Commercially Available Materials Selection in Sustainable Design: An Integrated Multi-Attribute Decision Making Approach

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Abstract: This paper presents an integrated multi-attribute decision-making (MADM) approach to aid selection of commercially available materials in the context of sustainable design. The MADM couples grey relational analysis (GRA) with an analytic hierarchy process (AHP) to rank alternative materials in terms of their economic, environmental, and social performance. AHP is used to determine the corresponding weighting values for the selected indicators. In addition, a case example is used to verify the proposed MADM method and demonstrate its practical application. Three alternative polymer materials, *i.e.*, poly(vinyl chloride) (PVC), polypropylene (PP), and polyethylene (PE), are examined to determine their sustainability for plastic pipe design. The associated MADM result and the limitations of the approach are discussed to lay the foundation for further improvement.

1. Introduction

In recent years, low-carbon development has been gradually entering product life-cycle management to combat climate change under umbrella terms such as "green design", "eco-design", "environmentally conscious design" or "design for environment" [1–3]. Green design, also called sustainable design and environmental design is a philosophy which seeks to improve design performance by incorporating environmental, health, and safety attributes into product design decisions, thus reducing the entire life-cycle impact [4–8].

Materials selection plays a crucial role in product design [9]. A number of studies have given emphasis on material selection by "design-oriented", *i.e.*, by functional demand of a product . For example, Chauhan and Vaish (2012) applied the VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) and the technique for order preference by similarity to ideal solution (TOPSIS) methods to soft and hard magnetic materials classification and selection [10]. Khare *et al.* (2012) proposed a multi-objective optimization model to identify the most appropriate phase change materials (PCMs) for latent heat storage design [11]. Similarly, Mansor *et al.* (2013) employed the multi-objective optimization methodology for materials selection in design of an automotive brake

lever [12]. O'Connor *et al.* (2016) proposed materials selection criteria for a new skin-wearable organic solar cell design based on its mechanical compliance [13].

Some studies have focused on materials selection by market demand. For instance, Prasad and Chakraborty (2013) used a quality function deployment (QFD)-based approach to select the suitable materials by integrating the voice of the customers with product functionality [14]. Tamani *et al.* (2015) designed a multi-criteria decision support system for fresh food packaging, in which consumers' preferences were considered [15]. Kwong *et al.* (2016) employed an artificial intelligence (AI) based methodology for materials selection in design of electric iron, by which the factors of affective design, engineering, and marketing issues were taken into account [16].

Materials selection is also oriented by cost consideration. Rahman *et al.* (2012) developed a decision support system for roofing materials selection, in which the conceptual cost for the roof element was assessed in the early stage of building design [17]. Kumar *et al.* (2014) used the entropy with TOPSIS method to evaluate the optimum material for exhaust manifold design, in which cost was taken as an important criterion [18]. IIg *et al.* (2016) calculated life cycle cost of several high-performance materials (HPM) in infrastructure. Discount rate, expected service life and external costs were identified as the major factors in affecting the performances of materials [19].

However, most of them have not taken environmental management as a key aspect of materials selection in product design. With raw materials being extracted at an increasing rate, product design is affected by a growing public attention to sustainable development [20–23]. In this context, selection of materials should follow the principles of green design to mitigate adverse impact on both environmental and human health, to enhance product quality and to minimize toxicity of materials [23,24].

In order to provide better, safer, and more sustainable products for publics, it is important to predefine the material in the initial period of product design. Materials for further industrial manufacture that are more environmentally friendly, e.g., minimizing environmental impact and maximizing economic and social benefits, should be identified. A number of studies have taken the life cycle assessment into materials selection as an environmental impact assessment [25–29]. For instance, Ribeiro *et al.* (2013) assessed the life-cycle-based performance of injection-molded samples made of four commercial biodegradable polymers [30]. Hosseinijou *et al.* (2014) proposed social-life cycle assessment (S-LCA) for building materials selection, in which three stages as pre-building, building and post-building were taken into account [31]. Van der Velden *et al.* (2015) employed LCA approach for materials selection to promote the sustainability of smart textile garment, in which eco-cost of resource depletion, carbon footprint, human health were taken as the typical indicators [32]. However, life cycle assessment (LCA) is difficult for engineering designers to implement in real applications, due to the predicament of required data acquistion, data quality control, product system boundary division etc. [33,34]. In this context, there is a need for an approach that is simple to use.

This study contributes to the literature by developing a computational method for the use of engineers or designers to aid in the selection of commercially available materials by taking some typical indicators into account, e.g., economic, environmental, and social performance, thus promoting green design and improving product quality.

The selection of materials may be influenced by many factors, such as product function, cost, environment, or consumer satisfaction [35,36]. Because of conflicting or competing objectives, such as economic cost and environmental restrictions, the selection of materials for engineering design may be treated as a multi-criteria decision-making problem (MCDM) [37–39]. MCDM is often divided into two categories, the multiple-objective decision-making (MODM) and multiple-attribute decision-making (MADM) methods [40]. The former is an optimization technique based on prioritized functional relationships such as the maximization of sales profit or the minimization of cost. By contrast, the latter one mainly focuses on the comparison and, subsequently the ranking of alternatives based on attribute weighting or user defined data [10,41,42].

In real process of materials selection, a number of variables should be taken into account. However, only several variables can be involved when using the MODM techniques for materials selection [43,44]. MADM methods such as analytic hierarchy process (AHP), TOPSIS, VIKOR, and Grey Relational Analysis (GRA) are able to rank material alternatives and help designers determine the best material, defined as the highest degree of satisfaction [45–49].

The MADM methodology for materials selection in our study provides an important decision-making tool when confronted with a number of closely differing materials for diversified needs. This study further integrates two common MADM methodologies: AHP, used for weighting of selected indicators, and GRA for further comparison. GRA is based on the measurement of the degrees of similarity or difference among several numerical sequences, which is used to identify the relative influences of the sequences for comparison with a predetermined reference sequence [50,51]. The GRA gives the preferential order of various investigated objects in terms of a certain performance index. However, the relative importance of the various indices is difficult to determine, e.g., some of the indicators may be conflicting [52]. In comparison, the analytic hierarchy process (AHP) is a classic method to fill this gap, as it is used to assess the relative importance among indices. Generally, the purpose of AHP is to decompose a complex decision issue into a variety of hierarchies and factors, which is a typical subjective weighting method based upon the judgment and synthesis of decision makers [53]. An ordered hierarchical decision is thus composed of a dominance relationship in which the weights among different indicators are determined through pairwise comparison [54]. Therefore, integration of the two methods can give rise to a maximization of their advantages, which also facilitates the multi-attributive decision-making of a complex system.

This study further gives preferences of selection between similar materials (with similar physical and chemical properties) to examine their performance. A case example is used to verify the proposed MADM method and demonstrate its practical application. Three alternative polymer materials, *i.e.*, poly(vinyl chloride) (PVC), polypropylene (PP), and polyethylene (PE), are examined to determine their sustainability for plastic pipe design. It is further expected that this integrated approach may help manufacturers to implement sustainable design, and thus to enhance product sustainability.

2. Integrated MADM Approach for Materials Selection

As environmental resources are increasingly depleted, products are gradually being developed with less impact to the environment, thus moving towards "sustainability." In this context, this study has identified a number of typical indicators to represent product sustainability as a basis for materials selection, based upon the basic principles and guidelines of sustainable design to construct a decision matrix, shown in Table 1 [2,24,55,56].

Table 1. Selected indicators for material selection.

Attributes	Indicators
Economic	Direct cost Manufacturing cost Manufacture defects Sales profit
Environmental	Energy consumption Health risk Waste-gas production Wastewater production Solid waste production
Social	Product satisfaction Material recyclability Material reusability Use of recycled Materials

For any manufacturer, there are triple bottom lines (TBL) to run a sustainable business from bottom to top, *i.e.*, as basic market demand, alternative materials and energy for production, and pursuing societal value for environmental protection [57–62]. The manufacturer is primarily driven by profit, as economic issues play a dominant role in business operations [61,63–65]. Thus, four economic indicators are taken into consideration including direct cost, manufacturing cost, manufacture defects and sales profit. With the conflicts between economic growth and environmental protection being paid more and more attention, the most preferable strategy for encompassing sustainable development is to implement cleaner production [66,67].The mitigation of adverse impact of products on environment and human health can be achieved partly by the careful selection of materials. Thus, five indicators are proposed to represent the product environmental performances: energy consumption, health risk, waste-gas production, wastewater production, and solid waste production [68,69].

The social attributes proposed in this study is from a perspective of corporate social responsibility (CSR), in order to extend manufacturer's responsibility through the improvement of product sustainability, such as improving product life cycle (including reusability and recyclability), reforming the quality of products, *etc.*, to provide better, safer and sustainable products for public consumption [70–72]. Proposed by McDonough and Brauggart (2002), all materials can be classified into two categories in a closed-loop social system: "technical" or "biological" nutrients [73]. The technical nutrients are those non-toxic and non-harmful materials, which can be reused directly in continuous cycles without losing their integrity or quality, and parts of which can be recycled for their quality and functionality, e.g., the cola bottle [74]. In this context, "material reusability", "material recyclability" and "use of recycled materials" are selected to reflect the manufacturer's social responsibility for product waste prevention.

The use of these evaluation indicators, by taking economic, environmental and social dimensions into account, is expected to help improve and monitor process of product design [75,76]. The proposed MADM approach combines GRA with AHP to rank alternative materials by their economic, environmental, and social performance. AHP is used to determine the weights of the selected indicators. GRA is then used to develop an evaluation approach to aid material selection. The detailed computational approach is presented below.

2.1. Weighting by AHP

Generally, the weighting approach can be divided into two categories: objective and subjective weighting determination [77]. The former obtains the weights derived from the collected data corresponding to each indicator. However, the different indicators may result in weighting variation, and the actual importance of indicators could be conflicted [78]. The latter is mainly dependent upon the decision maker's preferences regarding the attributes, e.g., AHP is a subjective decision-making tool, which is widely used for weighting determination [79]. Generally speaking, there are three steps to the AHP calculation [80]:

(1) decompose an issue into a hierarchy system: the above attributes are classified into three categories: economic, environmental, and social,

(2) establish a pairwise comparison matrix to compare a set of *n* attributes in relative importance:

$$ A = \begin{bmatrix} a_{11} & \cdots & a_{1j} & \cdots & a_{1n} \\ \vdots & & \vdots & & \vdots \\ a_{i1} & \cdots & a_{ij} & \cdots & a_{in} \\ \vdots & & \vdots & & \vdots \\ a_{n1} & \cdots & a_{nj} & \cdots & a_{nn} \end{bmatrix} \tag{1} $$

where a_1, a_2, ..., a_n, denote various attributes, $a_{ij} = 1/a_{ji}$ and $a_{ij} = a_{ik}/a_{jk}$ indicate how much more important objective i is than objective j to the decision maker. The relative importance

is measured by using a scale from 1 to 9, where 1 represents that objective *i* and *j* are equally important, 3 represents that objective *i* is just slightly more important than *j*, 5 represents objective *i* is somewhat more important than *j*, 7 represents that objective *i* is much more important than *j*, and 9 represents that objective *i* is far more important than *j* [53,79]. We measure the relative importance by using the scale 1 to 5 in this study.

(3) determine the relative weights; as a_{ij} approximates to w_i/w_j, i.e., $a_{ij} \cong w_i/w_j$, matrix A can be transformed as follows:

$$W = \begin{array}{c} \\ w_1 \\ \vdots \\ w_i \\ \vdots \\ w_n \end{array} \begin{array}{ccccc} w_1 & \cdots & w_j & \cdots & w_n \end{array} \\ \begin{bmatrix} w_1/w_1 & \cdots & w_1/w_j & \cdots & w_1/w_n \\ \vdots & & \vdots & & \vdots \\ w_i/w_1 & \cdots & w_i/w_j & \cdots & w_i/w_n \\ \vdots & & \vdots & & \vdots \\ w_n/w_1 & \cdots & w_n/w_j & \cdots & w_n/w_n \end{bmatrix} \tag{2}$$

The relative weights are derived by addressing the eigenvector w with the largest eigenvalue λ_{max} of matrix A, which should satisfy the equation $Aw = \lambda_{max}w$. In addition, the consistency index *C.I.* and the consistency ratio *C.R.*, as two examination indicators, should be calculated to ensure the accuracy of the relative weights and the consistency of the subjective decision. These are:

$$C.I. = (\lambda_{max} - n)/(n - 1) \tag{3}$$

$$C.R. = C.I./R.I. \tag{4}$$

where *R.I.* is a random consistency index which varies with the size of the matrices, e.g., 1.11 for a 5 × 5 matrix. *C.I.* should be less than 0.1 in order for a suitable result [53,80].

2.2. Grey Relational Analysis for Materials Evaluation

GRA or grey incidence analysis, proposed by Professor Deng Julong in 1984, has been developed as a quantitative approach to aid decision-making by examining the degree of similarity or difference between two sequences based upon the grade of relation [50,81–83]. The more similar the two sequences are, the greater the grey relational correlation is, and *vice versa* [50,84].

To use GRA, it is necessary to normalize the data related to the sequence of selected criteria to a common scale for comparison. Basically, there are three approaches for normalization [50,51]:

(1) If the ideal value of sequence of selected criteria is preferred to be larger, such as indicators of sales profit, materials recyclability, or reusability, the consequence can be normalized as follows:

$$\beta_i(k) = \frac{\beta_i(k) - \min\beta_i(k)}{\max\beta_i(k) - \min\beta_i(k)} \tag{5}$$

where $\beta_i(k)$ is the comparable sequence of selected evaluation criteria.

(2) If the ideal value of sequence of selected criteria is preferred to be smaller, such as direct cost, manufacturing cost, or energy consumption, the consequence can be normalized as follows:

$$\beta_i(k) = \frac{\max\beta_i(k) - \beta_i(k)}{\max\beta_i(k) - \min\beta_i(k)} \tag{6}$$

where $\beta_i(k)$ is the comparable sequence of selected evaluation criteria.

(3) If the ideal value is determined within a numerical value range, the sequence can be normalized as follows:

$$\beta_i(k) = 1 - \frac{|\beta_i(k) - \beta_i|}{\max\beta_i(k) - \beta_i} \tag{7}$$

where $\beta_i(k)$ is the comparable sequence of selected evaluation criteria, and β_i is the determined ideal value.

Following the above normalization, a grey relational coefficient is calculated. It demonstrates the relationship between the non-dimensional expected optimal sequence and the original sequence [24,85]. The grey relational coefficient is:

$$\delta_i(k) = \frac{\min_i \min_j ||\beta_0(k) - \beta_j(k)|| + \varepsilon \max_i \max_j ||\beta_0(k) - \beta_j(k)||}{||\beta_0(k) - \beta_j(k)|| + \varepsilon \max_i \max_j ||\beta_0(k) - \beta_j(k)||} \tag{8}$$

where ε is defined as the distinguishing coefficient and $\varepsilon \in (0,1)$. Generally, ε is set to 0.5 for further calculation [84].

Thus, the degree of grey incidence can be expressed as:

$$\gamma_i = \sum_{k=1}^{n} w_k \cdot \delta_i(k) \tag{9}$$

where w_k is the weighting value of the selected indicator k derived from the AHP approach.

The degree of grey incidence indicates the relationship between the comparability sequence and the reference sequence [83,86]. The reference sequence represents the best performance that can be achieved by any among the comparability sequences. When γ_i grows much bigger, the comparability sequence approaches the reference sequence. When γ_i reaches the maximum value, a comparability sequence of the corresponding material obtains the highest degree of grey incidence, which means the alternative material is better than its counterparts. Moreover, the performance of all the alternative materials can be ranked in a sequence, from most optimal to least.

3. A Case Example

A case example is presented in this section to demonstrate the application of the proposed methodology of materials selection for plastic pipe design. The plastic pipes are widely used in the water supply system of Sichuan Province, China, especially for indoor hot and cold water supply. They are manufactured out of three alternative materials: poly(vinyl chloride) (PVC), polypropylene (PP) and polyethylene (PE). Here, the PVC is specified as un-plasticized PVC (uPVC), with a synthesis of 15% chlorinated polyethylene (CPE) and 75% PVC, and PP as a polypropylene random (PPR), with 5% PE and 95% PP.

The case example employs a set of weight values determined by the principal engineer of the investigated manufacturer and adjusted by the retrieval results of the selected indicators from the online Scirus scientific database in order to avoid subjective judgment in comparing their importance. Scirus.com is a comprehensive academic search engine with over 440 million scientific items, including published scientific papers, patents, web sources, courseware, and current research progress [87]. Based on the retrieval results of each indicator using "hits" as the measure of importance, the relative importance is ranked from 1 to 13, as shown in Figure 1.

The grey relational result will be compared with the actual material selection in the investigated manufacturer of plastic pipe to verify the proposed approach. Table 2 shows how the selected indicators for the three alternative materials are measured.
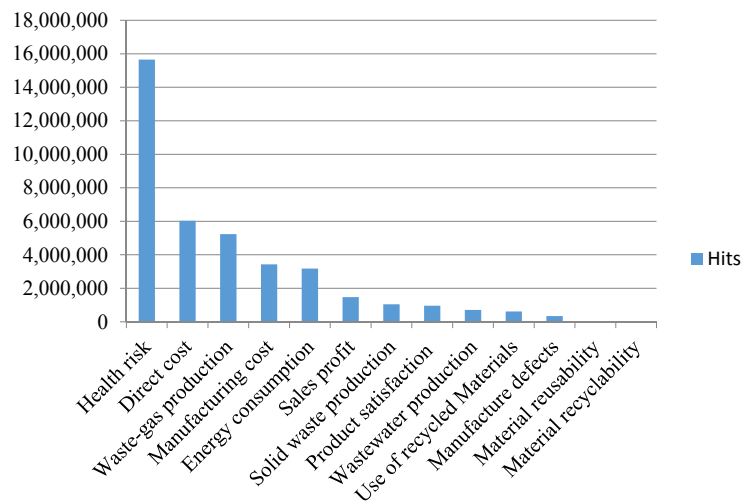
Figure 1. Rank of selected indicators as determined from Scirus.com retrieval.

Table 2. Measurements of the selected indicators.

Indicators	Measurements
Direct cost	$$p_i = \sum_{i=1}^{n} c_i / C$$ where p_i is the ratio of direct cost of the investigated pipe manufacturer, c_i is the material cost corresponding to the ith activity, e.g., $i = 1$ denotes the purchasing cost of a specific material (PVC, PP, PE), $i = 2$ denotes transportation cost of a specific material (PVC, PP, PE), $i = 3$ denotes labor cost of a specific material (PVC, PP, PE), and C is the total investment the investigated pipe manufacturer.
Manufacturing cost	$$p_m = c_m / C$$ where p_m is the ratio of the investigated plastic pipe manufacturing cost, c_m is the plastic pipe manufacturing cost of a specific material (PVC, PP, or PE), and C is the total investment of the pipe manufacturer.
Manufacture defects	$$p_d = M_d / Q_0$$ where p_d is the ratio of the investigated plastic pipe manufacture defects, M_d is the annual quantity of the manufacture defects of the investigated plastic pipe manufacturer, and Q_0 is the annual production of plastic pipes.
Sales profit	$$p_p = c_p / c_s$$ where p_p is the ratio of sales profit of the investigated plastic pipe manufacturer, c_p is the expected sales profit from using a specific material for plastic pipe production (PVC, PP, or PE), and c_s is the sales revenue of the investigated plastic pipe manufacturer.
Energy consumption	$$p_e = e_i / \sum_{i=1}^{n} e_i$$ where p_e is the ratio of energy consumption of the investigated plastic pipe manufacturer, e_i is the energy consumption from using the ith fuel, e.g., $i = 1$ denotes the natural gas consumption, $i = 2$ denotes electricity consumption, and $i = 3$ denotes coal consumption.
Health risk	Health risk is defined as the potential harm to human health in this study, especially the toxic and poisonous components posed to the workers in the material processing and manufacturing [88,89]. $$p_h = r_i / \sum_{i=1}^{n} r_i$$ where p_h is the ratio of health risk, r_i is the toxic risk from using the ith material for plastic pipe production, *i.e.*, $i = 1$ denotes PVC, $i = 2$ denotes PP, and $i = 3$ PE. The toxic risk r_i resulted from using the ith material (PP, PE, PVC) is given as follows [90]: $$r_i = P_i C_i$$ where P_i is the probability of personal injury resulting from the ith material process or manufacture, C_i the consequence of the personal injury, such as the number of workers suffered by allergic rhinitis, dermatosis *etc.*

Table 2. *Cont.*

Indicators	Measurements
Waste-gas production	$p_g = Q_g/Q_o$ where p_g is the ratio of waste-gas production of the investigated plastic pipe manufacturer, Q_g is the annual emission of waste gas from using a specific material for production (PVC, PP, or PE), and Q_0 is the annual production of plastic pipes.
Wastewater production	$p_w = Q_w/Q_o$ where p_w is the ratio of waste water production of the investigated plastic pipe manufacturer, Q_w is the annual emission of waste water from using a specific material for production (PVC, PP, or PE), and Q_0 is the annual production of plastic pipes.
Solid waste production	$P_s = Q_s/Q_o$ where p_s is the ratio of solid waste production of the investigated plastic pipe manufacturer, Q_w is the annual emission of solid waste from using a specific material for production (PVC, PP, or PE), and Q_0 is the annual production of plastic pipes.
Product satisfaction	p_z defined as the market share of plastic pipes while using a specific material (PVC, PP, or PE), which is based upon the market of the downstream distribution centers.
Material recyclability	Material recyclability is the extent to which waste materials can be converted into reusable material, which are used to make new items, given as follows [91]: $p_r = Q_r/Q$ where Q_r is the theoretical quantity of recycled materials (PVC, PP, or PE), and Q is the total quantity of waste materials produced of the investigated plastic pipe manufacturer.
Material reusability	Material reusability is defined as the extent to which the material can be reused directly in continuous cycles without losing their integrity or quality, which is given as follows [92]: $p_R = Q_R/Q$ where Q_R is the theoretical quantity of reused materials (PVC, PP, or PE), and Q is the total quantity of waste materials produced of the investigated plastic pipe manufacturer.
Use of recycled Materials	$p_t = Q\prime/Q_r$ where $Q\prime$ is the actual recycled materials (PVC, PP, or PE), and Q_r is the theoretical quantity of recycled materials of the investigated plastic pipe manufacturer.

The data for the selected indicators are derived from a feasibility study report of a plastic pipe manufacturer, located in Leshan City, Sichuan Province, China. According to the measurements, the data have been processed dimensionlessly by percentage for further application of GRA, as shown in Table 3.

Table 3. Processed data of the selected indicators.

Indicators	Alternative Materials		
	PE	PP	PVC
Direct cost	95.5	90.3	90.0
Manufacturing cost	1.43	1.40	10.00
Manufacture defects	1.5	2.0	2.0
Sales profit	29.4	20.0	38.2
Energy consumption	92.5	99.6	39.7
Health risk	0	0	0.00084
Waste-gas production	0.006	1.130	0.230
Wastewater production	11.0	150.0	45.5
Solid waste production	0.09	50.00	0.54
Product satisfaction	25	10	55
Material recyclability	94.50	0.28	65.90
Material reusability	30.7	2.5	16.5
Use of recycled Materials	100	100	98

4. Results and Discussion

Based upon the relative importance ranking list, the weighting value is calculated by the AHP method, as shown in Table 4. In order to simplify the computation, both AHP and GRA have been embodied into a compiled mathematical program implemented by MATLAB 2010. The degree of grey incidence γ_i of the PVC, PP, and PE is calculated as 0.800457709, 0.634945104, and 0.604756842, respectively. Different evaluated alternatives can be ranked in a sequence from the highest to the lowest grade. For instance, the ranking of degrees of grey incidence is deemed as the order of superiority for each material in this study. The assessed alternative material corresponding to the maximum grey correlative degree is deemed as the optimal material, and vice versa. Thus, $\gamma_{PVC} > \gamma_{PP} > \gamma_{PE}$ is obtained, which shows that the PVC is the optimum alternative material and PE is the least optimal choice.

Table 4. Weighting value of the selected indicators based on the Scirus.com retrieval results.

Indicators	Weighting Value
Direct cost	0.155623917
Manufacturing cost	0.088494826
Manufacture defects	0.008907485
Sales profit	0.038003123
Energy consumption	0.082127819
Health risk	0.404081921
Waste-gas production	0.135173217
Wastewater production	0.018335576
Solid waste production	0.027011282
Product satisfaction	0.024883922
Material recyclability	0.000545566
Material reusability	0.000975515
Use of recycled Materials	0.015835831

From Table 4, it is clear that the indicator "health risk" accounts for about 40% of the weightings. This is because the manufacturer's employees are likely exposed to toxic substances when PVC materials are processed [93]. However, PVC has the highest sales profit and market share (product satisfaction), along with the lowest proportion of direct cost and energy consumption. That is why PVC exhibits the best overall performance among the three alternative materials, even if its inherent health risk is higher than PP or PE. Similarly, PP's degree of grey incidence is higher than PE, although PE material is superior to PP based on most of the data for the selected indicators. This is because PP shows better performance in both direct cost and manufacturing cost, which accounts for a large proportion of the relative importance. This shows that the weighting value may play a critical role in the sensitivity of the grey relational model in this case study.

In the real world, a manufacturer may define profits as the main criterion of business success, while placing little emphasis on life-cycle environmental impact of its products [94,95]. Accordingly, the selection of materials is strongly influenced by market demand, cost-benefit analysis, materials properties, and fashion and popularity, as the fundamental drivers of design [24]. For instance, the investigated manufacturer in this study was originally cost-oriented in material selection, and PVC was used for plastic pipe manufacturing. This verifies the evaluation results of the integrated MADM approach. However, a sustainable business should focus on both economic prosperity, environmental and social performances [96,97]. In green design, the weighting assignment for materials selection should pay closer attention to the environmental and social perspectives. This could be expressed by increased weighting values for materials recyclability and reusability to enhance the sustainability of products.

This integrated MADM approach is flexible, which can provide a comprehensive matrix to judge a range of alternative materials, including index of environmental impact, economic perspective, *etc.*

For instance, a similar study can be found by Zhao *et al.* (2012), who has employed "binary-dominance matrix" with GRA to aid decision-making on materials selection while taking environmental evaluation into account. Five PVC materials with close properties have been subjected to environmental evaluation to determine their environmentally friendliness for handbag manufacture [24]. Furthermore, Kumar *et al.* (2014) have offered a MCDM approach in which criteria importance was computed by entropy method, and the alternative materials were ranked by using the TOPSIS method [18]. Wang *et al.* (2015) have employed AHP combined with GRA to select a biomass briquette fuel-system scheme based on a variety of evaluation criteria, such as economy, cleanness and environment protection, production capacity, product quality and production stability [52]. Yang *et al.* (2015) have focused on the materials selection from remanufacturing perspective and developed a MCDM model by using the Fuzzy TOPSIS approach to evaluate the performance of the alternative automotive materials [98]. These similar studies have reflected the extension and validity of the proposed method.

However, the weightings play a critical role to affect the sensitivity of the GRA, which is subject to the preference of the indicators. AHP is a subjective weighting approach, depending upon the judgment and synthesis of decision makers [99,100]. It may be replaced by the objective weighting methods, such as the Entropy method, TOPSIS, *etc.*, in which the weights are derived from the collected data corresponding to each indicator. Thus, the influence of weighting variation on materials selection can be investigated to identify the sensitivity of the integrated approach.

5. Conclusions

This paper introduces a computational approach for materials selection in the context of green design by using GRA, integrated with AHP. A set of selected indicators is determined using the principles of green design, while the AHP method is used to examine the relative importance and assign the corresponding weighting values for each indicator. Moreover, GRA is applied to rank the alternative materials based upon the multiple attributes of their performances. In order to demonstrate how to use the computational approach, a case example is provided. Three materials, PVC, PP, and PE, are investigated to determine their best economic, environmental, and social performances for plastic pipe design. With the weighting value for the selected criteria being determined by the principal engineer of the investigated manufacturer and adjusted by keyword retrieval from the Scirus database, PVC is determined as the optimal material, and PE the least optimal.

However, limitations of this computational approach still remain. Although the selected criteria are generic and may be easily extended to various applications, whether these indicators can be used to fully cover the three dimensions of sustainability, namely, the economic, environmental, and social dimensions, still requires further investigation. Second, the weighting determination should be re-adjusted by taking the engineering designer's preferences into account, while giving full priority to environmental and social considerations. This approach is expected to be applied to more case scenarios in order to examine and refine its validity and sensitivity in the future.

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Conflicts of Interest: The authors declare no conflict of interest.

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