# Application of the Grey System Theory in Construction Management

## A Case Study of Construction Paint Supplier Evaluation and Selection Criteria

Cuong Phu Pham
Faculty of Transport and Economics, Campus in Ho Chi Minh City, University of Transport and Communications, Vietnam
cuongpp_ph@utc.edu.vn

Phong Thanh Nguyen
Department of Project Management
Ho Chi Minh City Open University
Ho Chi Minh City, Vietnam
phong.nt@ou.edu.vn

Phuong Thanh Phan
Department of Project Management
Ho Chi Minh City Open University
Ho Chi Minh City, Vietnam
phuong.pthanh@ou.edu.vn

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**Abstract-Material management is an important task in building construction. They account for a substantial proportion of investment capital and construction volume. However, as material prices are often affected by the market, choosing the right construction supplier is not an easy decision for contractors, especially for those materials required during the finishing phase of the construction. As one of these finishing materials is paint, identifying core criteria for evaluating and selecting the best construction paint supplier is a crucial economic choice for construction contractors. Assessing the importance of these criteria is a complex multi-criteria decision-making problem. To reflect the risks and uncertainties in this problem, the current paper presents a grey system theory approach to prioritize important criteria for selecting paint material suppliers in construction projects.**

***Keywords-construction management; project management; evaluation and selection criteria; material management; paint supplier; grey theory***

### I. INTRODUCTION

Material management is an essential task in the construction management of any civil engineering project because construction materials account for a high proportion of the total construction cost [1, 2]. In this regard, evaluating and selecting an efficient supplier of construction materials is a very important economic decision and helps the contractor manage materials effectively [3]. One definition of an efficient supplier is a company that specializes in distributing high-quality products in the proper quantity, at the proper time, for a fair price [4]. In a construction project, one commonly required and evaluated material is construction paint. Determining the critical criteria in selecting the construction paint supplier is essential to choosing the material supplier. However, traditional assessment methods (e.g. scoring methods) are often based on the subjective opinions of construction experts, which often do not consider uncertainty in their expert judgments or opinions. This results in a final decision that is often irrational and sometimes inconsistent with reality. To improve this issue, this paper proposes a new quantitative model for prioritizing paint supplier evaluation and selection criteria based on the grey system theory.

### II. RESEARCH BACKGROUND

Construction paint in civil engineering projects is available in liquid, paste, or powder form. The effect of construction paint is to create a solid film that adheres firmly to the building surface for building structure protection and esthetics. Choosing an efficient construction paint supplier is crucial for construction managers. In addition to helping the construction project attain the highest quality, it also helps reduce project cost and shorten the project implementation time. This study identifies the eight most important factors to consider when selecting the construction paint supplier in civil engineering projects based on a literature review of research papers and in-depth interviews with experts [5-21]. These criteria are: (F1) the reputation of the paint supplier, (F2) the quality management system certification of the paint supplier, (F3) the quality of construction paint materials, (F4) the number of paint categories and products, (F5) delivery time, (F6) terms and conditions of payment, (F7) price of the paint product, and (F8) the warranty period.

### III. RESEARCH METHODOLOGY

One approach in studying uncertainty is the grey theory, introduced by Deng in [22-24]. It excels at analyzing mathematical systems with uncertain knowledge. When

Corresponding author: Phong Thanh Nguyen

working with discrete data and insufficient knowledge, grey system theory can be utilized to handle uncertainty or indeterminate problems. A grey system is defined as a system that includes grey variables and a grey number to provide ambiguous information [25]. Figure 1 illustrates the grey system theory.

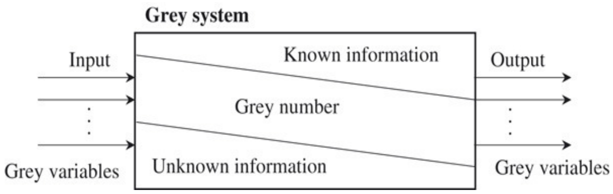


Fig. 1. Grey system theory.

The degree of information and connections between black and white systems are also explained by grey systems, in which grey numbers represent numbers with unknown precise values. Information that is partial, incomplete, or missing can take many different forms. This study uses grey numbers to reflect subjective judgments and reduce evaluation variance among construction experts. Table I [26] compares black, grey, and white systems.

TABLE I. COMPARISON OF BLACK, GREY, AND WHITE SYSTEMS

| **Parameter** | **Black system** | **Grey system** | **White system** |
|---|---|---|---|
| Information | Unknown | Incomplete | Completely known |
| Appearance | Dark | Blurred | Clear |
| Processes | New | Changing | Old |
| Properties | Chaotic | Multivariate | Order |
| Methods | Negation | Change for better | Confirmation |
| Attitude | Letting go | Tolerant | Rigorous |
| Outcomes | No solution | Multi-solutions | Unique solution |

TABLE II. LINGUISTIC SCALES WITH GREY NUMBERS

| **Level of importance** | **Linguistics scale** | **Grey numbers** |
|---|---|---|
| 1 | EI = Equivalent Importance | [1, 2] |
| 3 | MI = Medium Importance | [2, 4] |
| 5 | SI= Strong Importance | [4, 6] |
| 7 | VSI = Very Strong Importance | [6, 8] |
| 9 | EMI = Extreme Importance | [8, 10] |

Let $x$ denote a closed and bounded set of real numbers. A grey number, denoted as $\otimes x$, is a number with an unknown exact value but within a known range. These grey numbers represent uncertain and ambiguous data. In this study, we propose a combination of grey system theory and the Analytical Hierarchy Process (AHP) decision-making method to reduce subjective judgments in prioritizing weights of important criteria in evaluating and selecting paint suppliers for a construction project. In the grey AHP approach, grey numbers are used instead of crisp sets and crisp numbers. The grey AHP method uses pairwise comparisons with linguistic scales and gray scales. The main computational steps to use grey AHP in this study are [27-47]:

Step 1. Define the research problem using traditional AHP. In this step, we identify the research problem, create the hierarchical structure, and construct the pairwise comparison matrix using construction experts' evaluations with linguistic scales containing grey numbers in Table II. The grey comparison matrix using the geometrical mean formulation is constructed as follows:

$$D = \begin{bmatrix} \otimes x_{11} & \otimes x_{12} & \cdots & \otimes x_{1n} \\ \otimes x_{21} & \otimes x_{22} & \cdots & \otimes x_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \otimes x_{m1} & \otimes x_{m2} & \cdots & \otimes x_{mn} \end{bmatrix} \quad (1)$$

where $\otimes x_{ij}$ is the pairwise comparison concerning the $i^{\text{th}}$ criterion over the $j^{\text{th}}$ criterion.

Step 2. Calculate the normalized grey comparison matrix. The normalization for the grey numbers is given in (2)-(4).

$$D^* = \begin{bmatrix} [\underline{x}_{11}^*, \overline{x}_{11}^*] & [\underline{x}_{12}^*, \overline{x}_{12}^*] & \cdots & [\underline{x}_{1n}^*, \overline{x}_{1n}^*] \\ [\underline{x}_{21}^*, \overline{x}_{21}^*] & [\underline{x}_{22}^*, \overline{x}_{22}^*] & \cdots & [\underline{x}_{2n}^*, \overline{x}_{2n}^*] \\ \vdots & \vdots & \vdots & \vdots \\ [\underline{x}_{m1}^*, \overline{x}_{m1}^*] & [\underline{x}_{m2}^*, \overline{x}_{m2}^*] & \cdots & [\underline{x}_{mn}^*, \overline{x}_{mn}^*] \end{bmatrix} \quad (2)$$

$$\underline{x}_{ij}^* = \frac{\underline{x}_{ij}}{\frac{1}{2}\left(\sum_{i=1}^{m}\underline{x}_{ij} + \sum_{i=1}^{m}\overline{x}_{ij}\right)} = \frac{2\underline{x}_{ij}}{\sum_{i=1}^{m}\underline{x}_{ij} + \sum_{i=1}^{m}\overline{x}_{ij}} \quad (3)$$

$$\overline{x}_{ij}^* = \frac{\overline{x}_{ij}}{\frac{1}{2}\left(\sum_{i=1}^{m}\underline{x}_{ij} + \sum_{i=1}^{m}\overline{x}_{ij}\right)} = \frac{2\overline{x}_{ij}}{\sum_{i=1}^{m}\underline{x}_{ij} + \sum_{i=1}^{m}\overline{x}_{ij}} \quad (4)$$

Step 3. Calculate the grey weight of each criterion by determining the averages of the rows using (5):

$$\otimes w_i = \frac{\sum_{j=1}^{n}\otimes x_{ij}^*}{n} = \frac{\sum_{j=1}^{n}\left[\underline{x}_{ij}^*, \overline{x}_{ij}^*\right]}{n} \quad (5)$$

where $n = \{1, 2, \ldots, N\}$ is the criterion set.

Step 4. Calculate the whitenization of the grey weights. The whited value of an interval grey weight is a crisp number with a potential value between the interval grey weight's upper and lower bounds, as follows:

$$M_i = (1-\lambda)\underline{w}_i + \lambda\overline{w}_i \quad (6)$$

where $\lambda$ is the whitening coefficient and $\lambda \in [0,1]$.

Step 5. Calculate the Consistency Ratio (*CR*): To determine whether the decision-comparison preparers were consistent, this step involves examining the *CR* of the pairwise comparison matrix. The calculation of the *CR* from construction experts is [48-52]:

$$CR = \frac{CI}{RI} = \frac{\lambda_{\max} - n}{n-1} \times \frac{1}{RI} \quad (7)$$

where *CI* is the consistency index, *RI* is the random index, and $\lambda_{\max}$ is the largest eigenvalue.

## IV. RESULTS AND DISCUSSION

For calculation simplicity, Table III presents the integrated grey comparison matrix, developed based on the synthesis of construction expert opinions using the geometrical mean formulation for grey numbers given in Table II. Next, we calculated the normalized grey comparison matrix using (2)-(4), as shown in Table IV. After obtaining the normalized grey comparison matrix, we calculate the grey weight of each criterion for evaluating and selecting the construction paint supplier by determining the row averages using (5). The whitenization of the grey weights, obtained by applying (6), is shown in Table V. We choose the value of $\lambda$ to be 0.5 [52, 53]. Finally, we applied (7). The *CR* of this pairwise comparison matrix is $CR = 2.02\% < 10\%$, so the evaluation result is reliable because the pairwise comparison matrix is consistent. The top 5 most important criteria for evaluating and selecting the paint supplier in construction projects were determined to be F7, F1, F3, F2, and F6. Currently, the price of fuel (F7), especially gasoline, is quite high due to scarcity resulting from the conflict between Russia and Ukraine. This causes the paint prices on the market to increase. Therefore, construction contractors are more interested in the price than other criteria. Related to the second most important criterion, the reputation and branding of a paint supplier (F1): some large suppliers spend much money promoting their brands and products on all kinds of media, gaining notoriety in the business world, industry associations, and business partners. In contrast, some suppliers do not choose aggressive advertising methods but rely on their positive reputation to help them promote their branding. Terms and conditions of payment (F6) are usually provided in the purchase contract. Contracts are documents that detail agreements between transaction objects created to achieve the needs of all parties. There are many forms of payment, including one-time payments or partial payments. The ability of the supplier to permit customers to owe money with attractive conditions will make the method of partial payment very popular because the contractor's cash flow is rarely consistent. In addition, to assist customers, the payment process needs to include whether the currency of the transaction is local (VND) or foreign (USD). The variety of options and convenience in financial transactions by the supplier will provide the contractor with more payment options. Because each contractor has its own form of currency storage and its own trading methods, some businesses pay in cash. Others pay through bank transfers, and foreign-owned companies use USD in their projects.

## V. CONCLUSION

Applying a grey AHP, a new quantitative method, by integrating grey system theory with the AHP, we prioritize the critical criteria in the evaluation and selection process of building paint suppliers in construction projects. This new method has an advantage over traditional methods because it supports group decision-making. In addition, it also accounts for uncertainty in the judgments of construction professionals and data incompleteness. The 5 most important criteria for evaluating and selecting the paint supplier in construction projects are (F7) the price of the paint product, (F1) the reputation of the paint supplier, (F3) the quality of construction paint materials, (F2) the quality management system certification of the paint supplier, and (F6) the terms and conditions of payment.

TABLE III. INTEGRATED GREY COMPARISON MATRIX

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| [1.0000, 1.0000] | [1.5874, 3.1748] | [1.2599, 2.5198] | [4.5789, 6.6039] | [3.1748, 5.2415] | [2.5198 4.5789] | [0.6300, 1.2599] | [5.2415, 7.2685] |
| [0.3150, 0.6300] | [1.0000, 1.0000] | [0.7937, 1.5874] | [2.0000, 3.6342] | [1.2599, 2.5198] | [1.2599, 2.5198] | [0.1733, 0.2752] | [5.2415, 7.2685] |
| [0.3969, 0.7937] | [0.6300, 1.2599] | [1.0000, 1.0000] | [3.1748, 5.2415] | [2.0000, 3.6342] | [1.5874, 3.1748] | [0.3969, 0.7937] | [3.6342, 5.7690] |
| [0.1514, 0.2184] | [0.2752, 0.5000] | [0.1908, 0.3150] | [1.0000, 1.0000] | [0.7937, 1.5874] | [0.3467, 0.6300] | [0.1376, 0.1908] | [0.7937, 1.5874] |
| [0.1908, 0.3150] | [0.3969, 0.7937] | [0.2752, 0.5000] | [0.6300, 1.2599] | [1.0000, 1.0000] | [0.6300, 1.2599] | [0.1733, 0.2752] | [0.7937, 1.5874] |
| [0.2184, 0.3969] | [0.3969, 0.7937] | [0.3150, 0.6300] | [1.5874, 2.8845] | [0.7937, 1.5874] | [1.0000, 1.0000] | [0.1733, 0.2752] | [2.0000, 3.6342] |
| [0.7937, 1.5874] | [3.6342, 5.7690] | [1.2599, 2.5198] | [5.2415, 7.2685] | [,3.6342 5.7690] | [3.6342, 5.7690] | [1.0000, 1.0000] | [6.6039, 8.6177] |
| [0.1376, 0.1908] | [0.1376, 0.1908] | [0.1733, 0.2752] | [0.6300, 1.2599] | [0.6300, 1.2599] | [0.2752, 0.5000] | [0.1160, 0.1514] | [1.0000, 1.0000] |

TABLE IV. INTEGRATED GREY COMPARISON MATRIX

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| [0.2399, 0.2399] | [0.1474, 0.2948] | [0.1724, 0.3448] | [0.1908, 0.2752] | [0.1769, 0.2921] | [0.1642, 0.2984] | [0.1794, 0.3589] | [0.1690, 0.2343] |
| [0.0756, 0.1511] | [0.0929, 0.0929] | [0.1086, 0.2172] | [0.0833, 0.1514] | [0.0702, 0.1404] | [0.0821, 0.1642] | [0.0494, 0.0784] | [0.1690, 0.2343] |
| [0.0952, 0.1904] | [0.0585, 0.1170] | [0.1368, 0.1368] | [0.1323, 0.2184] | [0.1115, 0.2025] | [0.1035, 0.2069] | [0.1130, 0.2261] | [0.1172, 0.1860] |
| [0.0363, 0.0524] | [0.0255, 0.0464] | [0.0261, 0.0431] | [0.0417, 0.0417] | [0.0442, 0.0885] | [0.0226, 0.0411] | [0.0392, 0.0543] | [0.0256, 0.0512] |
| [0.0458, 0.0756] | [0.0368, 0.0737] | [0.0377, 0.0684] | [0.0260, 0.0530] | [0.0557, 0.0557] | [0.0411, 0.0821] | [0.0494, 0.0784] | [0.0256, 0.0512] |
| [0.0524, 0.0952] | [0.0368, 0.0737] | [0.0431, 0.0862] | [0.0660, 0.1200] | [0.0440, 0.0880] | [0.0652, 0.0652] | [0.0494, 0.0784] | [0.0645, 0.1172] |
| [0.1904, 0.3809] | [0.3374, 0.5357] | [0.1724, 0.3448] | [0.2184, 0.3029] | [0.2025, 0.3215] | [0.2369, 0.3760] | [0.2848, 0.2848] | [0.2129, 0.2778] |
| [0.0330, 0.0458] | [0.0128, 0.0177] | [0.0237, 0.0377] | [0.0263, 0.0525] | [0.0351, 0.0702] | [0.0179, 0.0326] | [0.0331, 0.0431] | [0.0322, 0.0322] |

TABLE V. WHITENIZATION OF THE GREY WEIGHTS

| | |
|---|---|
| (F1) The reputation of the paint supplier | 0.2362 |
| (F2) The quality management system certification of the paint supplier | 0.1226 |
| (F3) Quality of construction paint materials | 0.1470 |
| (F4) Number of paint categories and products | 0.0425 |
| (F5) Delivery time | 0.0535 |
| (F6) Terms and conditions of payment | 0.0716 |
| (F7) Price of the paint product | 0.2925 |
| (F8) Warranty period. | 0.0341 |

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REFERENCES

[1] B. Abdzadeh, S. Noori, and S. F. Ghannadpour, "Simultaneous scheduling of multiple construction projects considering supplier selection and material transportation routing," *Automation in Construction*, vol. 140, Aug. 2022, Art. no. 104336, https://doi.org/10.1016/j.autcon.2022.104336.

[2] S. Kar and K. N. Jha, "Exploring the Critical Barriers to and Enablers of Sustainable Material Management Practices in the Construction Industry," *Journal of Construction Engineering and Management*, vol. 147, no. 9, Sep. 2021, Art. no. 04021102, https://doi.org/10.1061/(ASCE)CO.1943-7862.0002125.

[3] N. T. Phong, V. N. Phuc, and T. T. H. L. N. Quyen, "Application of Fuzzy Analytic Network Process and TOPSIS Method for Material Supplier Selection," *Key Engineering Materials*, vol. 728, pp. 411–415, 2017, https://doi.org/10.4028/www.scientific.net/KEM.728.411.

[4] W. L. Ng, "An efficient and simple model for multiple criteria supplier selection problem," *European Journal of Operational Research*, vol. 186, no. 3, pp. 1059–1067, May 2008, https://doi.org/10.1016/j.ejor.2007.01.018.

[5] P. T. Nguyen, "Determination of construction supplier evaluation criteria using word tags," *International Journal of Advanced and Applied Sciences*, vol. 5, no. 11, pp. 75–79, Nov. 2018, https://doi.org/10.21833/ijaas.2018.11.010.

[6] M. K. Ghorabaee, M. Amiri, E. K. Zavadskas, and J. Antucheviciene, "Supplier evaluation and selection in fuzzy environments: A review of MADM approaches," *Economic research-Ekonomska istrazivanja*, vol. 30, no. 1, pp. 1073–1118, 2017, https://doi.org/10.1080/1331677X.2017.1314828.

[7] E. Plebankiewicz and D. Kubek, "Multicriteria Selection of the Building Material Supplier Using AHP and Fuzzy AHP," *Journal of Construction Engineering and Management*, vol. 142, no. 1, Jan. 2016, Art. no. 04015057, https://doi.org/10.1061/(ASCE)CO.1943-7862.0001033.

[8] R. M. Monczka, R. B. Handfield, L. C. Giunipero, and J. L. Patterson, *Purchasing and Supply Chain Management*. Boston, MA, USA: Cengage Learning, 2015.

[9] M. Safa, A. Shahi, C. T. Haas, and K. W. Hipel, "Supplier selection process in an integrated construction materials management model," *Automation in Construction*, vol. 48, pp. 64–73, Dec. 2014, https://doi.org/10.1016/j.autcon.2014.08.008.

[10] E. Eshtehardian, P. Ghodousi, and A. Bejanpour, "Using ANP and AHP for the supplier selection in the construction and civil engineering companies; Case study of Iranian company," *KSCE Journal of Civil Engineering*, vol. 17, no. 2, pp. 262–270, Mar. 2013, https://doi.org/10.1007/s12205-013-1141-z.

[11] J. Chai, J. N. K. Liu, and E. W. T. Ngai, "Application of decision-making techniques in supplier selection: A systematic review of literature," *Expert Systems with Applications*, vol. 40, no. 10, pp. 3872–3885, Aug. 2013, https://doi.org/10.1016/j.eswa.2012.12.040.

[12] K. Shaw, R. Shankar, S. S. Yadav, and L. S. Thakur, "Supplier selection using fuzzy AHP and fuzzy multi-objective linear programming for developing low carbon supply chain," *Expert Systems with Applications*, vol. 39, no. 9, pp. 8182–8192, Jul. 2012, https://doi.org/10.1016/j.eswa.2012.01.149.

[13] W. Xia and Z. Wu, "Supplier selection with multiple criteria in volume discount environments," *Omega*, vol. 35, no. 5, pp. 494–504, Oct. 2007, https://doi.org/10.1016/j.omega.2005.09.002.

[14] M. Sevkli, S. C. Lenny Koh, S. Zaim, M. Demirbag, and E. Tatoglu, "An application of data envelopment analytic hierarchy process for supplier selection: a case study of BEKO in Turkey," *International Journal of Production Research*, vol. 45, no. 9, pp. 1973–2003, May 2007, https://doi.org/10.1080/00207540600957399.

[15] C. Gencer and D. Gurpinar, "Analytic network process in supplier selection: A case study in an electronic firm," *Applied Mathematical Modelling*, vol. 31, no. 11, pp. 2475–2486, Nov. 2007, https://doi.org/10.1016/j.apm.2006.10.002.

[16] C. Ho, P.-M. Nguyen, and M.-H. Shu, "Supplier Evaluation and Selection Criteria in the Construction Industry of Taiwan and Vietnam," *Information and Management Sciences*, vol. 18, no. 4, pp. 403–426, 2007.

[17] C.-T. Chen, C.-T. Lin, and S.-F. Huang, "A fuzzy approach for supplier evaluation and selection in supply chain management," *International Journal of Production Economics*, vol. 102, no. 2, pp. 289–301, Aug. 2006, https://doi.org/10.1016/j.ijpe.2005.03.009.

[18] C. Kahraman, U. Cebeci, and Z. Ulukan, "Multi-criteria supplier selection using fuzzy AHP," *Logistics Information Management*, vol. 16, no. 6, pp. 382–394, Jan. 2003, https://doi.org/10.1108/09576050310503367.

[19] V. R. Kannan and K. C. Tan, "Supplier Selection and Assessment: Their Impact on Business Performance," *Journal of Supply Chain Management*, vol. 38, no. 3, pp. 11–21, 2002, https://doi.org/10.1111/j.1745-493X.2002.tb00139.x.

[20] S. H. Ghodsypour and C. O'Brien, "A decision support system for supplier selection using an integrated analytic hierarchy process and linear programming," *International Journal of Production Economics*, vol. 56–57, pp. 199–212, Sep. 1998, https://doi.org/10.1016/S0925-5273(97)00009-1.

[21] D. S. Jarallah and A. M. R. Mahjoob, "Supply Chain Management of Infrastructure Projects in Iraq," *Engineering, Technology & Applied Science Research*, vol. 12, no. 3, pp. 8611–8616, Jun. 2022, https://doi.org/10.48084/etasr.4904.

[22] S. Liu, Z. Fang, Y. Yang, and J. Forrest, "General grey numbers and their operations," *Grey Systems: Theory and Application,* 2012.

[23] G.-D. Li, D. Yamaguchi, and M. Nagai, "A grey-based decision-making approach to the supplier selection problem," *Mathematical and Computer Modelling*, vol. 46, no. 3, pp. 573–581, Aug. 2007, https://doi.org/10.1016/j.mcm.2006.11.021.

[24] D. Julong, "Introduction to grey system theory," *The Journal of Grey System*, vol. 1, no. 1, pp. 1–24, 1989.

[25] G. Comert, N. Begashaw, and N. Huynh, "Improved grey system models for predicting traffic parameters," *Expert Systems with Applications*, vol. 177, Sep. 2021, Art. no. 114972, https://doi.org/10.1016/j.eswa.2021.114972.

[26] S. Liu and J. Y. L. Forrest, *Grey Systems: Theory and Applications*. New York, NY, USA: Springer, 2010.

[27] Y. Celikbilek, "A grey analytic hierarchy process approach to project manager selection," *Journal of Organizational Change Management*, vol. 31, no. 3, pp. 749–765, Jan. 2018, https://doi.org/10.1108/JOCM-04-2017-0102.

[28] V. Thakur, "Locating temporary waste treatment facilities in the cities to handle the explosive growth of HCWs during pandemics: A novel Grey-AHP-OCRA hybrid approach," *Sustainable Cities and Society*, vol. 82, Jul. 2022, Art. no. 103907, https://doi.org/10.1016/j.scs.2022.103907.

[29] S. Duleba, Y. Celikbilek, S. Moslem, and D. Esztergar-Kiss, "Application of grey analytic hierarchy process to estimate mode choice alternatives: A case study from Budapest," *Transportation Research Interdisciplinary Perspectives*, vol. 13, Mar. 2022, Art. no. 100560, https://doi.org/10.1016/j.trip.2022.100560.

[30] A. Vafadarnikjoo and M. Scherz, "A Hybrid Neutrosophic-Grey Analytic Hierarchy Process Method: Decision-Making Modelling in Uncertain Environments," *Mathematical Problems in Engineering*, vol. 2021, Jun. 2021, Art. no. e1239505, https://doi.org/10.1155/2021/1239505.

[31] J. Lin, W. Zhou, and S.-S. Yuan, "Research on User Experience Optimization of Tutorial Design for Battle Royale Games Based on Grey AHP Theory," in *International Conference on Human-Computer Interaction*, Jul. 2021, pp. 75–88, https://doi.org/10.1007/978-3-030-77277-2_6.

[32] L. Li, Z. Liu, and X. Du, "Improvement of Analytic Hierarchy Process Based on Grey Correlation Model and Its Engineering Application," *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering*, vol. 7, no. 2, Jun. 2021, Art. no. 04021007, https://doi.org/10.1061/AJRUA6.0001126.

[33] P. Golfam, P.-S. Ashofteh, and H. A. Loaiciga, "Integration of Gray System Theory with AHP Decision-Making for Wastewater Reuse Decision-Making," *Journal of Hazardous, Toxic, and Radioactive Waste*, vol. 25, no. 3, Jul. 2021, Art. no. 04021019, https://doi.org/10.1061/(ASCE)HZ.2153-5515.0000619.

[34] S. Ghosh, "Application of a New Hybrid MCDM Technique Combining Grey Relational Analysis with AHP-TOPSIS in Ranking of Stocks in the Indian IT Sector," in *Computational Intelligence in Communications and Business Analytics*, Santiniketan, India, Jan. 2021, pp. 133–149, https://doi.org/10.1007/978-3-030-75529-4_11.

[35] G. Canbulut, E. Kose, and O. A. Arik, "Public transportation vehicle selection by the grey relational analysis method," *Public Transport*, Jun. 2021, https://doi.org/10.1007/s12469-021-00271-3.

[36] A. Alkharabsheh, S. Moslem, L. Oubahman, and S. Duleba, "An Integrated Approach of Multi-Criteria Decision-Making and Grey Theory for Evaluating Urban Public Transportation Systems," *Sustainability*, vol. 13, no. 5, Jan. 2021, Art. no. 2740, https://doi.org/10.3390/su13052740.

[37] F. Zhu, "Evaluating the Coupling Coordination Degree of Green Finance and Marine Eco-environment Based on AHP and Grey System Theory," *Journal of Coastal Research*, vol. 110, no. SI, pp. 277–281, Oct. 2020, https://doi.org/10.2112/JCR-SI110-065.1.

[38] J. Sun, "Research on faculty and staff for constructing the 'double first-class' universities based on Grey–AHP comprehensive evaluation model," *Grey Systems: Theory and Application*, vol. 10, no. 4, pp. 467–478, Jan. 2020, https://doi.org/10.1108/GS-12-2019-0059.

[39] Y. Qingchuan, N. Hai, S. Yuan, and Z. Jiaping, "Effectiveness Evaluation of Ship Communication System Based on Grey Analytic Hierarchy Process," in *International Conference on Aviation Safety and Information Technology*, New York, NY, USA, Oct. 2020, pp. 163–168, https://doi.org/10.1145/3434581.3434610.

[40] S. Moslem and Y. Celikbilek, "An integrated grey AHP-MOORA model for ameliorating public transport service quality," *European Transport Research Review*, vol. 12, no. 1, Dec. 2020, Art. no. 68, https://doi.org/10.1186/s12544-020-00455-1.

[41] J.-W. Liu, "Developing GAHP concepts for measurement of travel agency organizational performance," *Soft Computing*, vol. 24, no. 11, pp. 8051–8059, Jun. 2020, https://doi.org/10.1007/s00500-019-04115-y.

[42] F. Shengxin and W. Aimin, "Measurement of corporate social responsibility of automobile enterprises based on AHP-GRA model," *Journal of Intelligent & Fuzzy Systems*, vol. 38, no. 6, pp. 6947–6956, Jan. 2020, https://doi.org/10.3233/JIFS-179773.

[43] K. Zhou, G. Huang, and T. Xue, "Evaluation of Dangerous Chemical Transportation Scheme Based on Grey Analytic Hierarchy Process (GAHP)," in *6th International Conference on Frontiers of Industrial Engineering*, London, UK, Sep. 2019, pp. 62–66, https://doi.org/10.1109/ICFIE.2019.8907778.

[44] M. Younas *et al.*, "Multi-objective optimization for sustainable turning Ti6Al4V alloy using grey relational analysis (GRA) based on analytic hierarchy process (AHP)," *The International Journal of Advanced Manufacturing Technology*, vol. 105, no. 1, pp. 1175–1188, Nov. 2019, https://doi.org/10.1007/s00170-019-04299-5.

[45] Z. Meier, W.-T. Pan, S. Zhuohong, Z. Yingying, and Z. Zuchang, "Application of Data Mining Technology in Evaluating Real Estate Investment Plan Based on GRA-AHP," *Journal of Physics: Conference Series*, vol. 1284, no. 1, Dec. 2019, Art. no. 012037, https://doi.org/10.1088/1742-6596/1284/1/012037.

[46] K. Chen, P. Chen, L. Yang, and L. Jin, "Grey clustering evaluation based on AHP and interval grey number," *International Journal of Intelligent Computing and Cybernetics*, vol. 12, no. 1, pp. 127–137, Jan. 2019, https://doi.org/10.1108/IJICC-04-2018-0045.

[47] G. Huang, S. Sun, and D. Zhang, "Safety Evaluation of Construction Based on the Improved AHP-Grey Model," *Wireless Personal Communications*, vol. 103, no. 1, pp. 209–219, Nov. 2018, https://doi.org/10.1007/s11277-018-5436-8.

[48] P. V. Nguyen, P. T. Nguyen, Q. L. H. T. T. Nguyen, and V. D. B. Huynh, "Calculating Weights of Social Capital Index Using Analytic Hierarchy Process," *International Journal of Economics and Financial Issues*, vol. 6, no. 3, pp. 1189–1193, May 2016.

[49] L. T. H. Nhung, T. T. Phung, H. M. V. Nguyen, T. N. Le, T. A. Nguyen, and T. D. Vo, "Load Shedding in Microgrids with Dual Neural Networks and AHP Algorithm," *Engineering, Technology & Applied Science Research*, vol. 12, no. 1, pp. 8090–8095, Feb. 2022, https://doi.org/10.48084/etasr.4652.

[50] H. I. Mohammed, Z. Majid, Y. B. Yamusa, M. F. M. Ariff, K. M. Idris, and N. Darwin, "Sanitary Landfill Siting Using GIS and AHP: A Case Study in Johor Bahru, Malaysia," *Engineering, Technology & Applied Science Research*, vol. 9, no. 3, pp. 4100–4104, Jun. 2019, https://doi.org/10.48084/etasr.2633.

[51] T. N. Le, H. M. V. Nguyen, T. A. Nguyen, T. T. Phung, and B. D. Phan, "Optimization of Load Ranking and Load Shedding in a Power System Using the Improved AHP Algorithm," *Engineering, Technology & Applied Science Research*, vol. 12, no. 3, pp. 8512–8519, Jun. 2022, https://doi.org/10.48084/etasr.4862.

[52] S. Pant, A. Kumar, M. Ram, Y. Klochkov, and H. K. Sharma, "Consistency Indices in Analytic Hierarchy Process: A Review," *Mathematics*, vol. 10, no. 8, Jan. 2022, Art. no. 1206, https://doi.org/10.3390/math10081206.

[53] N.-A.-T. Nguyen, C.-N. Wang, L.-T.-H. Dang, L.-T.-T. Dang, and T.-T. Dang, "Selection of Cold Chain Logistics Service Providers Based on a Grey AHP and Grey COPRAS Framework: A Case Study in Vietnam," *Axioms*, vol. 11, no. 4, Apr. 2022, Art. no. 154, https://doi.org/10.3390/axioms11040154.