeling, see for example [19,20]. Negotiation is a technique aimed at finding some compromise or consensus (agreement) between and among the different stakeholders on some matter of collective interest but where individual interests, criteria, preferences or constraints may prevent such agreement.

Although the role played by communication in conceptual modeling was long recognized in trying to understand the process (act) of modeling [10,17] and collaborative modeling was explicitly found to be a negotiation process [19], little work, however, has been done to understand collaborative modeling as a "multi-actor and multi-criteria decision making process". The aim of this paper is to take an initial step in this direction by searching for an approach and a methodology for aggregating the modelers preferences and priorities in a multi-actor and multi-criteria collaborative modeling session. To achieve this, we focus on the application of Multi-Criteria Decision Making Aid (MCDA) methods from the area of Operations Research (OR).

Selecting a particular MCDA requires the decision maker and analyst to know the pros and cons, the problem being addressed and the context in which the problem is being solved. We motivate our choice by looking at some of the available MCDA methods. Due to paper size constraints, we cannot go into the comparative analysis of these methods. MCDA can broadly be categorized into two main classes: (i) continuous and (ii) discrete methods [9]. In the continuous methods there is a finite and explicit set of constraints in the form of defined functions that define an infinite number of alternatives to consider in the evaluation and decision making process by the so-called Decision Maker (DM). Decision making problems in this class are referred to as continuous multi-criteria decision making problems or multi criteria optimization (MCO) problems [28]. In the second class, the discrete case, there is a finite number of alternatives normally defined in tabular form with their corresponding evaluation criteria. Decision making problems in this class are referred to as discrete multi-criteria decision making problems or multi-criteria analysis (MCA) problems.

The decision making problem we study in collaborative modeling belongs to the discrete case and is therefore a MCA problem. For collaborative modelers to evaluate and decide on the best modeling approach that meets their quality goals they need, at both individual and group levels, to indicate their preferences among the alternatives through the evaluation of quality criteria. To achieve this, there is need to apply a preference model or approach to the MCA problem. There are three approaches to choose from: (i) the single synthesizing (weighting) criterion preference approach, (ii) the outranking synthesizing preference approach and (iii) the interactive local-judgement preference approach.

The single weighting criterion preference approach consists of a number of methods with Analytic Hierarchy Process (AHP) [23], the Multi-attribute Utility Theory (MAUT) and Multi-attribute Value Theory (MAVT) methods [5,11] with the Simple Multi-attribute Rating Technique (SMART) as a prominent representatives. The outranking synthesizing preference approach has the: "Elimination Et Choix Traduisant la Realité", i.e. Elimination and Choice Expressing Reality (ELECTRE) methods [22] and the Preference Ranking METHod for Enrichment Evaluation (PROMETHEE) methods [4] with different variants as the most prominent representatives. The interactive local-judgement preference approach has the Multiple Objective Mathematical Programming Methods (MOMP) [16] as the most prominent representatives.

A number of guidelines have been proposed [9] and a number of comparative studies done to help in selecting the most appropriate MCDA method, see for example [2][3][14][27] from the categories above. For collaborative modeling, modelers have to evaluate the different collaborative modeling approaches (CMA) using a set of defined criteria for the modeling artifacts used in and produced by the collaborative modeling effort. They take decisions individually and as a group. This requires their preferences and priorities to be aggregated using group decision methods employing any of the MCDA methods mentioned above. Considering the pros and cons, given in [12,14], of each of the representative methods for the weighting, outranking and interactive methods and following the guidelines in [9,27] we have zeroed down to the single synthesizing (weighting) criterion preference approach with AHP as the appropriate method to evaluate the collaborative modeling process quality and thus helping in selecting the best collaborative modeling approach. This should, however, not be interpreted to mean that AHP is superior to the other methods in all aspects. It is its flexibility and the availability of the mathematical axiomatic principles in the aggregation of individual preferences and priorities to obtain the group preferences and priorities that made it a favourite. It should also be noted that it is possible to use a hybrid method employing a combination of the MCDA methods as suggested in [14]. In the remainder of the paper we show how AHP can be used to aggregate the individual modelers' preferences and priorities into group preferences and priorities.

This paper is organized as follows. In Section 2 we present our proposal using analytic hierarchy process group decision making (AHP-GDM) approach for aggregating modelers preferences and priorities. In Section 3 we briefly outline an evaluation framework on which the AHP-GDM is applied during a negotiation process. We apply the evaluation proposal and framework to an illustrative example in Section 4. Section 5, finally, closes with a brief summary of our main conclusions and future directions.

2   Group Decision Making with AHP

The Analytic Hierarchy Process (AHP) developed by Saaty [23] is one of the most popular and widely used techniques in decision making. Its popularity stems from its ability to combine the subjective aspects and intangibles associated with human analysis of complex problems. AHP's wide use in decision making further stems from its ability to integrate the subjective and objective opinions, its ability to integrate the individual and group priorities (and/or preferences).

2.1   AHP Group Decision Making Aggregation Methods

To employ AHP in a multi-actor decision making process, there are two important issues that need to be addressed [24]: *how to combine the individual judgements in a group into a group's judgement* and *how to construct a group*

preference from the individual preferences. In order to answer the above questions, there is need to determine [8]: 1) whether the group acts together as a "unit" or acts as "separate individuals", 2) which aggregation procedure (mathematical or otherwise) may be used to combine the individual judgements, and 3) how to obtain and incorporate individual weights in the aggregation if they are not equally weighted. In the next sections we describe two aggregation methods for analytic hierarchy process group decision making (AHP-GDM) based on the above principles, see also [7,18].

2.2   Aggregation of Individual Judgements (AIJ)

Under this techniques, the group normally becomes the "new individual" rather than a collection of independent individuals [8]. Individual actors, in a bid to embrace the new individual - the group, give up their individual preferences (interests, goals, objectives, etc.) for the group. Following the procedure suggested in [7], we show how group priorities can be got. Let $A_i, i \in \{1, n\}$, be the n alternatives to be evaluated and upon which the selection decisions are to be based, and let r be the number of decision makers, and let $k, 1 \leq k \leq r$, be the k-th decision maker. Let the pair-wise comparison (judgement) matrix for the k-th decision maker be given by $A^{[k]} = (a_{ij}^{[k]}), i, j \in \{1, n\}$ and let $w^{[k]} = (w_1^{[k]}, w_2^{[k]}, ..., w_n^{[k]})$ be its corresponding priority vector $(w_i^{[k]} > 0, \sum_{i=1}^{n} w_i^{[k]} = 1)$. If β_k is the weight of the k-th decision maker in contributing to the group decision, where $\sum_{k=1}^{r} \beta_k = 1, \beta_k \geq 0$, then the group pair-wise (judgement) matrix is given by:

$$A^{[G]} = \left(a_{ij}^{[G]} \right), \quad where \quad a_{ij}^{[G]} = \prod_{k=1}^{r} \left(a_{ij}^{[k]} \right)^{\beta_k}, \quad i, j \in \{1, n\} \qquad (1)$$

which is obtained by aggregating the individual priorities using the weighted geometric mean method (WGMM) [8,18] with the following corresponding group vector obtained by using the row geometric mean method method (RGMM) [1,6,7], in this case.

$$w^{[G]} = \left(w_i^{[G]} \right), \quad where \quad w_i^{[G]} = \left(\prod_{j=1}^{n} a_{ij}^{[G]} \right)^{1/n}, \quad i, j \in \{1, n\} \qquad (2)$$

with $a_{ij}^{[G]}$ given by Eq. 1. Note that from Eq. 1 and 2, the WGMM is first used to obtain the group judgement matrix $A^{[G]}$ from the k-th decision maker's matrix, $A^{[k]}, k \in \{1, r\}$. Then using any prioritization techniques: eigenvector method (EGVM) [23] or row geometric mean method RGMM), the group priorities , $w^{[G]}$, are computed, see [6,15].

Remark 1. If the decision makers have the same weight, which is a special case, then $\beta_k = 1/r$.

2.3   Aggregation of Individual Priorities (AIP)

In this technique, unlike the aggregation of individual judgements (AIJ) technique, individuals act in their own right with different value systems resulting in individual alternative priorities [8]. To aggregate the individual priorities into group priorities, we can use either the weighted geometric method (WGMM) or the weighted arithmetic mean method (WAMM). Let $w^{[k]} = (w_1^{[k]}, w_2^{[k]}, ..., w_n^{[k]})$, where $w_i^{[k]} > 0, \sum_{i=1}^{n} w_i^{[k]} = 1$, be the priority (weight) vector of the k-th individual actor (decision maker). Then the group's aggregated priority vector, $w_i^{[G]}, i \in \{1, n\}$ for the alternatives, using WGMM, is given by:

$$w_i^{[G]} = \prod_{k=1}^{r} \left(w_i^{[k]} \right)^{\beta_k}, \quad where \quad w_i^{[k]} = \left(\prod_{j=1}^{n} a_{ij}^{[k]} \right)^{1/n}, \quad i \in \{1, n\} \quad (3)$$

The group priority vector is finally assembled as:

$$w^{[G]} = \left(w_i^{[G]} \right), \quad i \in \{1, n\} \quad (4)$$

Equations 3 and 4, reveal that the individual decision maker's priorities, $w^{[k]}, k \in \{1, r\}$, in the AIP technique, are first computed from their corresponding pairwise matrices, $A^{[k]}, k \in \{1, r\}$, using any prioritization techniques (RGMM or EGVM). Group priorities, $w^{[G]}$ are then obtained from these individual priorities using the WGMM, see for example, [6,15].

Theorem 1 *If WGMM is used as the aggregation method and RGMM is used as the prioritization procedure, then $w_i^{[G]}(AIJ) = w_i^{[G]}(AIP)$*

Proof. [6] □.

2.4   Consistency of Judgements in AHP-GDM

To check whether the decision makers' judgments are consistent, we need to check the consistency of the comparative matrices at each level of the hierarchy. This is done , for the EGVM prioritization method, via the *Consistency Index (CI)* and the *(Consistency Ratio (CR)* calculated, respectively, by [23]:

$$CI = (\lambda_{max} - n)/(n - 1), \qquad CR = CI/RI(n) \quad (5)$$

where RI is a *Random Index* (the average consistency index) calculated as an average of a randomly generated pair-wise matrix of the same order. The inconsistency threshold values are $CR < 0.05$ for n = 3, $CR < 0.08$ for n = 4 and $CR < 0.1$ for $n > 4$. If the RGMM prioritization method is used, then the group consistency is computed using the *geometric consistency index (GCI)* [1].

$$GCI = \frac{2}{(n-1)(n-2)} \sum_{i<j} log^2 (e_{ij}), \; where, \; e_{ij} = a_{ij} w_j / w_i, \; i, j \in \{1, n\} \quad (6)$$

Remark 2. The condition $i < j$ requires that only the elements above the principal diagonal in the pair-wise comparative matrix $A = (a_{ij}), i, j \in \{1, n\}$ are used in the computations.

Because of the subjectivity and inconsistency, there are always errors associated with any k-th decision maker, $k \in \{1, r\}$, when comparing alternatives A_i and A_j. In this case the geometric consistency index of the k-th decision maker, $GCI^{[k]}$, and the group, $GCI^{[G]}$, are, respectively, given by:

$$GCI^{[k]} = \frac{2}{(n-1)(n-2)} \sum_{i<j} \left(\epsilon_{ij}^{[k]} \right)^2, \ where, \ \epsilon_{ij}^{[k]} = log \left(e_{ij}^{[k]} \right), \ i, j \in \{1, n\}$$
(7)

$$GCI^{[G]} = \frac{2}{(n-1)(n-2)} \sum_{i<j} \left(\epsilon_{ij}^{[G]} \right)^2, \ where, \ \epsilon_{ij}^{[G]} = log \left(e_{ij}^{[G]} \right) = \sum_{k=1}^{r} \beta_k \epsilon_{ij}^{[k]}$$
(8)

Theorem 2 *If WGMM is used as the aggregation method and RGMM is used as the prioritization procedure and GCI is used as the measure for inconsistency, then $GCI^{[G]} \leq \max_{k=1 \in \{1,r\}} \{GCI^{[k]}\}$*

Proof. (see [6]) □.

Aguarón and Moreno-Jiménez [1] have established a relationship between the group consistency index (GCI) and Saaty's consistency index(CI) and consistency ratio (CR). In [6,7,29] it is noted that when the WGMM is used as the aggregation procedure and the decision makers have an acceptable level of inconsistency, then so has the group irrespective of the method (EGVM or RGMM) used.

Corollary 1. *If the individual decision makers' judgements are of acceptable inconsistency, so are those of the group, i.e.,*

$$If \quad GCI^{[k]} \leq \tau, k \in \{1, r\}, \quad then \quad GCI^{[G]} \leq \tau$$
(9)

where τ is the threshold of the acceptable inconsistency.

In [1] the corresponding threshold for GCI to those of Saaty's CI are given as: $GCI = 0.031$ for $n = 3$, $GCI = 0.35$ for $n = 4$ and $GCI = 0.37$ for $n \geq 4$.

3   Evaluation of Collaborative Modeling Sessions

In collaborative modeling a number of artifacts are used in, and produced during, the modeling process. These include the modeling language, the methods or

approaches used to solve the problem, the intermediary and end-products produced and the medium or support tool that may be used to aid the collaboration. All these do impact on the quality of the modeling process and need to be evaluated if we are to understand, measure and assess the quality of the modeling process. Figure 1 shows our evaluation framework for the modeling process artifacts with their (selected) attributes and the cause-effect relationships indicated by the arrows. The definitions of the attributes are given in [25].
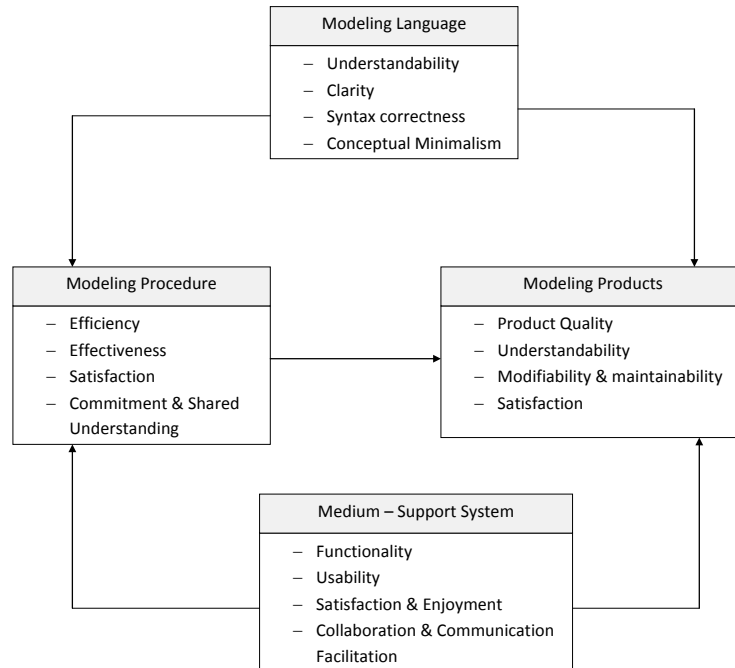

Fig. 1. Mutli-criteria evaluation framework for modeling process artifacts

4   Illustrative Example

The priorities of the decision makers need to be aggregated so as to reach agreement (consensus) on what should be the group's position as far as modeling process quality is concerned. Reaching agreement requires group decision making. It is on this basis that we use the analytic hierarchy process group decision making (AHP-GDM), a multi-criteria decision-making tool in a multi-actor (collaborative or group) modeling environment to show how stakeholders can reach consensus about the quality of the modeling process. We illustrate how this can be done using the analytic hierarchy process (AHP).

4.1   Modeling Process Evaluation - AHP Hierarchy

Using the AHP decomposition steps [23,26] we decomposed the modeling process evaluation problem as shown in Fig. 2. This is the structural decomposition of the identified problem - *Modeling Process Evaluation (MPE)* of collaborative modeling approaches (CMAs) which are the alternatives. The different alternatives (A), sub-criteria (S) and criteria (C) for each artifact and the overall goal (G) are identified. By weighting these, modelers are able to assign and determine their priorities and preferences.
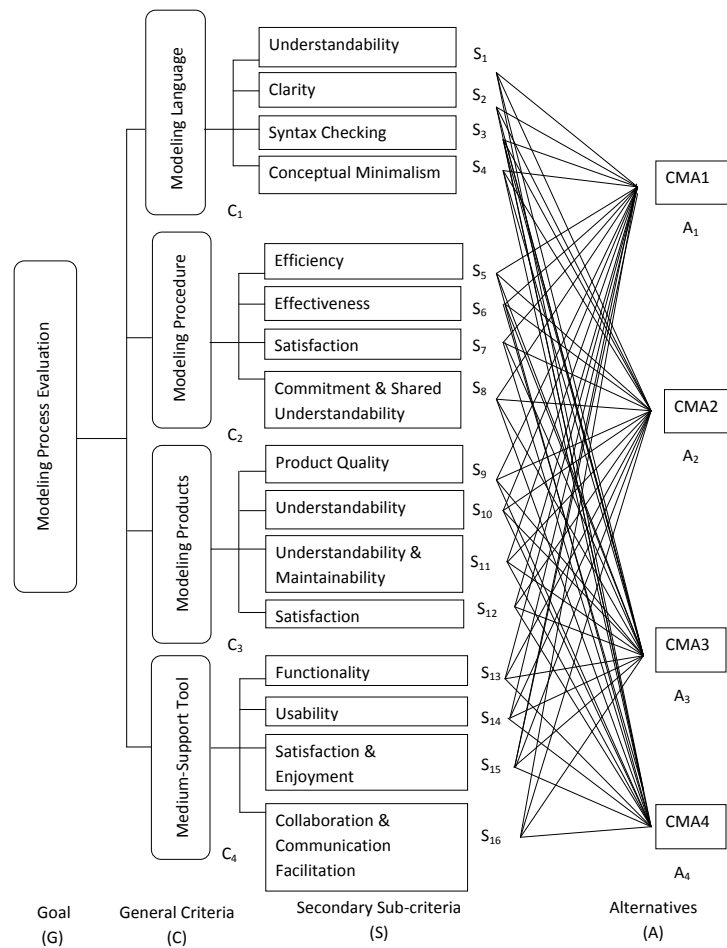

Fig. 2. AHP hierarchy for modeling process evaluation

4.2 Aggregating Individual Preferences into Group Preferences

To illustrate the theoretical concepts developed in Section 2 we consider the example also discussed in [6], initially used in [29]. In this case four decision makers (modelers: M1, M2, M3 and M4) are tasked with the problem of deciding the best collaborative modeling approach (from among the alternatives: CMA1, CMA2, CMA3 and CMA4) which meets the quality goals by measuring and evaluating modeling process quality via the criteria shown in Fig. 1. It should, however, be noted that this example (hypothetical in nature) is chosen to just illustrate the concepts of the methodology being developed for using AHP-GDM to evaluate the modeling process artifacts by aggregating modelers' judgements and priorities. It should further be noted that we illustrate the approach using only AIJ because of Theorem 1. Let the following be the pairwise comparison matrices for the four decision makers for the four alternatives.

$$\mathbf{A}^{[\mathbf{M1}]} = \begin{bmatrix} 1 & 4 & 6 & 7 \\ 1/4 & 1 & 3 & 4 \\ 1/6 & 1/3 & 1 & 2 \\ 1/7 & 1/4 & 1/2 & 1 \end{bmatrix} \qquad \mathbf{A}^{[\mathbf{M2}]} = \begin{bmatrix} 1 & 5 & 7 & 9 \\ 1/5 & 1 & 4 & 6 \\ 1/7 & 1/4 & 1 & 2 \\ 1/9 & 1/6 & 1/2 & 1 \end{bmatrix}$$

$$\mathbf{A}^{[\mathbf{M3}]} = \begin{bmatrix} 1 & 3 & 5 & 8 \\ 1/3 & 1 & 4 & 5 \\ 1/5 & 1/4 & 1 & 2 \\ 1/8 & 1/5 & 1/2 & 1 \end{bmatrix} \qquad \mathbf{A}^{[\mathbf{M4}]} = \begin{bmatrix} 1 & 4 & 5 & 6 \\ 1/4 & 1 & 3 & 3 \\ 1/5 & 1/3 & 1 & 2 \\ 1/6 & 1/3 & 1/2 & 1 \end{bmatrix}$$

The corresponding priorities with consistency values obtained using the AHP steps and Eq. 5 (see, for example [26], for the details of these steps) are:

$$\mathbf{w}^{[\mathbf{M1}]} = \begin{pmatrix} 0.615 & 0.225 & 0.099 & 0.062 \end{pmatrix}^T, \ \lambda_{max} = 4.102, \ CI = 0.034, \ CR = 0.038$$

$$\mathbf{w}^{[\mathbf{M2}]} = \begin{pmatrix} 0.646 & 0.227 & 0.079 & 0.048 \end{pmatrix}^T, \ \lambda_{max} = 4.179, \ CI = 0.060, \ CR = 0.067$$

$$\mathbf{w}^{[\mathbf{M3}]} = \begin{pmatrix} 0.569 & 0.276 & 0.097 & 0.058 \end{pmatrix}^T, \ \lambda_{max} = 4.090, \ CI = 0.030, \ CR = 0.034$$

$$\mathbf{w}^{[\mathbf{M4}]} = \begin{pmatrix} 0.597 & 0.221 & 0.109 & 0.074 \end{pmatrix}^T, \ \lambda_{max} = 4.126, \ CI = 0.042, \ CR = 0.047$$

It should be noted that all individual judgements are consistent since all $CRs <$ 0.10, Saaty's inconsistency threshold for $n \geq 4$.

Case I: Decision makers with equal weights. In this first case, we consider modelers with the same weights (see, Remark 1. Let $\beta_i = 1/4, i \in \{1, 4\}$. Using WGMM in Eq. 1 as the aggregation method and RGMM as the prioritization technique, if $A^{[GI]}$ is the group comparative matrix for case I, then it has the following entries:

$$\mathbf{A}^{[\mathbf{G1}[} = \begin{bmatrix} 1 & 3.936 & 5.692 & 7.416 \\ 0.254 & 1 & 3.464 & 4.356 \\ 0.176 & 0.289 & 1 & 2 \\ 0.135 & 0.230 & 1/2 & 1 \end{bmatrix}$$

with corresponding group judgements, $w^{[G1]}$, obtained using Eq. 2:

$$\mathbf{w^{[G1]}} = \begin{pmatrix} 0.608 & 0.237 & 0.096 & 0.060 \end{pmatrix}^T$$

Case II: Decision makers with different weights. In this second case, we consider modelers with different weights. Let, in this case, $\beta_1 = 1/10$, $\beta_2 = 1/5$, $\beta_3 = 1/10$ and $\beta_4 = 4/10$. Using the WGMM in Eq. 1 and RGMM as the prioritization techniques, if $A^{[G2]}$ is the group comparative matrix, then it has the following entries:

$$\mathbf{A^{[G2]}} = \begin{bmatrix} 1 & 3.837 & 5.446 & 7.204 \\ 0.261 & 1 & 3.464 & 4.134 \\ 0.184 & 0.287 & 1 & 2 \\ 0.139 & 0.242 & 1/2 & 1 \end{bmatrix}$$

with corresponding group judgements, $w^{[G2]}$, obtained using Eq. 2:

$$\mathbf{w^{[G2]}} = \begin{pmatrix} 0.602 & 0.239 & 0.098 & 0.062 \end{pmatrix}^T$$

GCI values are computed from Eqs. 6 - 8 and are give below:
$GCI^{[M1]} = 0.135 \quad GCI^{[M2]} = 0.236 \quad GCI^{[M3]} = 0.119 \quad GCI^{[M4]} = 0.166$
$GCI^{[G1]} = 0.155 \quad GCI^{[G2]} = 0.155$

The results are summarized in Tables 1. One important observation from the results is that the results are similar and they are of acceptable consistency: $CR < 0.10$ for $n \geq 4$ for Saaty's EGVM and $GCI \leq 0.35$ for $n \geq 4$ for AIJ/AIP using WGMM and RGMM. The individual preferences and priorities as well

Table 1. Priorities and consistency indices for alternatives

Modelers Alternatives	M1	M2	M3	M4	G1	G2
CMA1	0.615	0.646	0.569	0.597	0.608	0.602
CMA2	0.225	0.227	0.276	0.221	0.237	0.239
CMA3	0.099	0.079	0.097	0.109	0.096	0.098
CMA4	0.062	0.048	0.058	0.074	0.060	0.062
Consistency measures						
λ_{max}	4.102	4.179	4.090	4.126		
$CI = (\lambda_{max} - n)/(n-1)$	0.034	0.060	0.030	0.042		
$CR = CI/RI(n)$	0.038	0.067	0.034	0.047		
$GCI^{[k]}$	0.135	0.236	0.119	0.166		
$GCI^{[G]}$					0.155	0.155

as the group preferences and priorities indicate that CMA1 is the preferred alternative thus indicating that this collaborative modeling approach satisfies the modelers' quality criteria.

5   Conclusion and Future Directions

In this paper we have applied a known AHP method from the area of Operations Research to an evaluation framework being developed to measure and evaluate the process of modeling. We have demonstrated the approach at the hand of a case example, hypothetical but still semi-realistic, to collaborative modeling artifacts with their associated attributes. The method proposed is to be a key part of a larger setup: a "laboratory" for the study of operational (i.e. real) modeling sessions and related study and development of methods and tools deployed in them. In this laboratory emphasis is on the interactions (e.g., negotiation and decision making), rules (set and strived for) and models as developed in a "Rules, Interactions and Models (RIM) framework [25]. Our immediate goal is to apply the methodology to a real modeling session where we track the interactions of the modelers and their preferences and priorities via a research instrument, e.g., questionnaire using the attributes of the artifacts used in, and produced during, the modeling process. We have made initial attempts towards this as shown in [26]. Subsequent work is aimed at tying up and validating our observations.

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