The Potential application of Bio-polymeric materials in Building Facades: A Framework of multi-performance criteria matrix for selecting optimal materials by the AHP and TOPSIS methods

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ABSTRACT

Although Bio-polymeric materials have successfully replaced many conventional materials in various applicable fields, their applications in the building façade realm have hitherto been limited. The emergence of countless new materials along with the availability of numerous manufacturing processes in the market has made the material selection procedure a difficult task to undertake by most of architects and engineers nowadays. This explains the need of adopting a novel scientific approach for the material selection process to help in selecting the most compatible material for the required façade application instead of following an outdated traditional selection path relying mainly on previous personal experiences. Accordingly, losing the best candidate will be a highly anticipated option. This paper presents a rigorous mathematical approach (framework) that will aid architects, engineers, and other design professionals in screening all the potential Bio-polymeric materials while evaluating the performance status of each one to rank them in view of their order of pereference in achieving the desired multifaceted façade requirements. By increasing the complexity of the modern building façade assemblies and the diversity of their evaluation criteria, the paper discusses a new algorithm based on multi-criteria decision analysis methods to support decision makers with structured tools for sorting, ranking, and selecting the most appropriate candidate with the highest weighted scores for the intended façade application. Both the AHP and TOPSIS methods are adopted to develop a single pairwise comparison matrix of criteria and determine the positive and negative ideal solutions used to rank the available candidates according to their separation measures from these positive and negative solutions. This will open a new door for architects and engineers to explore new material families and examine their potentiality in achieving the diverse building façade requirements.

INTRODUCTION

The production of the emerging Bio-polymeric materials derived from renewable biomass has witnessed a notable progress globally in the recent years with an expectation to reach 7.8 million tons by the year 2019. Despite covering 10-15% of the current global plastic market with an anticipated growth reaching 25-30% of the market by 2020 (Helmut Kaiser Consultancy 2016), the application of the Bio-polymeric materials in the field of building facades hasn't lived up to expectations yet. Unlike the other conventional façade materials, Bio-polymeric materials can lessen the carbon footprint of the building façade significantly and contribute in alleviating the amount of construction and demolition waste dumped in landfills each year by providing more sustainable end of life options. According to the U.S National Bioeconomy Blueprint 2012 and the EU-Horizon 2020 Research and Innovation Programme, it is expected that the expansion in developing new biological raw materials and processing methods could reduce up to

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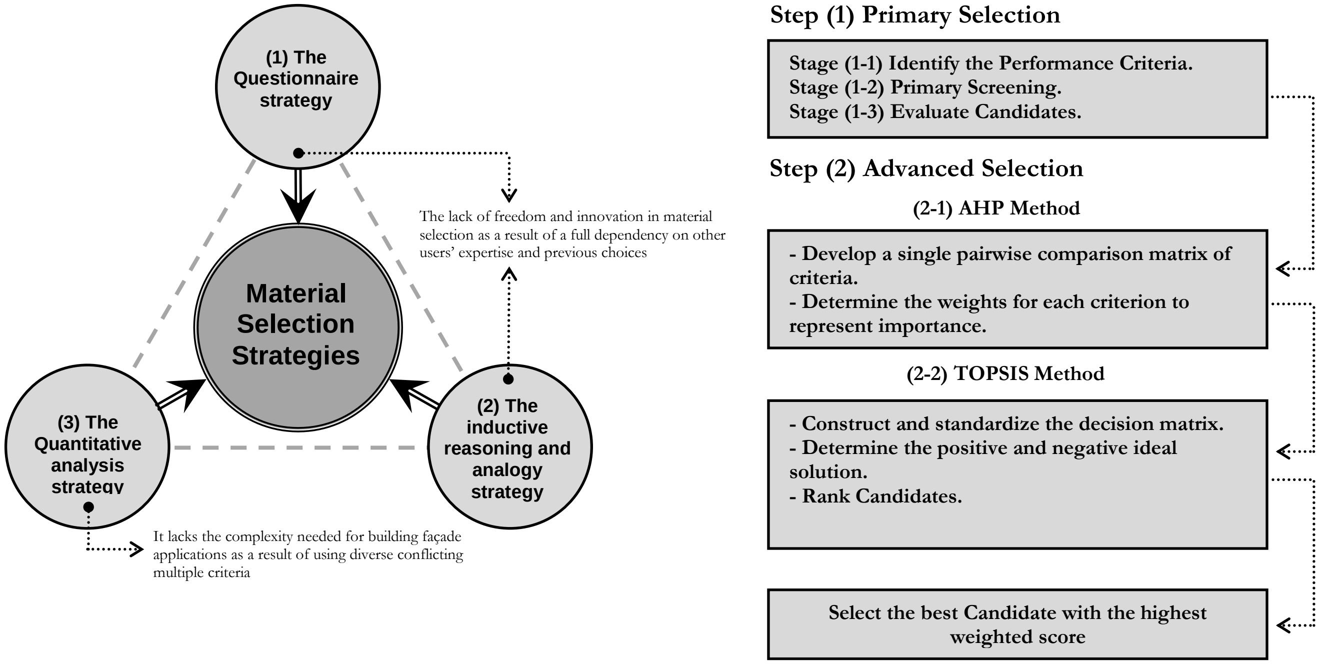
2.5 billion tons of CO^2 equivalent per year by 2030 and open new markets and fields for bio-based materials including the building industry (European Commission 2012). This will help in saving the natural resources, conserving landfill spaces, decreasing pollution rates, reducing the overall building weight and energy consumption. Consequently, the emergence of new material families with advanced chemical compositions and unprecedented properties in the near future will subsequently require the advent of innovative screening mechanisms and novel selection methods. This will enable architects and design professionals to examine the potentiality of these candidates to be used as façade materials considering all the challenges facing the building façade components such as the loading-carrying capacity and durability, thermal performance, exposure to external conditions and fire hazards (Elnimeiri and Hassan 2015). Therefore, this paper will present an attempt to develop a scientific framework for the material selection process considering these challenges and all the various requirements of the building facades.

PROBLEM BACKGROUND: THE LIMITATIONS OF THE CURRENT MATERIAL SELECTION STRATEGIES

Since the material selection process is a complex, yet delicate procedure, designers tend to adopt several material selection strategies to facilitate choosing the best candidate for the intended application. These current strategies include the questionnaire strategy, the inductive reasoning and analogy strategy, and the quantitative analysis strategy (Ashby, et al. 2004). In general, the first two strategies rely on expertise-capture methods while the last one depends on a rigorous mathematical approach. In the questionnaire strategy, designers use a pre-determined path developed by experts to assist in reaching a suitable solution through following a simple yes/no questions-survey. In the inductive reasoning and analogy strategy, designers are required to investigate former case studies alike the new intended problem and derive logic correlations necessary to be adapted with the new needs. On the other hand, the quantitative analysis strategy relies basically on analyzing the problem algorithmically with standard engineering methods. Designers are required to establish a precise algoritm to solve the intended problem after defining its main function, identifying its important constraints, and determining its objectives that should be supported, survived and fulfilled respectively. The lack of freedom and innovation in material selection as a result of a full dependency on other users' expertise and previous choices are considered the main drawbacks of the first two strategies. Although adopting the quantitative strategy is fast, accurate, and usually reveals new and innovative solutions, it lacks the complexity needed for building façade applications as a result of using diverse conflicting multiple criteria. Accordingly, this research will address this gap in knowledge in more details. Please see Fig (1-a).

RESEARCH GOAL AND STRUCTURE

The main goal of this paper is to develop a new framework that Architects can pursue when choosing new Bio-polymeric materials for building façade applications. This framework will go through two consecutive steps. It will adopt the quantitative strategy as a primary selection step then followed by multi-criteria decision making methods as an advanced selection step towards choosing the most convenient candidate. The primary selection step will comprise three consecutive stages. The first stage discusses the performance criteria requirements needed for the new building façade materials. The second stage sheds the light on the primary screening procedure essential for scrutinizing and sorting the available Bio-polymeric materials with the aim of selecting whichever is more suitable for the intended application. The third stage focuses on evaluating and comparing the different candidates according to their performance in meeting the facade requirements. Moreover, the advanced selection step will comprise two consecutive stages. The first stage discusses the Analytic Hierarchy process (AHP method) needed to determine the relative weights for each criterion to represent importance. The last stage discusses the Technique for order of preference by similarity to ideal solution (TOPSIS method) needed to rank the candidates according to their performance status in meeting the facade requirements and subsequently to select the best candidate with the highest weighted score. Please see Fig (1-b).



a) b)

Figure 1 (a) The Limitations of the current material selection strategies and (b) Selection Framework.

STEP (1) PRIMARY SELECTION

Stage (1-1) Performance Criteria: Definition and Basis of Assessment

The importance of selecting building façade materials based on a scientific evaluation system is fundamental to architects for a successful planning and an effective decision making process in the future. According to Oxford dictionary, Performance is defined as "the action or process of carrying out or accomplishing an action, task, or function", while Criterion is defined as "a principle or a standard by which something may be judged or decided" (Dictionaries 2017). In light of that, the Performance Criteria stage is meant to establish the desired standards, principles, specifications or requirements by which the materials performance is evaluated. Thus, providing a basis of assessment for materials by not only identifying what is to be evaluated, but also by determining the required level of performance the material should have to be considered acceptable for the desired building façade application.

Materials Assessment Format. It is intended to provide a reliable basis for evaluating the candidate façade materials where the suitable selection process will rely on the capacity of their different properties to attain the required performance attributes. Consequently, the physical, mechanical, thermal, optical and environmental properties of each material should be quantified to give an insight of how satisfactory will be the candidate material to meet the functional, aesthetic, sustainable and economic requirements of building façades. This assessment format should include but not limited to:

1. General / Physical Properties
   - 1.1. Density: Mass per unit volume. It implies whether the façade material is heavy, bulky or light. Units: Kg/m^3 (SI units) - Lb/in^3 (IP units).
   - 1.2. Price: Cost of materials. Units: USD$/lb.

2. Mechanical Properties

2.1. Young's Modulus: It is the ratio between stress (force per unit area) and strain (proportional deformation) in a material ($Ȩ = \sigma/\varepsilon$). It implies whether the façade material is stiff, which can withstand forces and still recover its original shape, or soft which will deform after applying small amount of forces.
Units: Pa or N/m^2 (SI units) - psi or ksi (IP units).

2.2. Yield Stress: Stress (force per unit area) at yield point (the point which a material begins to deform plastically). It implies the applied stress the façade material can withstand before changing its shape permanently.
Units: Pa or N/m^2 (SI units) - psi or ksi (IP units).

2.3. Tensile Strength: Stress at Failure under a tensile load. It implies the maximum applied stress the façade material can withstand before failing or breaking due to a tensile load (Stretching / pulling) load.
Units: Pa or N/m^2 (SI units) - psi or ksi (IP units).

2.4. Compressive Strength: Stress at Failure under compressive load. It implies the maximum applied stress the façade material can withstand before failing or breaking due to a compressive load.
Units: Pa or N/m^2 (SI units) - psi or ksi (IP units).

2.5. Flexural Strength: Stress at Failure under bending load. It implies the maximum applied stress the façade material can withstand before failing or breaking due to a bending load.
Units: Pa or N/m^2 (SI units) - psi or ksi (IP units).

2.6. Impact Strength: It is the ratio between the absorbed impact energy and the test specimen cross-section.It implies the façade material's ability to absorb shock (high force) and impact energy without breaking.
Units: J/m^2 (SI units) - $ft{\bullet}lb/in^2$ (IP units).

2.7. Elongation at Break: It is the ratio between the new changed length and the initial length at break. It implies the ability of the facade material to resist changes in shape due to a tensile load without forming cracks.
Units: % (Percentage).

2.8. Hardness: It is the resistance of the material to plastic deformation, usually by indentation. It implies the ability of the facade material to resist permanent deformation or being scratched, cut or abraded by another material due to a compressive load.
Units: Arbitrary Scale where 100= (Extremely hard) and 0 = (Extremely soft).

2.9. Toughness: It is a good combination of strength and ductility of a material. It expresses how much energy the façade material can absorb and plastically deform before rupturing (fracture).
Units: J/m^3 (SI units) - $in.lbf/in^3$ (IP units).

2.10. Creep: It is a time-dependent deformation that takes place under a permanent load. It implies the vulnerability of the façade material to deform slowly over time when subjected to a constant load.
Units: N.A.

3. Thermal Properties

3.1. Melting Point: It is the temperature at which the material melts and softens completely.
Units: °C (SI units) - °F (IP units).

3.2. Max. Service Temp: It is the maximum temperature at which the material can be used without loss of strength. Units: °C (SI units) - °F (IP units).

3.3. Min. Service Temp: It is the minimum temperature at which the material can be used without becoming too brittle.
Units: °C (SI units) - °F (IP units).

3.4. Thermal Conductivity: It is the rate of heat transfer across the material.
Units: W/m•°K (SI units) - Btu/hr•ft•°F (IP units).

3.5. Heat Deflection Temp: It is the temperature at which stiff plastics lose stiffness under a given bending stress (1.80 or 0.45 MPa).
Units: °C (SI units) - °F (IP units).

3.6. Thermal expansion Coefficient: It is the increase in the length of a material per degree rise of temperature.
Units: °C-1 (SI units) - (microstrain/C) or 10-6 °C-1 or °K-1.

4. Optical / Visual Properties

4.1. Light Transmittance: It is the percentage of light that passes through the material.
Units: % (Percentage).

4.2. Color: It reflects the way light interacts with the material, interpreted by brain and viewed by eyes.
Units: N.A.

4.3. Refractive index: It measures the bending of light rays when passing through the material.
Units: N.A.

5. Environmental Properties

5.1. CO^2 Footprint: It measures the amount of carbon dioxide and related GHGs emitted during the production and consumption of the material.
Units: Carbon dioxide equivalent per unit of time or per unit of product.

5.2. End of Life: It describes the material various end-of life options.
Units: Recycle - Reuse - Incineration - Landfill.

5.3. Moisture Absorption: It measures the material capacity to absorb moisture from the surrounding environment (air, water).
Units: % (Percentage).

5.4. Chemical & UV radiation Resistance: It describes the ability of the material to resist the effect of chemicals and degradation by ultraviolet (UV) radiation from sunlight.
Units: N.A.

Identify Performace-Baseline. This benchmark performance guideline is intended to provide a mark, or a reference level where all candidates may be compared and/or evaluated. The importance of establishing such performance-baseline lies in differentiating between these materials based on their performance rates (materials properties) and their ability to achieve the target competency (façade requirements). This will contribute in determining which of these candidates are performing optimally close to or surpasses the exemplar's level of performance and which are showing poor performance rates. Thus highlighting the optimal materials to the façade applications and excluding the least suited ones. For instance, in the case of curtain wall, Glass and Aluminum will be the targeted materials (the exemplar) to compete with. Performance will be satisfactory if the new candidate materials properties equal or exceed the values of such defined components. Consequently, in order to identify this benchmark, four of the most widely used glass types and Aluminum alloys in building façades will be analyzed and compared in terms of their optical, mechanical, thermal, physical and environmental properties respectively. Please see tables (1 & 2).

Table 1. Properties of Glass Types

Properties	Glass Types			
	Soda Lime-0070	**Silica (96%)**	**Low-e glass**	**Laminated glass**
General/Physical Properties				
Density (lb/in^3)	0.0892 - 0.091	0.0777 - 0.0795	0.0882 - 0.09	0.0849 - 0.0885
Price (USD$/lb)	0.64 - 0.753	2.73 - 4.54	0.64 - 0.753	2.61 - 4.21
Mechanical Properties				
Flexural Strength (ksi)	5.71 - 6.07	28.6 - 31.5	4.64 - 5.08	5.8 - 6.53
Flexural Modulus (10^6 psi)	9.86 - 10.4	9.62 - 10.1	9.57 - 10.3	10.2 - 10.7
Impact Toughness (ksi.in$^{0.5}$)	0.573 - 0.592	0.573 - 0.582	0.501 - 0.637	0.91 - 1.18
Thermal Properties				
Thermal Conductivity (Btu/hr•ft•°F)	0.404 - 0.751	0.578 - 0.867	0.413 - 0.75	0.361 - 0.642
Glass temperature (°F)	849 - 1120	2360 - 3080	826 - 1090	212 - 1100
Optical / Visual Properties				
Transparency (%)	85-90	85-90	85-90	85-90
Refractive index	1.5 - 1.52	1.45 - 1.47	1.5 - 1.52	1.5 - 1.52
Environmental Properties				
UV radiation (sunlight)	Excellent	Excellent	Excellent	Excellent
Flammability	Non-Flammable	Non-Flammable	Non-Flammable	Non-Flammable

Table 2. Properties of Aluminum Alloys

Properties	Aluminum Alloys			
	Alum 6063-O	**Alum 6063- T1**	**Alum 6063- T4**	**Alum 6063- T5**
General/Physical Properties				
Density (lb/in^3)	0.0965 - 0.0983	0.0961 - 0.0979	0.0965 - 0.0983	0.0961 - 0.0979
Price (USD$/lb)	1 - 1.15	1 - 1.15	1 - 1.15	1 - 1.15
Mechanical Properties				
Flexural Strength (ksi)	6.61 - 7.31	8.95 - 9.89	12.4 - 13.7	16.4 - 18.1
Flexural Modulus (10^6 psi)	9.75 - 10.2	9.75 - 10.2	9.75 - 10.3	9.75 - 10.3
Impact Toughness (ksi.in$^{0.5}$)	27.3 - 32.8	27.3 - 32.8	27.3 - 32.8	27.3 - 32.8
Thermal Properties				
Thermal Conductivity (Btu/hr•ft•°F)	121 - 131	107 - 116	109 - 118	116 - 125
Melting Point / temperature (°F)	1140 - 1210	1140 - 1210	1140 - 1210	1140 - 1210
Optical / Visual Properties				
Appearance (Color -Transparency)	Opaque (colored)	Opaque (colored)	Opaque (colored)	Opaque (colored)
Environmental Properties				
UV radiation (sunlight)	Excellent	Excellent	Excellent	Excellent
Flammability	Non-Flammable	Non-Flammable	Non-Flammable	Non-Flammable

Stage (1-2) Primary Screening

In this stage, selection priorities, and selection criteria should be highlighted, and assigned. This will not only contribute in eliminating the materials that do not meet the façade requirements and constraints but also in nominating the possible candidates, from the bio-polymeric materials family, to replace glass and aluminum within the glazing and framing sections of the curtain wall system..

Selection Priorities. The glazing and framing units are the main elements of most windows and curtain wall systems. The main purpose of the glazing unit (infill element) is to provide a clear view of the exterior spaces, while allowing considerable daylight to penetrate it and illuminate the interior spaces. Therefore, the optical/visual properties of the glazing material should be the main factor directing the selection process followed by the mechanical, thermal, physical and environmental properties to ensure good visibility, safety and durability rates, good thermal performance and high resistance to different weather conditions. On the other hand, the main purpose of the framing unit (mullions and rails) is to provide utmost structural support to the glazing unit, while safely transferring dead loads, live loads and wind loads to the structure below or to the ground. Accordingly, the mechanical properties, in this case, should be the major driving force for the material selection process followed by the thermal, physical, environmental and optical properties respectively to assure that the chosen material is strong, durable and has a good thermal performance and high resistive rates to the exterior environmental conditions.

Selection Criteria. This is the most critical step of the entire primary screening stage. It will focus in the beginning on transforming the design considerations and requirements into measurable limits and constraints, which will then be applied to the selection data (material pool) to acquire the highest possible candidates. Accordingly, reviewing the different codes and standards related to building façade and fenestration performance is the primary key to summarize the minimum design requirements needed for developing a durable energy efficient curtain wall assembly made from bio-polymeric materials. These reference codes and standards, such as NFRC rating system, ASHRAE Standard 90.1, NAFS- AAMA/WDMA/CSA, IECC, and the City's municipal code, should be reviewed to outline the minimum thermal, optical, and structural/mechanical requirements for building envelopes. This will ensure that the selected materials have adequate strength, stiffness and durability to withstand the several exterior forces affecting the façade of a specific building within a definite location and an exact climate zone. Please see Fig (2).

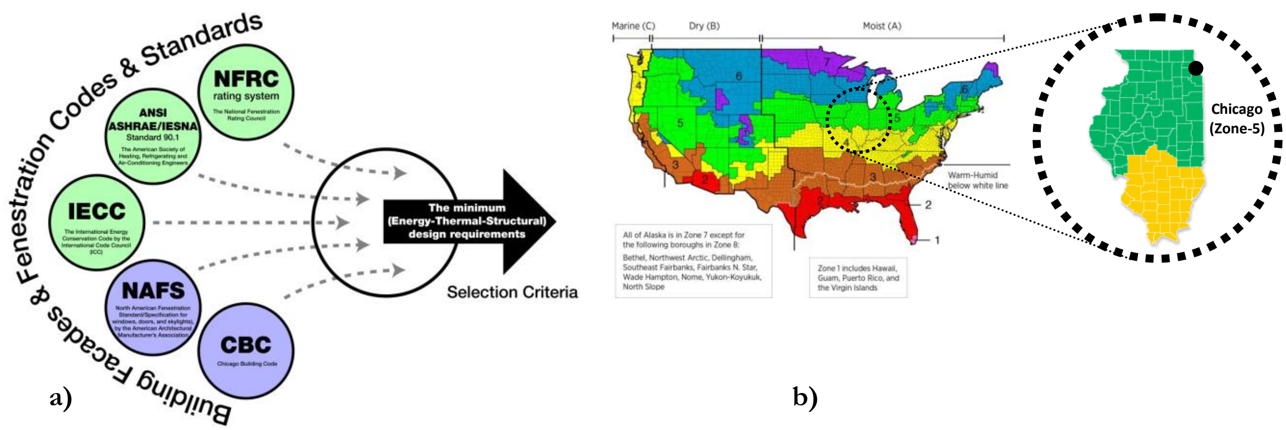


Figure 2 (a) Building Façade and Fenestration Codes and (b) USA Climate Zones.

For instance, to develop a Biobased, strong, stiff and lightweight curtain wall panel made from bio-polymeric materials for a mid-rise office building (4-12 floors, 48-144 ft height) located in Chicago (Climate Zone 5), the selected materials should conform to the following minimum requirements (measurable limits):

- **Wind Loadings:** In reference to the Chicago building code (CBC), the design wind pressure for buildings whose height is 200 ft or less is (25 psf). Meanwhile, the North American Fenestration Standard (NAFS) requires that the structural load of the designed curtain wall must withstand one and a half times the minimum design wind pressure for the CW (low and mid-rise building) class. Accordingly, the required materials should withstand a pressure of (45 psf) to comply with both codes.

- **Panel Weight:** In order to ensure that the new panel weight will be lighter in weight than the conventional glass and aluminum curtain wall, the mass of the new materials should be minimized as much as possible. Given that the panel mass depends on its volume (area and thickness) and the density of the selected material, the only guarantee to do that is to select materials whose densities are lower than glass and aluminum for the same panel area and thickness. Accordingly, the selected glazing material density should be lower than (0.0892 lb/in^3) while the selected framing material density should be lower than (0.0965 lb/in^3).

  $\therefore (\rho_{max})\ Glazing \leq (\rho_{glass}) \leq (0.0892\ lb/in^3) \leq (2470\ kg/m^3)$
  $\therefore (\rho_{max})\ Framing \leq (\rho_{aluminum}) \leq (0.0965\ lb/in^3) \leq (2670\ kg/m^3)$

- **Panel reaction to wind pressure (Resistance to stress and deflection):** In order to ensure that the selected material is strong enough to carry the applied bending force due to the wind pressure (external applied stress) safely, the material flexural strength (the maximum allowable stress the material can withstand before fracture) should exceed or equalize the (45 psf) minimum design wind pressure. On the other hand, selecting a material with a high stiffness value will be essential to ensure minimizing the panel's deflection beyond the maximum allowable deflection value required by the International building code (IBC-2012). Accordingly, the selected material deflection value shouldn't exceed (L/175" or ¾", whichever is lower, where L is the glass edge length).

  $\therefore$ *The material flexural strength* $(\sigma_f) \geq$ *Wind Pressure* (W_p)
  $\therefore (\sigma f) \geq (45\ psf) \geq (0.0003125\ ksi) \geq (2154.6\ pa)$
  $\therefore (\delta_{material}) \leq (\delta_{max})$ *Max. allowable deflection* $\leq (L/175)$ *or* ¾"
  $\therefore (\delta_{max})$ *flat panel (Plate)* $= 0.142\ wb^4 / Et^3[2.21(b/a)^3+1]$
  $\therefore (\delta_{max})$ *frame (beam)* $= (5/384) \times WL^4/ EI$

- **Panel Durability:** In order to ensure that the selected materials are hard and durable enough to withstand strong wind gusts and possible bird strikes without shattering, the impact strength of these materials (Charpy Notched Impact) should exceed (0.003 btu/in^2) to exclude brittle materials.

- **Panel Optical and aesthetic requirements:** In order to ensure that the selected materials satisfy the optical and aesthetic requirements of the conventional curtain wall panel, the visible light transmittance of the glazing material should equalize or exceed the VLT of glass and the appearance of the framing material should provide more options than Aluminum. Therefore the VLT of the selected glazing material should equalize or exceed 80% while the selected framing material should be customizable in design, color, and texture.

Screening with Constraints. In this step, the quantifiable limits are employed to screen out the materials that don't meet the criteria output values. The screening process goes through four consecutive levels. The process starts by exposing all the materials to the sustainability level fundamentals, which concerns with selecting only the Biobased long-lasting eco-friendly polymeric materials and screening out all the biodegradable bio-polymeric ones. The remaining Biobased materials proceed to the workability level that concerns with the polymer type, functional screening and transparency. This level focuses on selecting the suitable thermoplastic materials that meet all the mechanical, optical and aesthetic requirements for the intended façade application, in terms of weight, strength, stiffness, and transparency, while screening out all the other impractical thermosets and elastomers. The aptitude of the materials for light transmittance or impenetrability needs to be considered in this sub-level to examine their transparency and opacity properties. Accordingly, some of the qualified materials will be categorized transparent whereas the others will be classified opaque. All the qualified transparent and opaque materials will be then subjected to the weatherability level standards to ensure their suitability to withstand the weathering effect emerged from the prolonged exposure to the outdoor environmental conditions. This will ensure that the selected materials have high resistance to the harmful effects of the UV radiations, extreme temperatures, moisture penetration, and chemical exposure. Consequently, the remaining set of materials proceeds to the final screening level that concerns with the fundamentals of durability. The main objectives of this level are to guarantee a high standard of impact resistance to strong gusts of wind and possible bird strikes, without shattering, and to maximize fire safety measures with the aim of providing the occupants with the utmost level of safety and protection. By the end of this screening process, architects, engineers, and design professionals will be able to carry out a closed oriented comparison procedure among a few qualified candidates. This will not only diminish the risk of losing a possible candidate, but also will ensure that all the selected materials are sustainable, bio-based, long-lasting, light-weight, strong, stiff, durable and tough with high weatherability resistance, good processing economics and multiple end-of-life options. Please see Fig (3).

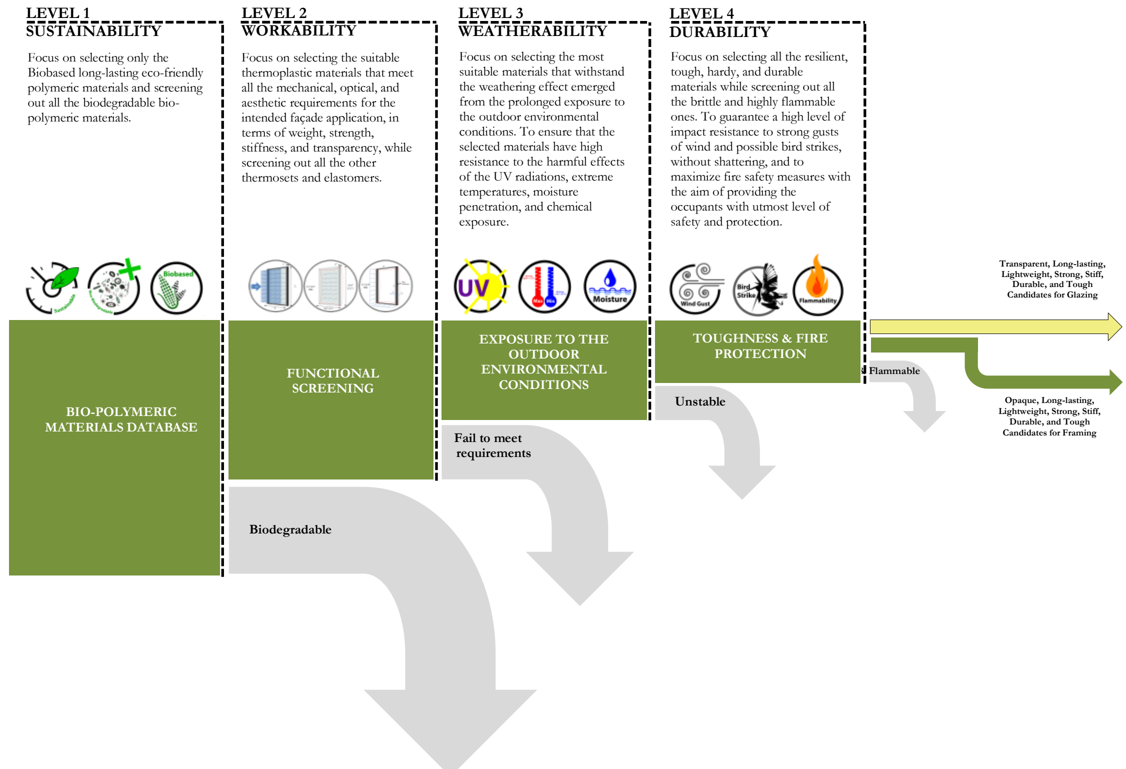


Figure 3 Levels of screening the Bio-Polymeric materials.

Stage (1-3) Evaluation of Candidates

After exposing all the available bio-polymeric materials to the aforementioned screening process, through rigorous levels and structured criteria, a few candidates have demonstrated great abilities in meeting all the mechanical, physical, thermal, visual/optical, and environmental requirements of building façades. Accordingly, the evaluation of candidates stage is essential in both expounding and explicating the candidates' order of preference to facilitate the decision making process. Since the multi-criteria requirements of building façades aim at minimizing the density (to reduce façade weight), price and thermal conductivity of façade materials (to reduce heat transfer through the façade assembly), while maximizing their strength, stiffness, toughness, renewable bio-content, UV resistance, heat deflection temperature, flammability resistance, appearance and optical transmittance, therefore identifying the performance status of each material should be considered for materials evaluation and ranking in view of their order of preference in achieving the aforesaid performance attributes. Consequently, the performance status of each material will be displayed in the form of a traditional two-dimensional radar chart consists of sequential eleven to twelve multivariate attributes to measure the magnitudes of the material performance across all levels to reflect its status and compare it with the other materials.

The Limitations of the Performance Status charts and the need for MCDM methods. By virtue of the multiplicity and diversity of the performance criteria employed to assess the ability of each material in achieving the multifaceted façade requirements, the performance status charts do not provide sufficient evidences of a material superiority over its counterparts. Thus it is a challenging task to select the best fitted candidate among all of them using this traditional comparison technique. The challenge stems from the need to assess these material candidates against a set of conflicting criteria with incommensurable units. This explains the necessity to use a new algorithm to establish a common base of comparison that will facilitate sorting, ranking and inferring the best compromise solution that satisfies the overall required criteria. Please see Fig (4).

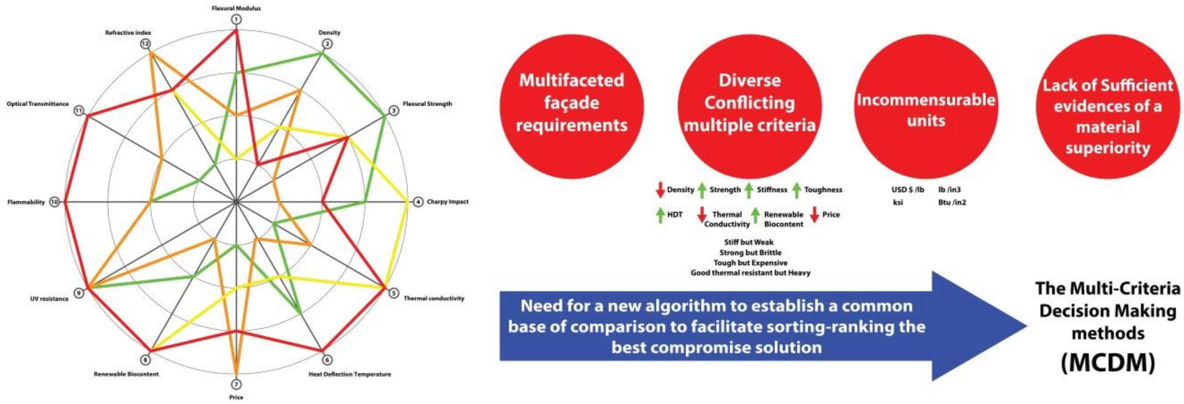


Figure 4 The Limitations of the traditional Performance Status charts.

STEP (2) ADVANCED SELECTION

The Multi-Criteria Decision Making methods (MCDM) or Multi-Criteria Decision Analysis methods (MCDA) are a set of mathematical tools, methods and techniques that help decision makers in evaluating a discrete set of alternatives and choose the most appropriate candidate among them (Triantaphyllou 2011). Several theories and models for MCDM have emerged since the early 1970'es to solve inaccessible decision problems instead of the traditional techniques. This period saw many seminal contributions in the theory and method development of multiple criteria decision making, including the publication of Ralph Keeney and Howard Raiffa's book on multiattribute utility theory in 1976, and Jared cohon's book on multiobjective programming and planning in 1978 (Koksalan, Wallenius and Zionts 2011). Since then, Multi-Criteria Decision Making methods have been used to support the decision makers with structured tools when dealing with vital planning problems involving multiple criteria or objectives. After identifying the performance criteria/attributes in the previous stage, the Multi-Criteria Decision Making process (MCDM) will go through two main stages to select the best alternatives with the highest weighted scores for the framing and glazing components. Firstly, the Analytic Hierarchy Process (AHP method), developed by Thomas L. Saaty in 1970, will be used to develop a single pairwise comparison matrix of criteria to determine the weights for each criterion to represent importance. Secondly, the technique for order of preference by similarity to ideal solution (TOPSIS method), developed by Hwang and Yoon in 1980, will focus, in the first place, on constructing and standardizing the decision matrix to identify both the positive and negative ideal solutions. It then will rank the available candidates according to their separation measures; closeness to the ideal positive solution and distance from the negative one to select the best alternative among all candidates (Hassan 2017).

Stage (2-1) AHP Method

The Analytic Hierarchy Process method is an effective tool needed to help architects and decision makers in solving complex decisions regarding building façade material selection. It helps in capturing both the subjective and objective attributes set by the architect and transforms these qualitative and quantitative evaluations into a series of pairwise comparisons to generate a relative weight for each criterion/attribute. To develop the pairwise comparison matrix, it is important to deal with the problem as a hierarchy by identifying the goal, which is for instance selecting the best suitable framing material, and defining the different attributes such as density, flexural strength, flexural modulus, charpy impact, thermal conductivity, heat deflection temp, renewable bio-content, price, UV resistance, flammability, color, texture, optical transmittance, etc. Since no criterion/attribute has the same importance, therefore deriving the relative priorities for the evaluation criteria is essential to determine the weight of each criterion with respect to the others using Saaty's 9-point scale. Please see Fig (5).

(Saaty's 9-point scale)	
1	Equally preferred
2	Equally to moderately preferred
3	Moderately preferred
4	Moderately to strongly preferred
5	Strongly preferred
6	Strongly to very strongly preferred
7	Very strongly preferred
8	very to extremely strongly preferred
9	Extremely preferred

Number of Criteria (n)	RI
1	0
2	0
3	0.58
4	0.9
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49
11	1.51
12	1.54

criteria/attributes	1-Density	2-Flexural Strength	3-Flexural Modulus	4-Charpy Impact	5-Thermal Conductivity	6-Heat Deflection Temperature	7-Renewable Bio-Content	8-Price	9-UV resistance	10-Flammability	11-Appearance (Color+Texture)	nth root where n is the number of criterions = 11 = (n1*n2*n3*****) to the power (1/11)	(The Priority vector) Appropriate Weights for each criterion	
1-Density	1.00	1.00	1.00	1.00	2.00	2.00	3.00	3.00	4.00	4.00	5.00	2.063	0.15	15%
2-Flexural Strength	1.00	1.00	1.00	1.00	2.00	2.00	3.00	3.00	4.00	4.00	5.00	2.063	0.15	15%
3-Flexural Modulus	1.00	1.00	1.00	1.00	2.00	2.00	3.00	3.00	4.00	4.00	5.00	2.063	0.15	15%
4-Charpy Impact	1.00	1.00	1.00	1.00	2.00	2.00	3.00	3.00	4.00	4.00	5.00	2.063	0.15	15%
5-Thermal Conductivity	0.50	0.50	0.50	0.50	1.00	1.00	2.00	2.00	3.00	3.00	4.00	1.221	0.09	9%
6-Heat Deflection Temperature	0.50	0.50	0.50	0.50	1.00	1.00	2.00	2.00	3.00	3.00	4.00	1.221	0.09	9%
7-Renewable Bio-Content	0.33	0.33	0.33	0.33	0.50	0.50	1.00	1.00	2.00	2.00	3.00	0.741	0.06	6%
8-Price	0.33	0.33	0.33	0.33	0.50	0.50	1.00	1.00	2.00	2.00	3.00	0.741	0.06	6%
9-UV resistance	0.25	0.25	0.25	0.25	0.33	0.33	0.50	0.50	1.00	1.00	2.00	0.464	0.03	3%
10-Flammability	0.25	0.25	0.25	0.25	0.33	0.33	0.50	0.50	1.00	1.00	2.00	0.464	0.03	3%
11-Appearance (Color+Texture)	0.20	0.20	0.20	0.20	0.25	0.25	0.33	0.33	0.50	0.50	1.00	0.313	0.02	2%
SUM	6.37	6.37	6.37	6.37	11.92	11.92	19.33	19.33	28.50	28.50	39.00	13.418	1.000	
SUM*PV	0.978871	0.978871	0.978871	0.978871	1.084494	1.084494	1.067839	1.067839	0.986555	0.986555	0.90838326		Total weights = 1.0	
Lambda-max	11.10164													
CI = (Lambda-max - n)/ (n-1)	0.010164											Pair-wise Comparison Matrix		
Random Consistency index (RI) for 11 criterions (from table)	1.51			For checkup										
CR = CI/RI	0.0067	Since CR ≤ 0.10			Therefore the pairwise comparison are relatively consistent and no corrective action is necessary									

Figure 5 AHP method to calculate the weights for each criterion.

Stage (2-2) TOPSIS Method

The Technique for Order of Preference by Similarity to Ideal Solution is an effective tool to rank the different alternatives based on their geometric distances from the positive and the negative ideal solutions. Accordingly, the best alternative should have the closest distance to the positive ideal solution (with the best criteria values) and the farthest distance from the negative ideal solution (with the worst criteria values). For instance, to select the best opaque bio-polymeric material for facade applications, 4 materials have been analyzed and ranked by AHP and TOPSIS methods. Therefore, the best alternative will have the highest weighted score as shown in Fig (6) and Fig (7).

Attributes/Criteria	(A) ATTRIBUTE WEIGHT (From AHP method)	(B) CONSTRUCT THE DECISION MATRIX: m1 (NFC-Natural Fiber Composite) Performance Status	m1 Weight	m2 (RVB-Reinforced Vegetable Oil Biocomposites) Performance Status	m2 Weight	m3 (VOB-Vegetable Oil-based Bioplastics) Performance Status	m3 Weight	m4 (FRC-Fiber reinforced composite) Performance Status	m4 Weight
1-Density	0.154	10	0.15	6	0.09	8	0.12	4	0.06
2-Flexural Strength	0.154	4	0.06	10	0.15	6	0.09	8	0.12
3-Flexural Modulus	0.154	4	0.06	10	0.15	6	0.09	8	0.12
4-Charpy Impact	0.154	10	0.15	6	0.09	8	0.12	4	0.06
5-Thermal Conductivity	0.091	8	0.07	6	0.05	10	0.09	4	0.04
6-Heat Deflection Temperature	0.091	4	0.04	10	0.09	6	0.05	8	0.07
7-Renewable Bio-Content	0.055	8	0.04	6	0.03	10	0.06	4	0.02
8-Price	0.055	6	0.03	4	0.02	10	0.06	8	0.04
9-UV resistance	0.035	10	0.03	10	0.03	10	0.03	10	0.03
10-Flammability	0.035	6	0.02	10	0.03	6	0.02	10	0.03
11-Appearance (Color+Texture)	0.023	10	0.02	10	0.02	6	0.01	6	0.01

(C) STANDARDIZE THE DECISION MATRIX	(D) IDENTIFY THE WEIGHTED STANDARDIZED DECISION MATRIX (WSDM): m1 (Weighted Standardized decision matrix) WSDM	m2 (Weighted Standardized decision matrix) WSDM	m3 (Weighted Standardized decision matrix) WSDM	m4 (Weighted Standardized decision matrix) WSDM
0.23	0.10	0.06	0.08	0.04
0.23	0.04	0.10	0.06	0.08
0.23	0.04	0.10	0.06	0.08
0.23	0.10	0.06	0.08	0.04
0.13	0.05	0.04	0.06	0.02
0.13	0.02	0.06	0.04	0.05
0.08	0.03	0.02	0.04	0.02
0.08	0.02	0.02	0.04	0.03
0.07	0.02	0.02	0.02	0.02
0.06	0.01	0.02	0.01	0.02
0.04	0.01	0.01	0.01	0.01

(E) IDENTIFY THE POSITIVE & NEGATIVE IDEAL SOLUTIONS: POSITIVE IDEAL SOLUTION	NEGATIVE IDEAL SOLUTION	(F) DETERMINE THE SEPARATION MEASURES FROM THE POSITIVE & NEGATIVE IDEAL SOLUTIONS: S1+ (Separation from the positive ideal solution)	S2+ (Separation from the positive ideal solution)	S3+ (Separation from the positive ideal solution)	S4+ (Separation from the positive ideal solution)	S1- (Separation from the negative ideal solution)	S2- (Separation from the negative ideal solution)	S3- (Separation from the negative ideal solution)	S4- (Separation from the negative ideal solution)
0.10	0.04	0.00002	0.00139	0.00027	0.00338	0.00417	0.00052	0.00191	0.00000
0.10	0.04	0.00338	0.00002	0.00139	0.00027	0.00000	0.00417	0.00052	0.00191
0.10	0.04	0.00338	0.00002	0.00139	0.00027	0.00000	0.00417	0.00052	0.00191
0.10	0.04	0.00002	0.00139	0.00027	0.00338	0.00417	0.00052	0.00191	0.00000
0.06	0.02	0.00011	0.00052	0.00000	0.00124	0.00087	0.00029	0.00176	0.00002
0.06	0.02	0.00124	0.00000	0.00052	0.00011	0.00002	0.00176	0.00029	0.00087
0.04	0.02	0.00010	0.00030	0.00001	0.00062	0.00010	0.00001	0.00031	0.00002
0.04	0.02	0.00030	0.00062	0.00001	0.00010	0.00001	0.00002	0.00031	0.00010
0.02	0.02	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001
0.02	0.01	0.00005	0.00000	0.00005	0.00000	0.00001	0.00012	0.00001	0.00012
0.01	0.01	0.00002	0.00002	0.00000	0.00000	0.00002	0.00002	0.00000	0.00000
		TOTAL	TOTAL	TOTAL	TOTAL	TOTAL	TOTAL	TOTAL	TOTAL
		0.09295	0.06553	0.06250	0.09685	0.09690	0.10777	0.08684	0.07054

(G) DETERMINE THE RELATIVE CLOSENESS TO THE POSITIVE IDEAL SOLUTIONS Si- /(Si+ +Si-)	ALTERNATIVES: m1 (NFC-Natural Fiber Composite)	m2 (RVB-Reinforced Vegetable Oil Biocomposites)	m3 (VOB-Vegetable Oil-based Bioplastics)	m4 (FRC-Fiber reinforced composite)
Si+	0.0929	0.0655	0.0625	0.0968
Si-	0.0969	0.1078	0.0868	0.0705
(Si+ +Si-)	0.1899	0.1733	0.1493	0.1674
Materials Score : Si- /(Si+ +Si-)	0.5104	0.6219	0.5815	0.4214
Materials Ranking	3	1	2	4

Best Alternative m2>m3>m1>m4

Figure 6 TOPSIS method to calculate the score of each material and determine the final ranking results.

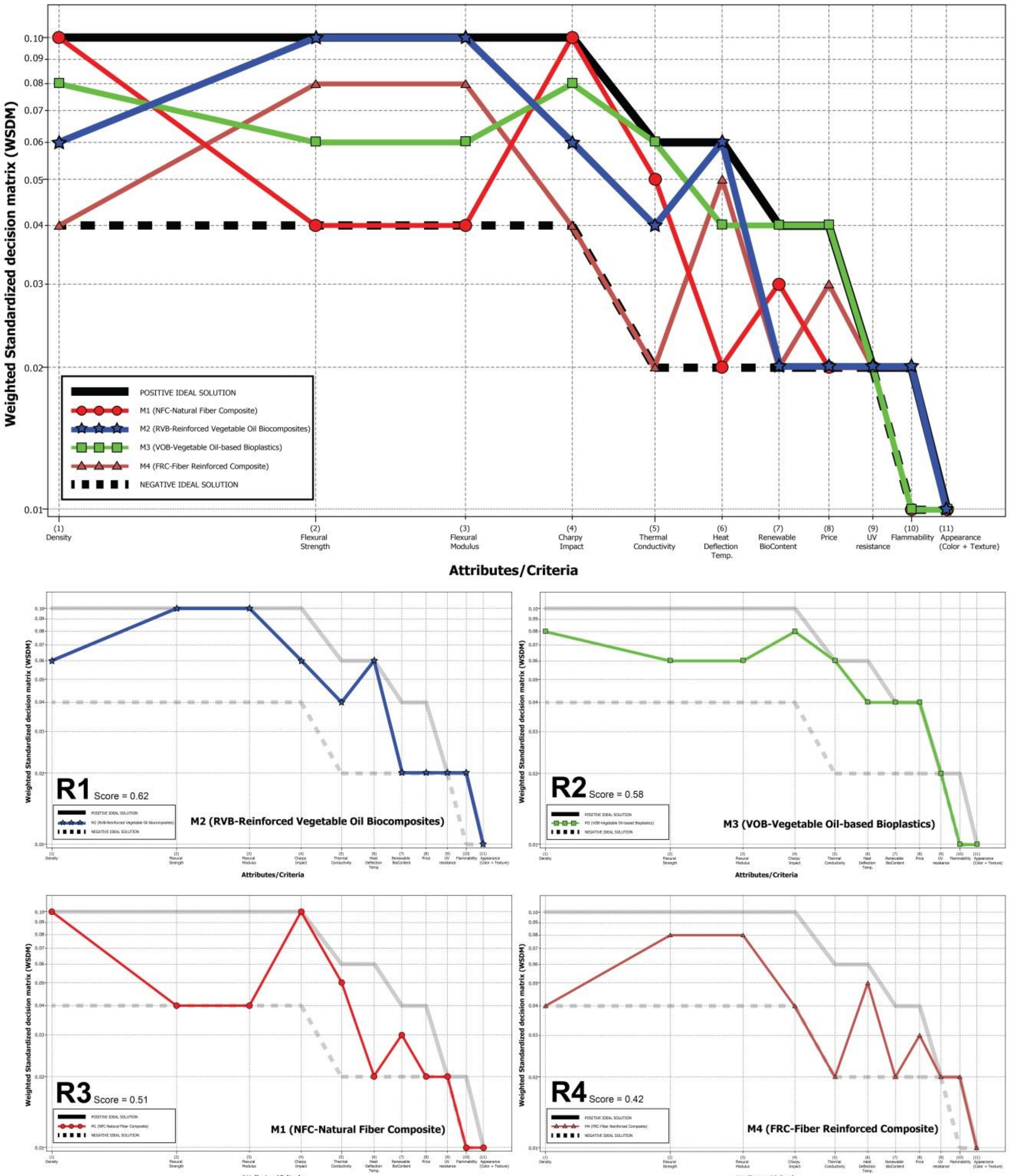


Figure 7 Ranking of materials based on their relative distances from the positive and negative ideal solutions.

CONCLUSION

This paper has discussed progressively both the potentials and the limitations of the current material selection strategies while explaining the needs to develop a new framework that Architects and Engineers can pursue when selecting new Bio-polymeric materials for building façade applications. The paper has demonstrated rigorous selection criteria to facilitate proposing innovative building façade materials capable of handling all the environmental, thermal, optical, functional, and economic considerations of the building façade. Several quantifiable constraints have been used to screen out the materials that didn't match the mimium requirements of the building façade codes and standards. Multi-criteria decision making methods such as AHP and TOPSIS methods have been discussed and then employed to enable sorting and ranking the material candidates considering their order of preference in achieving the building façade's multifaceted performance criteria.

REFERENCES

Ashby, M. F., Y Bréchet, D Cebon, and L Salvo. "Selection Strategies for Materials and Processes." *Materials and Design 25*, 2004: 51-67.

Ashby, Michael F. *Materials Selection in Mechanical Design.* Elsevier, 2011.

Dictionaries, Oxford. *Oxford University Press.* 2017. https://en.oxforddictionaries.com/definition/us/performance (accessed Dec. 26, 2017).

Dictionaries, Oxford. *Oxford University Press.* 2017. https://en.oxforddictionaries.com/definition/us/criteria (accessed Dec. 26, 2017).

Elnimeiri, Mahjoub, and Ahmed Ali Hassan. "Potentials and Challenges of Emerging Bio-Polymeric Facade Materials." *10th Conference on Advanced Building Skins.* Bern, Switzerland: Economic Forum, 2015. 645-655.

European Commission. *Horizon 2020-EU Bioeconomy research and innovation.* 2012. http://ec.europa.eu/research/bioeconomy/index.cfm?pg=home (accessed Dec. 25, 2017).

Hassan, Ahmed Ali. *The BioEnclos© Facade Panel : From Selection to Design, Assessment, and Beyond.* PhD diss., Illinois Institute of Technology, 2017.

Helmut Kaiser Consultancy. *Bioplastics Market Worldwide 2011-2025.* 2016. http://www.hkc22.com/bioplastics.html (accessed 12 25, 2017).

Koksalan, Murat, Jyrki Wallenius, and Stanley Zionts. *Multiple Criteria Decision Making: From Early History to the 21st Century.* Singapore: World Scientific Publication Co., 2011.

National Bioeconomy Blueprint. April 2012. https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/national_bioeconomy_blueprint_april_2012.pdf (accessed Dec. 25, 2017).

Triantaphyllou, Evangelos. *Multi-criteria decision making methods: a comparative study.* Springer, 2011.