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Conceptual Design of a Sustainable Bionanocomposite Bracket for a Transmission Tower's Cross Arm Using a Hybrid Concurrent Engineering Approach

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Abstract: This research article elaborates on the conceptual design development of a sustainable bionanocomposite bracket for bracing installation in composite cross arm structures. The product design development employed the hybrid techniques of the theory of inventive problem solving (TRIZ), morphological chart, and analytic network process (ANP) methods. The current bracket design in the braced composite cross arm is composed of heavy and easy-to-rust steel material. Therefore, this research aims to develop a new bionanocomposite bracket design to replace the heavy and easy-to-rust steel bracket. This research also aims to implement a concurrent engineering approach for the conceptual design of bionanocomposite bracket installation to enhance the overall insulation performance. A preliminary process was implemented, which covered the relationship between the current problem of the design and design planning to build a proper direction to create a new design product using TRIZ. Later, the TRIZ inventive solution was selected based on the engineering contradiction matrix with specific design strategies. From the design strategies, the results were refined in a morphological chart to form several conceptual designs to select the ANP technique to systematically develop the final conceptual design of the bionanocomposite bracket for the cross arm component. The outcomes showed that Concept Design 1 scored the highest and ranked first among the four proposed designs. The challenges of the bionanocomposite bracket design for cross arm structures and the improvement criteria in concurrent engineering are also presented.

Keywords: conceptual design; bionanocomposites; composite brackets; TRIZ; morphological chart; ANP

1. Introduction

Electrical transmission towers hold power cables along transmission lines to supply power from the power generator. In general, the transmission towers are classified into two types: (1) monopole steel tubes and (2) latticed steel towers [1–3]. In many areas, a latticed transmission tower is usually used due to their ability to withstand higher wind loads and various land topography surfaces. The latticed transmission tower has been widely used in Malaysia since 1929 [4–6]. The latticed tower is divided into several sections and components, which include a cross arm, peak, boom tower body, and cage. The primary purpose of a cross arm is to support and secure electrical lines. Currently, the suspension tower's cross arm is composed of a nonconductive, lightweight, and highly durable material. The cross arm of a suspended lattice structure is frequently made of high-strength materials, such as wood timber and composite. These structures serve as network lines to transport electricity from power generators to substations before it reaches consumers. To ensure the power cable is hung above the ground, cross arms and insulators are secured to the electrical wires to resist electrical jumps, which can damage the transmission tower and nearby pedestrians [7,8].

The creep phenomenon of fiber-reinforced polymer (FRP) composites may jeopardize the reliability and longevity of structural components [7,8]. In this sense, understanding the long-term creep reactions of the FRP composite can help to overcome structural concerns. If creep occurred, the material would eventually break quickly and without warning [9,10]. The long-lasting performance of composite cross arms has been employed to replace wooden structures in transmission and distribution towers. One of the benefits of composite cross arms is their endurance; they may also be employed as cantilever beams for streetlight support structures due to their strength, durability, and lightweight features [10–12]. As an alternative, pultruded glass fiber-reinforced polymer (PGFRP) composite was proposed by many researchers to replace the wooden cross arm [13], such as the implementation of PGFRP composite in a 132 kV tower at transmission lines from Pekan town at the Tanjung Batu line [7]. Glass fiber-reinforced polymer composites have been widely implemented in many products, such as structural components [14], household products, fire extinguisher tanks, and shoe racks [15], because the composite material has better bending [16], compressive [17], and tensile [18] properties. This is because of the creep behaviour of PGFRP structures in transmission towers. Identifying the concerns regarding the consequences of composite degradation that lead to composite failure in this circumstance would aid in their reduction in the composite structure. Therefore, creep behaviour is a significant concern for material structures that have been subjected to pressures for protracted periods of time [13].

The deterioration of the composite material could have some bearing on the catastrophic collapse of the structures. Throughout the course of its existence, the composite may suffer from degradation as a result of extreme stress or the manufacturing process [19,20]. This inquiry might focus on the safe limit parameter of the cross arm construction in order to provide consistent safety standards. For example, it could carry out a critical assessment on the safe limit parameter of the cross arm structure in order to produce a standard safety requirement [19–22]. Experimentation and computer modelling are two methods that may be used to characterize the mechanical characteristics of a composite construction after they have been determined to be necessary. Recent studies have conducted a variety of experimental assessments and testing, using either coupon-scale or full-scale structural tests. These tests have been carried out in full size. Studies that were conducted during the early stages of mitigation evaluation also included the use of computer simulations to model composite cross arms.

From the conducted literature review, several suggestions on increasing the mechanical properties of the cross arm, including the installation of bracing and the use of sleeves, were reported. Sharaf et al. [23] conducted a numerical analysis on a full-scale cross arm in a 132 kV transmission tower. It was found that the cross arm experienced severe bending at the main member beams and would potentially cause torsional failure in broken wire conditions. These issues were addressed by Sharaf et al. [24] by implementing optimized bracing designs for the cross arm assembly to ensure that the structure can support the loading in its working and extreme broken wire conditions. Later on, Asyraf et al. [25] evaluated the creep analysis by physically experimenting with the cross arms' current and braced designs in a full-scale structure. Based on the study, it was shown that bracing applications in cross arm structures significantly enhanced the creep-resistant performance for long-term usage. However, the study implemented a steel bracket as a connector between the tie member of the cross arm and its braced members. Since the cross arm structure was implemented outdoors, it was frequently exposed to high temperatures and humidity changes. These cause rusting and bracket degradation for braced arms. Abdul Rahman et al. [26] also studied the steel bracket installation system connecting the bracing members and cross arm members that adversely affect the lightning insulation performance.

In this point of view, no proper standards and specifications were published in the literature regarding the bracket installation system of the cross arm. Most research works focus on the study enhancing the mechanical performance of cross arm structure either by the addition of bracing members [20,27], the addition of sandwich core structure [28,29], or the installation of sleeves [30]. Thus, this research aims to develop a new bionanocomposite bracket design as an alternative to steel brackets. This research also aims to implement a concurrent engineering approach for the conceptual design of bionanocomposite bracket installation to enhance the overall insulation performance. In this case, bionanocomposites have excellent mechanical properties, such as tensile and flexural strengths, tensile and flexural moduli, thermal resistance, and low cost, due to their availability from different resources, abundance in nature, and degradability, which are not available in synthetic fillers, making bionanocomposites an excellent bio-filler for both synthetic and natural polymer matrices [15]. Cellulose must be extracted before it can be utilized as a substance. According to Alias et al. [18], bionanocomposites are renowned not only for their biodegradability, superb properties, unique structures, low density, excellent mechanical performance, high surface area and aspect ratio, biocompatibility, and natural abundance, but also for their ability to have their surfaces modified in order to improve their nanoreinforcement compatibility with other polymers. As such, this design approach could add value to the available knowledge and act as a pioneer in leading the experimental work to design the actual bracket part.

2. Methodology

In this project, the conceptual design of the bracket installation system on the cross arm was developed by integrating the TRIZ–morphological chart–ANP technique. A suitable solution was explored for the conceptual design stage that engaged the current design issues. Generally, the overall process to establish the conceptual design of the bracket installation system to connect the bracing with the cross arm in this project involves four main stages: (1) idea generation, (2) idea refinement, (3) concept design development, and (4) concept design selection. In short, the TRIZ approach was used in Stage 1 to help generate the ideas to solve the current problem designs of bracket installation systems on the cross arm by implementing 39 engineering parameters and 40 inventive principles. The main aims of the TRIZ are to identify the problems of the existing design, to eliminate contradictions, and to provide a new solution by using the systematic design approach.

Then, the morphological chart was used as the idea refinement tool that provides a way to express fewer solutions for every design element. Based on the listed solutions for every element, the potential solution that contributed to the design's functionality was chosen. The morphological chart allows the designers to explore various possible solutions for each design element and to analyze the good characteristics to produce the optimum conceptual design. A few designs of the cross arm bracket installation system were developed based on the design elements in the morphological chart. Then, in the concept design selection stage, using the ANP technique, the best conceptual design that satisfied the design intent was selected using Super Decision 3.2 software.

To execute the ANP technique, the Super Decision 3.20 software was used. The network was developed to find the best conceptual design for the bracket installation on the cross arm, as shown in Figure 1. The process of judgment in the Super Decision Software 3.2 is presented in Figure 2 to show the example of a pair-wise judgment technique between the concept designs with respect to strength. In this project, the raw material cost was set to be equal to density because the design's mass determines the cost of the raw material. The stiffness and strength performance were the key objective during the selection and were set to be the highest, while the composite assembly was set to be the second highest after the performance because the method of assembly is one of the main differences among the concept designs. Figure 3 shows the overall flowchart of conceptual design development using the hybrid concurrent engineering process.

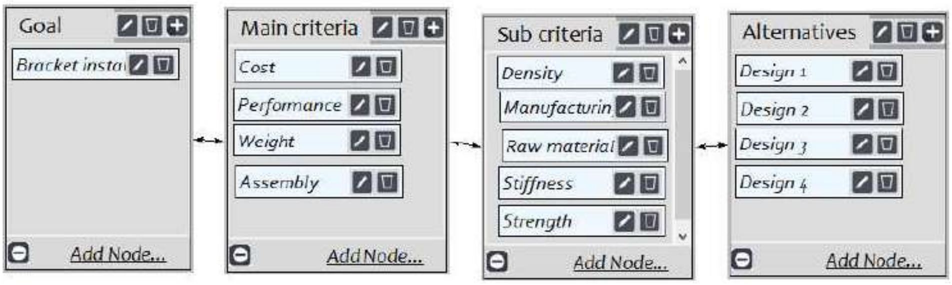


Figure 1. ANP hierarchy frame network for a hybrid flax/E-glass nanocomposite bracket installation system on the cross arm.

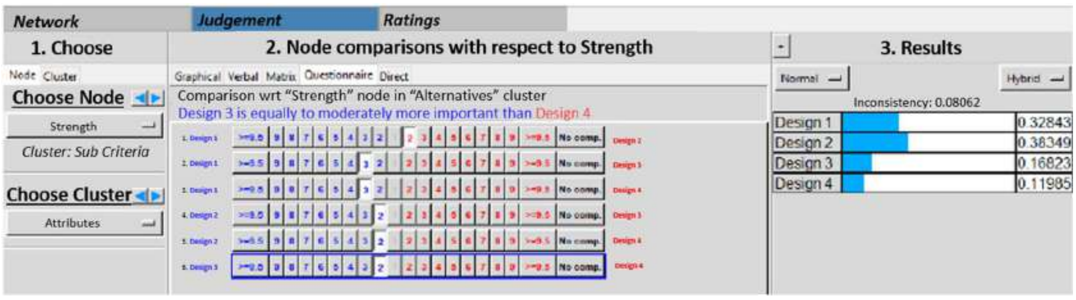


Figure 2. Pair-wise judgement process between the concept designs with respect to strength.

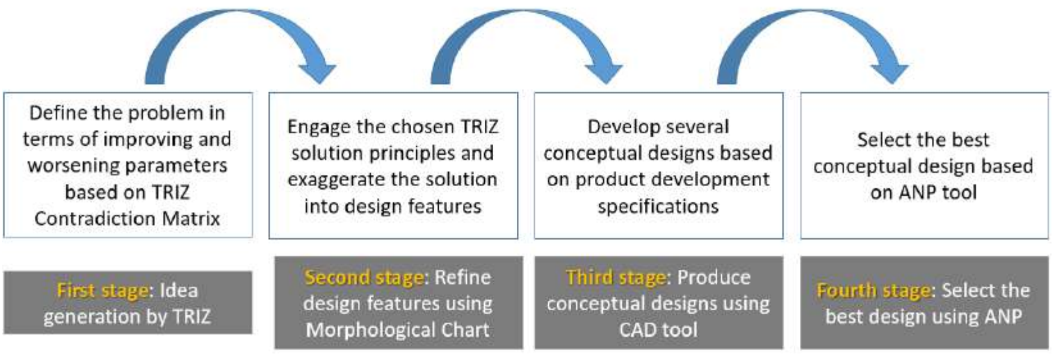


Figure 3. Overall process of optimum conceptual design including TRIZ–morphological chart–ANP.

3. Case Study on the Development of a Bracket Installation System on a Cross Arm of the Transmission Tower

Incorporating additional bracing arms has been proven to reduce the buckling reaction and, subsequently, to improve the cross arm's structural integrity [25,27]. The fastener bracket installation system attaches the bracing bars with the cross arm members [23]. The current bracket installation system design on the cross arm uses steel as the material, and bolts and nuts are used to join the bracket with the members. Figures 4 and 5 show that the bracket installation system uses mild steel to join the cross arm with the bracing members.

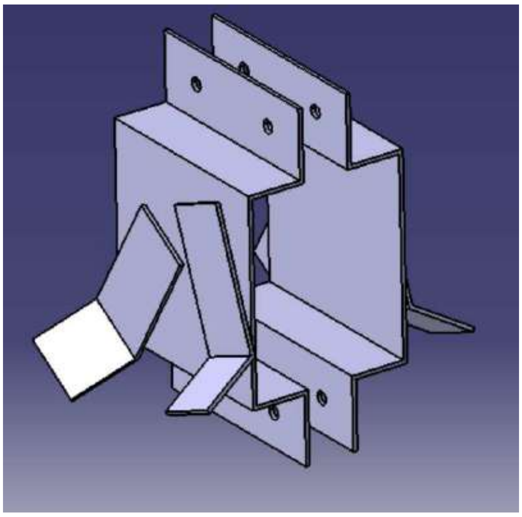


Figure 4. Current fastener bracket design to connect braced members with tie member cross arms.

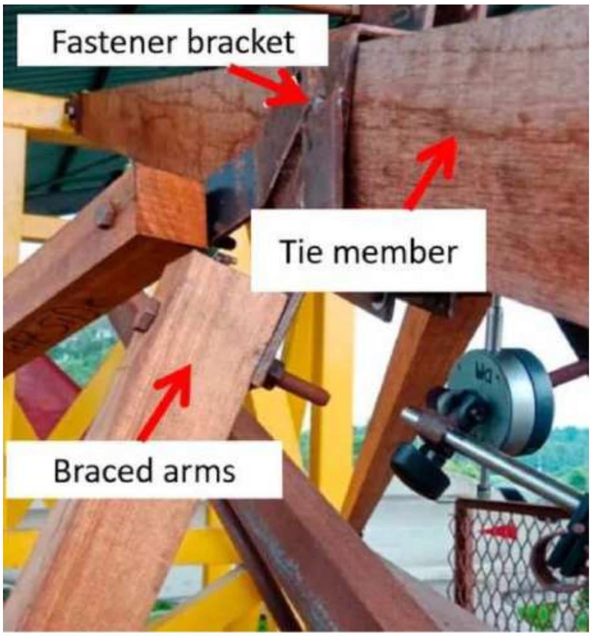


Figure 5. Joint of the tie member with the bracing members using a mild steel fastener bracket [27].

Several issues have arisen regarding the bracket installation system of the bracing with the cross arm. One of the concerns is the material used, because the current bracket of the bracing that connects the bracing with the cross arm member uses galvanized steel [23,24]. This material is conductive, affecting the insulation performance, especially during lightning strikes. Furthermore,, steel has a major drawback as it can easily rust when continuously exposed to water and oxygen for a period of time. The bracket on the cross arm will constantly be exposed to various environmental conditions, including rain and hot weather, that can cause rust to form while the bracket is in service.

The main objective of this research is to enhance the insulation performance on the cross arm and avoid rusting on the bracket. To achieve the objectives, the composite material was chosen to replace steel due to its nonconductive and rust-resistant properties. Using natural fibers as an alternative material in many industrial sectors has been one of the significant global interests in moving towards a greener environment and sustainability [31,32]. Therefore, the natural fiber-reinforced polymer (NFRP) composite was chosen as the possible candidate to achieve the goal of this project while coping with the environmental issue [31].

To discover and perform in-depth analysis regarding the problem of the NFRP bracket installation system, the functional analysis technique was used to find out the underlying contradictions of the problem. This technique is an analytical tool that provides engineers and designers with information on the system's components and the functional relationship between the components. The steps in the functional analysis include generating the component analysis, identifying the interaction analysis, and developing the function modelling [6]. Generally, the steps in the functional analysis guide the engineer to determine the contradictions of the system, which can be interpreted in terms of technical and physical contradictions. Technical contradictions are related to the properties of the whole technical system, while physical contradictions are related to the physical properties of one characteristic of an element of the system. Based on this project, the contradictions from the bionanocomposite bracket installation system can be visualized in terms of the technical contradictions because it is easier to interpret the possible parameters. Figure 6 shows the functional analysis of the bionanocomposite bracket installation system on the cross arm.

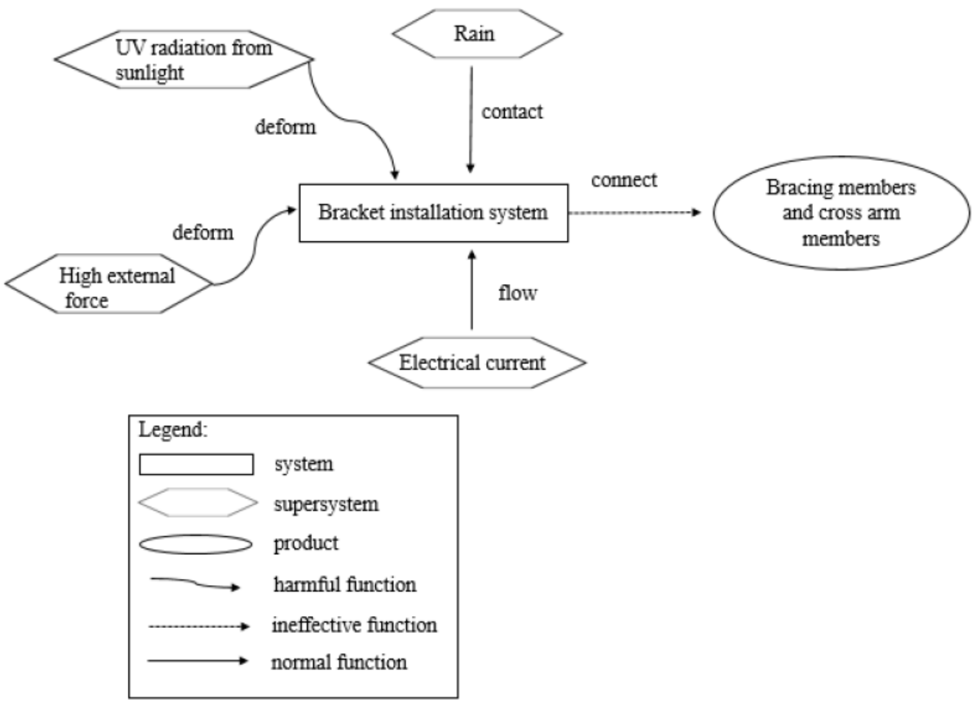


Figure 6. Functional analysis of the bionanocomposite bracket installation system on the cross arm.

Based on the functional analysis flowchart, the supersystem of rain and electrical current might benefit from replacing steel with the NFRP composite because the composite can prevent the bracket from rusting and disturbing the flow of the electrical charge from flowing at the bracket. However, several contradictions may arise due to the material replacement. Firstly, the NFRP composite undergoes ultraviolet radiation degradation. According to Mayandi et al. [33], delamination and cracks were observed on the matrix of NFRP that was continuously exposed to sunlight. The cracks could disturb the interfacial bonding between the fibers and matrices and, thus, lead to debonding of the two constituents' materials which could reduce the stiffness and durability of the structure. This is a crucial condition that should be considered in the bracket system design because the material is used on a structure that is openly exposed to many environmental conditions on the tower.

Next, the mechanical strength might be reduced due to material replacement. Based on previous studies, natural fiber permits low strength and stiffness compared to synthetic fibers, such as carbon and Kevlar. The bracing members are designed to provide support to the cross arm to sustain the mechanical load from the conductors and insulators. Hence, the bracket which connects the bracing members with the cross arm should have high strength to prevent it from breaking as the external force is high.

To ensure every supersystem from the functional analysis chart can benefit from the use of bionanocomposites in the design of the bracket installation system, improvement on the material properties should be made. Therefore, TRIZ was used to tackle the issue.

4. Integration Strategy of TRIZ–Morphological Chart–ANP

The TRIZ method is commonly used for conceptual designs in many engineering fields along with the integration of morphological chart and ANP method approach. Based on Table 1, the implementation of hybrid concurrent engineering to produce conceptual designs comprises four stages. The first stage is the idea generation stage using TRIZ. The approach of this method originates from the ideas and findings as the problems and solutions are repeated across industries and sciences, patterns of technical evolution are also repeated across industries and sciences, and the innovations used scientific effects outside the field in which it was developed. This technique implements the engineering contradiction technique. This method aids the user in comparing the improving and worsening parameters from the TRIZ contradiction matrix, which may arise from the current problem. This contradiction method selects several TRIZ solution principles as general solutions from the identified problem. Next, the general solutions from the first stage are refined into design features using the morphological chart. This stage allows the designers to detail the characteristics of the conceptual designs, which could aid in solving the problem. From the identified and selected design features, the third stage is commenced by constructing several potential computer-aided drawing (CAD) models as candidates for producing the final conceptual designs. The conceptual designs are based on the product development specifications (PDSs) to fulfill the design intends. Lastly, the analytic network process is applied in the design development framework to select the best design based on the PDSs created.

Table 1. Design techniques to develop bionanocomposite bracket.

Design Techniques	Functions	Tools
TRIZ	• Problem solving technique • Idea generation process	• TRIZ Engineering Contradiction Matrix
Morphological Chart	• Refining ideas and solutions generations • Translate idea solutions to design features	• Morphological chart
Analytic Network Process	• Selection of final conceptual design based on PDS document	• Super Decision 2.0 tool

Generally, the hybrid TRIZ–morphological chart–ANP was employed in the study because this method is well-established based on previous works by other researchers. This was due to the development of a conceptual design for the product catered to more specific solutions with refined characteristics and optimal selection of designs. In this case, various researchers have been working on the method to produce the conceptual design of a product. For instance, Asyraf et al. [6] also used the integration of TRIZ–morphological chart–ANP method to choose the best design of the creep test rig of a full-scale cross arm. Throughout the process, five new concept designs could be developed in the morphological chart, which practiced the principle of TRIZ before the best design was selected at the end of the process using ANP. Sharaf et al. [24] reported that the TRIZ method provides a way of designing by eliminating any compromise, which can increase the gap generated among the ideas and develop better outcomes with low risk. A study on the conceptual design of a wooden cross arm was conducted by integrating the TRIZ theory approach and morphological chart to connect the design elements related to the cross arm and the TRIZ solution principle. Lastly, the ANP was used to select the best design by using the PDS. The selection design of a kenaf fiber polymer composite automotive parking brake lever also was carried out by Mansor et al. [34] through the integration of the TRIZ–morphological chart–ANP method, which uses the 40 TRIZ principles approach, which is "segmentation", "local quality", and "composite materials. The best design was selected using ANP and verified using the finite element structural analysis.

4.1. Implementation of TRIZ Principles

In the TRIZ principle, the contradiction matrix is developed to identify the proper solution principles for every worsening parameter related to the design intent. In every design project, it is expected that while trying to improve one desirable design element, another desirable design element could deteriorate [35–39]. Thus, the contradiction matrix provides a way to tackle the conflict between the improving and worsening parameters of the design intent using the 40 inventive principles. Generally, 39 engineering parameters are used in the TRIZ principle to guide engineers and designers in discovering the contradiction between the improving and worsening features of the design during the preliminary development phase [40,41]. On the other hand, the TRIZ 40 inventive principles are applied to provide an adequate solution theory to identify the complication. The contradiction of the problem should be identified first before the contradiction matrix can be developed.

The contradiction of the problem was identified by using the TRIZ if-then-but tool. Table 2 explains the structure of the tool. The tool is dedicated to finding the contradiction of a problem where the user must discover the improving and worsening parameters [42,43].

Table 2. Structure of TRIZ if-then-but [42,43].

Keyword	Substance	Parameter
If	Manipulative	Potential for change in parameter/subject
Then	Responding	Improving parameter
But	Responding	Worsening parameter

As discussed before, the design intent of this project is to replace the material of the bracket installation system of the cross arm from steel to NFRP to enhance the insulation performance without disregarding the structural integrity, safety, and functionality of the product. Therefore, by using the TRIZ if-then-but tool, the identified contradiction of the current design of the bracket installation system is as follows:

If the current material of the bracket is changed from steel to a bionanocomposite site;

Then the insulation performance of the bracket is increased because it is a nonconductive material;

But the strength of the bracket to sustain high external loads while providing support to bracing members is diminished.

The NFRP composite was proposed as the construction material of the bracket installation system due to its advantages. Firstly, the composite has a low manufacturing cost because its fibers can be obtained mainly from plant, animal, and mineral sources [44]. Agricultural waste, such as kenaf, oil palm, pineapple, rice husk, and banana, is the most abundant form of natural fibers [45,46]. Plenty of agricultural waste represents a tremendous threat to the environment. Therefore, converting the waste to natural fibers will not only provide a sustainable and less expensive material but, at the same time, will contribute to good waste disposal management as well as to overcoming environmental problems. In fact, the industry is now shifting towards sustainable development due to the increasing global awareness regarding environmental issues. Furthermore, natural fibers exhibit high structural strength and stiffness with good thermal resistance, increasing the scope of natural fibers for various industrial applications. Glass fiber is widely used in because it is the cheapest man-made fiber compared to Kevlar fiber and carbon fiber. Nevertheless, glass fiber possesses low mechanical strength compared to natural fiber, as reported by Mayandi et al. [47], where the elastic modulus of E-glass fiber (73 GPa) was lower than that of the cellulose fiber (167.5 GPa).

After the improving and worsening parameters were identified, the parameters were matched with the list of 39 engineering parameters available in the TRIZ solution approach. In this project, the identified improving parameter is "#31 Object-generated harmful factors". This parameter usually covers any inefficiency internal to or around a system that manifests as a harmful effect on something around the system. In this case, the improving parameter is "#31 Object-generated harmful factors" because the NFRP acts as a nonconductive material which may increase the insulation performance. The engineering parameter "#31 Object-generated harmful factors" is used when there is a harmful effect that can reduce the efficiency or quality of the functioning system. According to Abdul Rahman et al. [26], the conductive properties of steel brace fittings promoted a path for the traveling voltage, which led to the reduction in the insulation strength of the cross arm. As part of the components on the cross arm, the bracket installation system should be ensured to have high lightning insulation strength to prevent lightning strikes on the cross arm which can cause the material to degrade. The service life of the cross arm will tend to be short compared to its expected lifespan because the material degrades if the cross arm is frequently exposed to lightning strikes [19]. Other than that, this material can prevent rusting. Normally, galvanized steel is used to build the transmission poles because it exhibits low corrosion rate that prevents rusting for the longest time [22]. However, it is not suitable for the bracket installation system of the cross arm because it is heavy, making the installation work difficult. Therefore, the engineering parameter "#31 Object-generated harmful factors" was used as the improving feature because the harmful effect on low insulation performance and rusting events could be overcome by using the NFRP composite material.

For the worsening parameter, "#14 Strength" was identified as the feature that needs to be preserved in this product development. The parameter is a feature that explains the ability of the object to resist changing in response to force. This parameter is also known as the resistance to breaking, which can be generalized into the elastic limit, plastic limit, and ultimate strength in the form of tensile, compressive, and bending actions. For this research, the worsening parameter related to a reduction in the strength of the bracket, which satisfies the engineering parameter "#14 Strength". The parameter describes the extent to which the object can resist changing in response to force or the resistance to breaking. As mentioned, the main drawback of the NFRP composites is the inferior load requirement and mechanical properties due to the lack of adhesive bond between the natural fiber and polymer matrix. The bracket installation system is supposed to connect the bracing bars and cross arm members where the bracings provide support to the cross arm. Therefore, the bracket installation system should be strong enough to withstand the load from the bracings to play the role as the supporter to the cross arm. Hence, during the design process, the improvement method should be carried out on the NFRP for better stiffness and strength.

Next, the expandable TRIZ contradiction matrix that includes the expected solution theory to tackle the complication was developed as suggested by TRIZ. In this step, a few solution principles were recommended by the TRIZ method, which can be referred to in the general table of the contradiction matrix. Table 3 shows the four solutions recommended by TRIZ. Nevertheless, the suggested solutions were too general, in which not all recommended solutions can contribute to the development of the bracket installation system on the cross arm. Therefore, the outcomes on the table of contradiction matrix were analyzed, and the most relevant principle was selected as a guideline to improve the new NFRP bracket installation system of the cross arm. The most relevant solution that was chosen to compromise with this project contradiction was the solution principle "#35 Parameter change". The broad idea of this specific solution principle is to change any parameter that governs the outcome of the function of the object, including the change in an object's physical state, the change in the concentration or consistency, the change in the degree of flexibility, and the change in the temperature.

Table 3. Contradiction matrix for a bionanocomposite bracket in a braced composite cross arm.

Improving Parameter	Worsening Parameter	TRIZ Solution Principle
#31 Object-generated harmful factors	#14 Strength	#15 Dynamics #35 Parameter Change #2 Taking out #22 'Blessing in disguise'

4.2. Specific Solution Development Based on the Selected 40 Inventive Principles Method

The design strategy to increase the mechanical strength of the bionanocomposite bracket installation system on the cross arm was developed based on the solution principle "#35 parameter change". Generally, the performance of NFRP depends on the type of fiber used. Alsubari et al. [31] mentioned that certain fibers, such as bast fibers, show superior flexural strength, while leaf fibers offer excellent impact properties. Nevertheless, the mechanical properties of natural fibers could not be compared with synthetic fibers, such as carbon and Kevlar, because these materials exhibit excellent properties in terms of strength and stiffness. Table 4 shows the mechanical properties of natural fibers compared to conventional reinforcing fibers. This is due to the strengthening mechanism, which originates from the stiffer and stronger synthetic glass fibers. Furthermore, the presence of glass fiber also decreased the moisture absorption caused by the natural fiber and, thus, increased its dimensional stability. The most important reason for using the hybridization approach was to develop a balanced solution between performance and cost to the design because synthetic fibers offer high mechanical performance. In contrast, natural fibers have a low manufacturing cost. Only a few studies in the literature implemented the hybridization of natural and synthetic fibers. For example, Mansor et al. [34] used kenaf and glass in the conceptual design of an automotive parking brake lever. Therefore, the combination of natural and synthetic fibers could be a solution to enhance the mechanical performance for better strength of the bionanocomposite bracket installation system on the cross arm.

Table 4. Mechanical performance of natural fibers in comparison to synthetic fibers.

Fibers	Density (g/cm^3)	Tensile Strength (MPa)	Elongation at Break (%)	Tensile Modulus (GPa)
Natural fibers				
Bamboo	1.25	140–230	-	11–17
Bagasse	1.5	290	-	17
Coir	1.2	138.7	30	4–6
Kenaf	1.45	215.4	1.6	53
Flax	0.6–1.1	345–1035	2.7–3.2	27.6
Hemp	1.48	690	1.6–4	70
Jute	1.3	393–773	1.5–1.8	26.5
Sugar palm	1.292	156.96	7.98	4.96
Sisal	1.5	511–535	2.0–2.5	9.4–22
Ramie	1.5	560	2.5–3.8	24.5
Pineapple	0.8–1.6	400–627	14.5	1.44
Synthetic fibers				
E-glass	2.5	2000–3500	0.5	70
S-glass	2.5	4570	2.8	86
Aramid	1.4	3000–3150	3.3–3.7	63.0–67.0

Another critical issue that also affects the mechanical strength of NFRP is the poor interfacial adhesion between natural fibers and the polymer matrix. The composition of natural fibers consists of hemicellulose, pectin, and lignin, which exhibit hydrophilic properties, while the polymer matrix usually exhibits hydrophobicity [48]. This condition creates some drawbacks, which cause high moisture absorption and poor compatibility between the two materials, weakening the bond, especially for microscale materials. Therefore, nanocellulose, nanosized cellulose, can be introduced as the reinforcing agent. The nano size allows a large surface area with many hydroxide (OH) groups, which increases the reactivity and reduces the composite's water uptake and swelling. According to Trache et al. [49], nanocellulose has been established to be a substantial reinforcement, even at low filler loading, where its elastic modulus could reach up to 150 GPa with a staggering aspect ratio of up to 640, low thermal expansion coefficient (0.01 ppm$\cdot$K^{-1}), and high specific surface area (several 100 m$^2\cdot$g^{-1}). Another design strategy that can be implemented in designing the cross arm's bionanocomposite bracket installation system is the compression molding method in fabrication. This method is widely used among other fabrication techniques to manufacture NFRP composites because of its high reproducibility and low cycle time. It also has the advantage of fiber bridging through fiber pullout. The compression offers high performance to the NFRP composite using epoxy thermoset polymer as the matrix. The method also produces compression molded NFRP composites with high mechanical strengths and impact strengths [50]. Table 5 shows the specific solution principles generated based on the selected TRIZ inventive solution principle.

Table 5. Selected solution principles generated based on selected TRIZ inventive solution principle.

TRIZ Solution Principle	Design Strategy Descriptions
#35 Parameter Change	1. Use nanocellulose as reinforcing material to enhance the mechanical properties of the bionanocomposite bracket installation system on the cross arm. 2. Use hybrid composition where natural fiber is combined with stronger and stiffer synthetic fiber to increase the composite strength and stiffness in order to withstand high external force from the cross arm. 3. Fabricate the bracket installation system of the cross arm by using the compression molding method.

4.3. Refining the Selected Solution Principles Using Morphological Chart

In this stage, morphological charts further refined the chosen TRIZ solution principles into relevant system elements. The morphological chart aids the designers in identifying the subsolutions for each subfunction of the design in which it is developed based on the product functional analysis [51]. Therefore, by integrating the TRIZ solution and morphological chart, the designer can transform the general TRIZ solution to the specific design solutions of design features in an organised approach. Generally, morphological charts guide the engineers to narrow down the list of design features by choosing the appropriate design feature that can achieve the product's design intent. In this project, "#35 Parameter change" was selected as the TRIZ solution. Several design strategies were proposed and explained in general. Therefore, a morphological chart was developed to further interpret the design strategies by proposing design features for each design strategy. Table 6 describes the morphological chart of the bionanocomposite bracket installation system of the cross arm based on the identified TRIZ inventive solution principle.

Table 6. Morphological chart in developing design feature for bionanocomposite bracket.

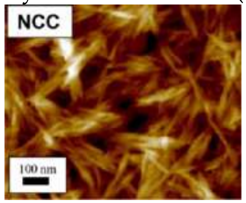
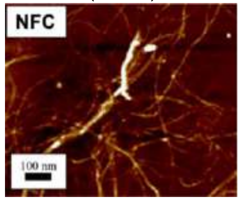
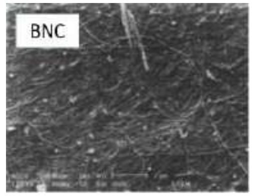
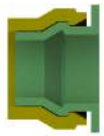
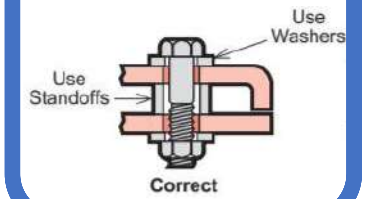
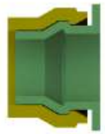
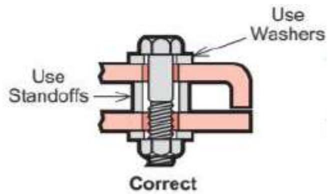
Design Strategies	**Design Features**	**Solution**			
#35 Parameter Change		**1**	**2**	**3**	**4**
- Use nanocellulose as a reinforcing material to enhance the mechanical properties of the bionanocomposite bracket installation system on the cross arm.	Addition of nanocellulose	Nanocrystalline cellulose (NCC) 	Nano-fibrillated cellulose (NFC) 	Bacterial cellulose (BC) 	
- Use hybrid composition where natural fiber is combined with stronger and stiffer synthetic fiber to increase the composite strength and stiffness	Natural fiber	Sisal 	Jute 	Flax 	Hemp 
	Hybrid with synthetic fiber	Aramid 	E-glass 	Carbon 	

Table 6. *Cont.*

-	Polymer resin	Epoxy	Unsaturated Polyester	Vinyl Ester
- Fabricate the bracket by using the compression molding method.	Design of installation system	Plug in + circular pin bolt  +  Concept 1 and 2	Plug in  Concept 3 and 4	Pin bolt 

Based on this feature, selection using a morphological chart is made to narrow down the selection criteria. As shown in Table 6, the selection is performed according to the designer's interest or creativity. Thus, by integrating the TRIZ solution and morphological chart approach, the designer can instantly transform the general TRIZ solutions within the specific solution of design features into an organised approach and order. In this case, the solution criteria were chosen in one route because the best material is selected with high strength and stiffness to ensure the product is resistant in a rigorous environment. In this section, the selection of the solutions is discussed thoroughly to show the significance of the criteria. The type of nanocellulose was suggested as the design feature under the design strategy of using nanocellulose as the reinforcing material to enhance the mechanical properties of the bionanocomposite bracket installation system on the cross arm. Nanocellulose was proposed due to its unique characteristics, such as high mechanical strength, environmental friendliness, good thermal stability, and low cost. The nanofiber cellulose (NFC) was chosen as the reinforcement material of this project to develop the bionanocomposite bracket installation system on the cross arm. This is because the NFC provides higher strength and modulus compared to the NCC at the same nanocellulose concentration. After all, the NFC has a larger aspect ratio and fiber entanglement [52]. In general, nanocellulose can be categorized into NFC, nanocrystal cellulose (NCC), and bacterial nanocellulose (BNC) according to the dimensions and extraction method. NFC and NCC are considered as plant-based nanocellulose, and BNC is considered microbial-based nanocellulose. All CNF, CNC, and BNC are in nanoscale size but differ in shape, size, and composition [52]. BC was not chosen due to its high production cost. For NFC and NCC production, the fabrication methods involved the disintegration of plant cellulose using mechanical or chemical methods, while for BNC they involved the bioformation of cellulose by bacteria [53–57]. Figure 7 shows the comparison of nanocellulose in various applications.

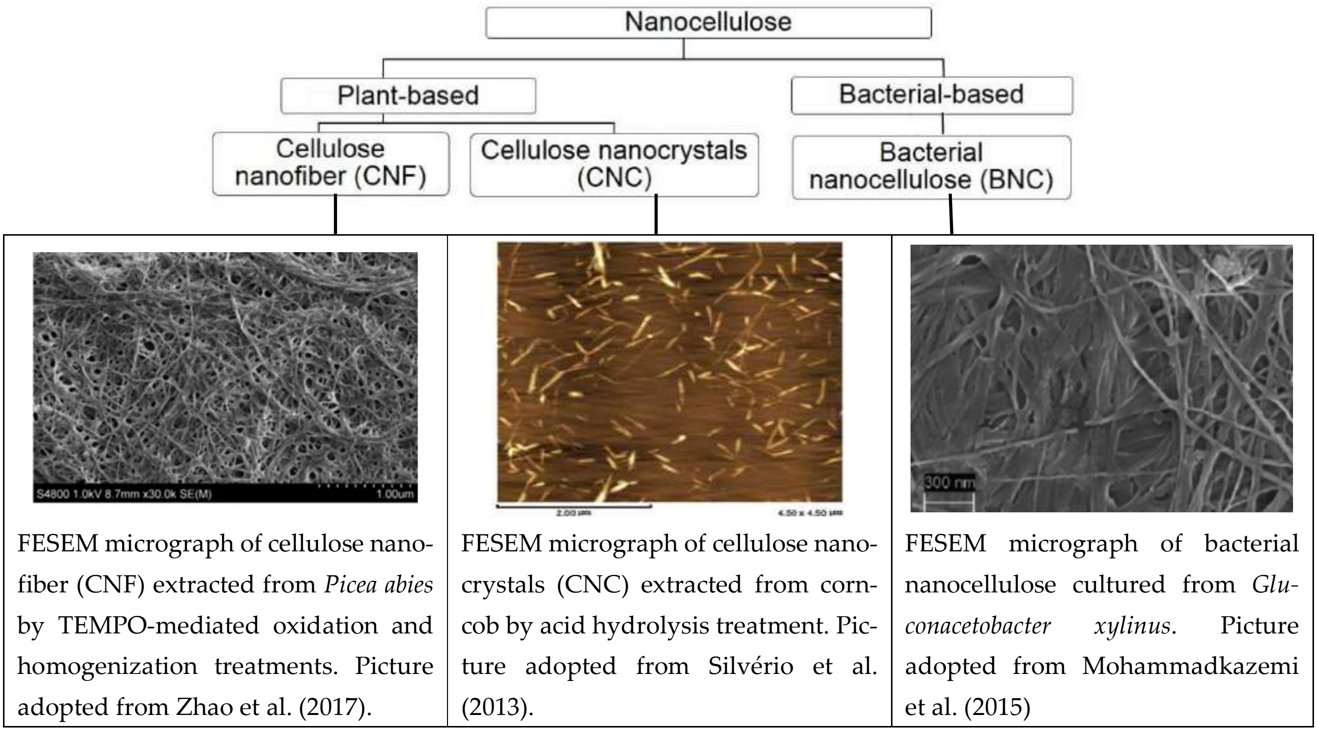


Figure 7. Comparison of nanocellulose based on production methods and morphological structure [55–60].

Next, the natural and synthetic fibers that are hybridized together were chosen under the design strategy of using the hybrid composition of natural and synthetic fibers to increase the composite strength and stiffness. Several natural fibers were listed, such as sisal, jute, flax, and hemp, while man-made fibers that were considered in the morphological chart included aramid, E-glass, and carbon. In this project, the hybridization of flax and E-glass fibers was chosen to design the bracket installation system of the cross arm. The hybridization of the two materials would develop high mechanical strength for the bracket to withstand the high external forces of the cross arm members and bracing members. Flax fiber was chosen because it provides the highest tensile strength and elastic modulus, as shown in Table 4. Flax has fine and regular long fibers, generally spun into yarn. Flax plants can be harvested to produce fibers and fabrics for various usages, especially composite materials. Technically, flax fibers can be employed to produce high-strength structural products, such as exterior automotive components, since it produces a strong linen fabric [61]. Additionally, flax is widely available and is considered as a global crop commodity since EU countries produced nearly 122,000 tons of flax fiber in 2007 alone [62]. The high production of the fiber throughout the globe is due to increasing worldwide demand for linen and short growing periods of around 100 days from March to July [63]. Thus, using flax fiber-reinforced composites could provide good strength and stiffness with wide availability of a sustainable biomass material.

Furthermore, Table 4 also shows that the E-glass fiber has high tensile strength and an elastic modulus of 3500 MPa and 70 GPa, respectively. In this case, biaxially oriented polymeric fibers and fillers inside the matrix act as load-bearing components and interact with one another, having the effect of combining many elements into woven textiles [64,65]. For instance, Zaghloul et al. [66] discovered that surface-reinforced arranged composites have a higher lifespan after being exposed to bending fatigue as it is 61 times longer than the bulk-reinforced arranged composites at 56 MPa bending stress. Aside from textile engineering, the composite cross arm can be improved by adding supports to the structure. Employing additives in E-glass fiber composites can also enhance its durability and mechanical performance [67,68]. Additionally, good compatibility of E-glass and flax fibers in polymer matrix forming hybrid composites, as mentioned by Dhakal et al. [69], could be additional advantages of the selection of these fibers. It can be proven that the hybrid flax/glass composites can improve the toughness properties, thermal stability, and water absorption behaviour, as well as enhance the overall strength and stiffness of the composites. Furthermore, E-glass fiber is the cheapest synthetic fiber, which can be advantageous in terms of its manufacturing cost, and it also functions as an insulator toward electricity [70].

Regarding the matrix, the unsaturated polyester resin was chosen due to its low cost, performance properties, and easy processing techniques with fillers and reinforcements. In addition, the modern cross arm beams in the transmission are usually fabricated from an unsaturated polyester (UPE) matrix via the pultrusion process; common ratios are 37:63 to fabricate the composite beam with densities of 2580 and 1350 kg/m^3 [71]. Dos Reis [72] found that the unsaturated polyester resin computed lower loss in terms of compressive strength compared to the epoxy resin at high temperature. The good compatibility between E-glass fiber and UPE resin could form a rigid composite structure to resist high load-bearing capacity from static loading of the electrical cable in a transmission tower. For instance, Asyraf et al. [10] studied five different stacking sequences of pGFRP composites in terms of flexural and creep properties. It was discovered that nine layers of the $0°/45°/0°/-45°/0°/-45°/0°/45°/0°$ fiber orientation sequence for glass fiber composite cross arms produced high flexure performance. This stacking sequence configurations seemed to be optimally manufactured in continuous roving fiber by alternating between $0°$ and $\pm 45°$. Regarding mechanical characteristics, for the pultruded composite cross arm, the rupture and elasticity moduli are 29.8 GPa and 858.0 MPa, respectively [73]. This demonstrates that the pGFRP composite for the cross arm application has outstanding mechanical performance. Therefore, this polymer was selected for use in this project because it exhibits an almost good performance with respect to epoxy and, simultaneously, requires a lower cost.

Last but not least, the compression molding method was chosen as the fabrication design of the bracket installation system of the cross. The design features focus on the design of the bracket installation system. As shown in the morphological chart, three designs of brackets were considered: (1) plug-in plus circular pin bolt, (2) plug-in, and (3) pin bolt. The plug-in bracket design is also known as a snap fit, in which the molded plastic products can clip two parts together. The joining process has various advantages, such as easy assembly and fewer moving parts [74]. However, this design has an inherent risk that the snaps will not work correctly the first time. The pin bolt design allows the assembly to form a lasting joint stronger than any joining that is resistant to vibration and material fatigue [75]. Nevertheless, it needs accurate and precise tools. This research chose the plug-in and plug-in with a circular pin bolt as the bracket design. These designs are more robust and resilient, sustaining the high external load from the cross arm and bracing members.

5. Final Concept Design Selection Using ANP Method Based on the PDS

Four new designs of bracket installation systems were developed based on the design strategy adopted from the TRIZ solution principles and design features selected in the morphological chart. The 3D CAD models of the designs were developed using CATIA V5. Figure 8 displays the conceptual designs produced from design strategies and features from the morphological chart.

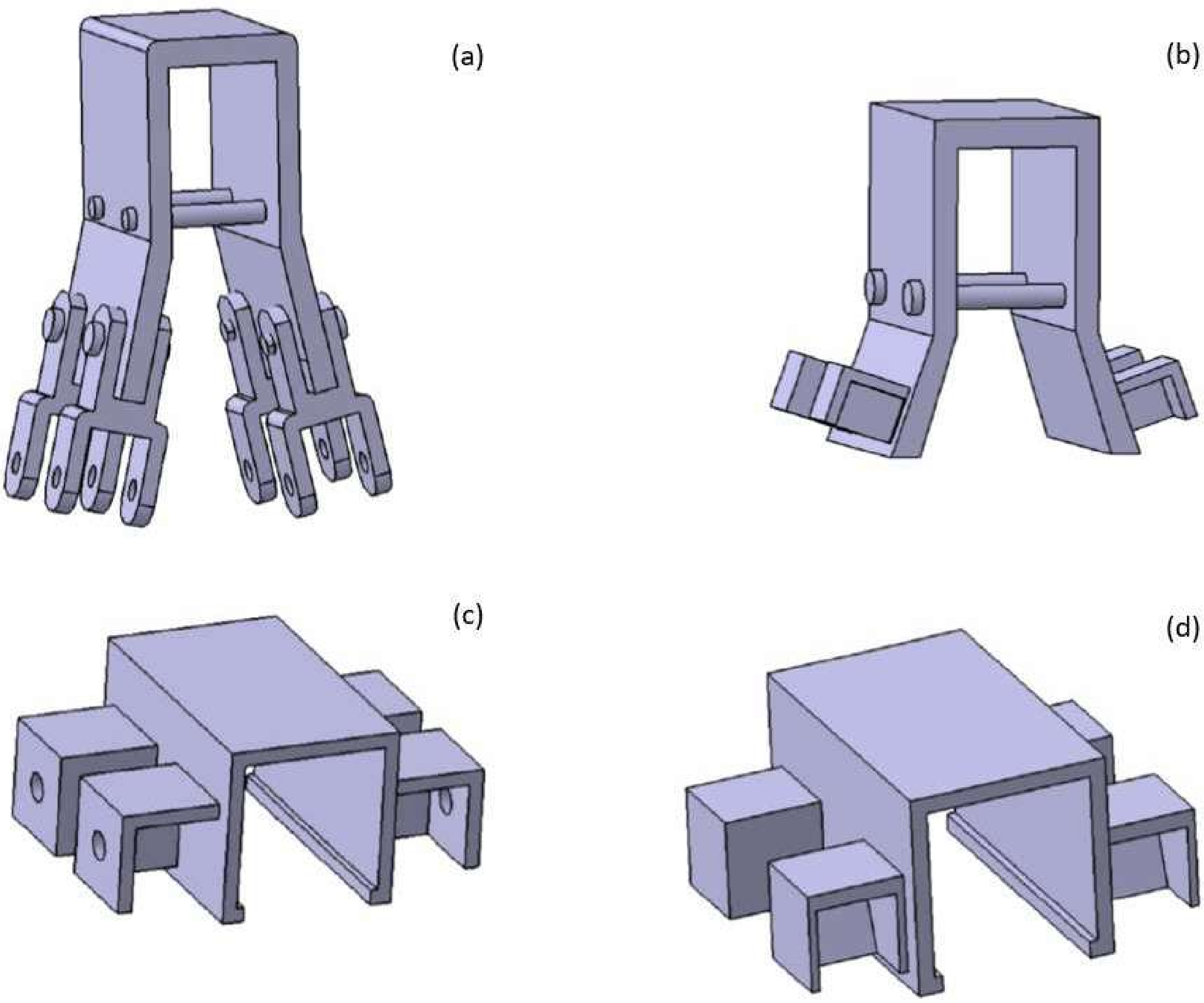


Figure 8. Conceptual design of new bracket installation system on the cross arm—(**a**) Concept Design 1, (**b**) Concept Design 2, (**c**) Concept Design 3, and (**d**) Concept Design 4.

All conceptual designs in Figure 6 were expected to be produced from hybrid NFC/flax/glass fiber-reinforced unsaturated polyester bionanocomposite. Figure 8a shows that five main assemblage components, namely one U-shape extended bracket with four separated adapters for cross arms, were proposed in Concept Design 1. These adapters are expected to assemble in the composite bracket using bolts and nuts. Figure 8b shows that Concept Design 2 has the same shape and design of bracket, and these brackets are fixed using the composite bolt and nut at the neck, which is also used in Concept Design 1. Unlike Concept Design 1, the rectangular socket connects the braced members of the cross arms in Concept Design 2. On the other hand, Concept Designs 3 and 4 have a spider-mimic design where the four connecting sockets are located at the side of the bracket, as shown in Figure 8c,d. However, Concept Design 3 comprises composite sockets which are fixed using bolt insertion. At the same time, Concept Design 4 implements plug-in or snap-fit technique of sockets for braced members of the cross arm structure.

Next, the best design was selected by using the ANP technique. This technique provides a multi-criteria decision-making process with the help of a pair-wise comparison technique and consistency index indicator during the judging and analysis processes. The selection was made based on the PDS of the bracket installation system of the cross arm. Generally, PDS is a listing of critical parameters, specifications, and requirements of the products to explain what the product should be and should do. The PDS of the bracket installation system of the cross arm was developed. Based on the PDS, four main elements, namely performance, weight, cost, and assembly, were chosen as the criteria for the selection process. The elements of safety and environment were not considered during the design selection process because the two elements were considered during the material selection process, and all concept designs used the same material, namely hybrid flax/E-glass fiber. The subsequent sub-elements of the four main elements from the overall PDS document considered during the design selection are shown in Table 7.

Table 7. PDS elements for the biocomposite bracket and all the equivalent design indicators.

PDS Element	Sub-Element	Equivalent Design Indicator
Performance	Strength	Von Mises Stress (N/m^2)
	Stiffness	Deformation (mm)
Weight	Density	Mass (g)
Cost	Raw material cost	Raw material price
	Manufacturing cost	Shape complexity
Assembly	Composite assembly	Assembly complexity

Figure 9 shows the hierarchy framework of ANP, which comprises four levels. First, the best conceptual design of the hybrid flax/E-glass nanocomposite bracket installation system of the cross arm was defined at Level 1. Then, the main criteria considered in the design selection process were listed at Level 2, which consist of performance, weight, cost, and assembly. The main criteria were subdivided into a few sub-criteria defined at Level 3. Lastly, the alternatives of the design selection consisting of Concept Designs 1, 2, 3, and 4 were developed at Level 4 by considering the TRIZ solution principles and morphological chart. Figure 9 displays the ANP hierarchy of the bionanocomposite bracket for the braced composite cross arm.

The judgment process for all concept designs concerning each main criterion and sub-criteria was made by using the pair-wise comparison technique. Generally, the pair-wise comparison technique compares entities to judge which entities are preferred or contribute to a great number of quantitative properties. The evaluation was conducted based on the essential criteria of the nanocomposite bracket, where cost and weight attributes are known as relatively lower critical than performance. Thus, performance was determined as more important than cost and size. On top of that, performance is a vital criterion for selecting the final conceptual design in terms of the design's stiffness (deformation) and strength (von Mises strength). Due to the product's operation, stiffness is more important than strength because the test rigs are subjected to bending loading that can affect the total performance. Less deformation indicates that the design has higher stiffness. The final conceptual designs for the bionanocomposite bracket for the braced cross arm were selected after the TRIZ and morphological chart development. These final conceptual designs were chosen based on the ANP approach via Super Decision 2.0 software by ranking all the developed conceptual designs. The final conceptual design was selected based on the PDS as per ANP's framework, as each criterion at every level was evaluated based on the relative importance of the pair-wise comparison basis, as illustrated in Table 8.

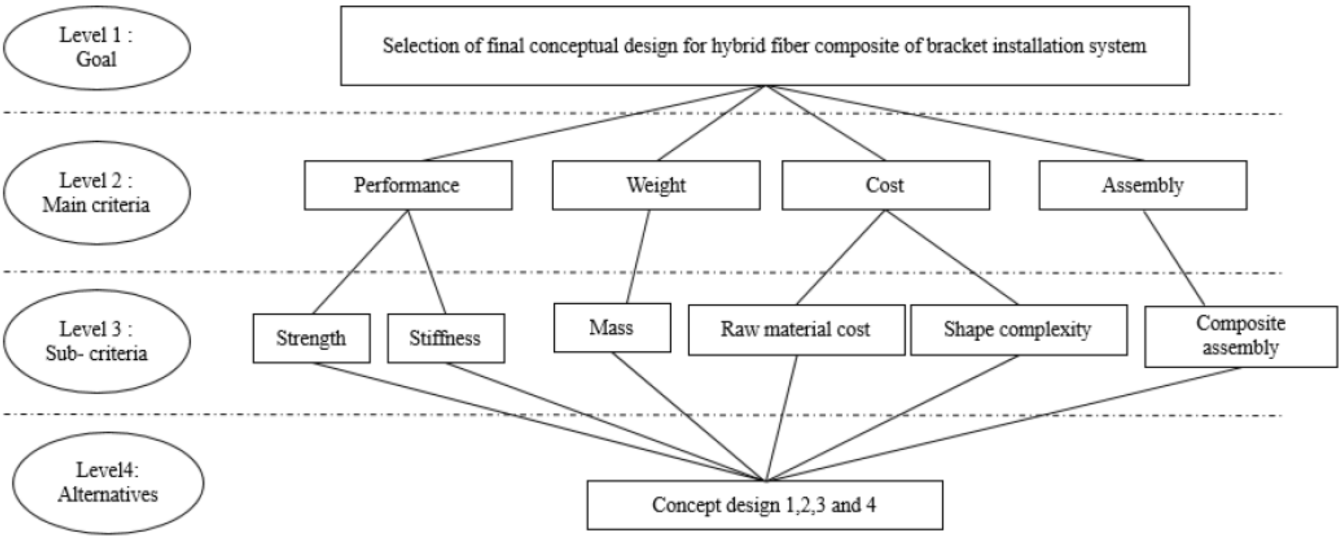


Figure 9. ANP hierarchy of bionanocomposite bracket for braced composite cross arm.

Table 8. Scale for pairwise comparison for design evaluation [76–78].

Relative Intensity/Score	Definition	Explanation
1	Equal value	Those two requirement are same value
3	Slightly more value	Difference slightly favors one requirement over another
5	Essential or strong value	Difference strongly favors one requirement over another
7	Very strong value	A requirement is strongly favored and its dominance is demonstrated in practice
9	Extreme value	The evidence favoring one over another of the highest possible order affirmation
2, 4, 6, 8	Intermediate value between two adjacent judgement	When compromise is needed
Reciprocal	Reciprocal for inverse comparison	-

The pairwise comparison was synthesized into a matrix form, and the priority vector value, w, was formulated using Equation (1), as follows:

$$w = \frac{1}{n}\sum_{j=1}^{n} \frac{a_{ij}}{\sum_{i=1}^{a} a}, \quad i, j = 1, 2, \ldots, n \tag{1}$$

where w is the priority vector, a_{ij} is the important scale, and n is number of criteria.

The overall ranks of the alternative concept designs in the ANP method were obtained from the overall priority values attained from the pair-wise comparison (priority vector) method.

Static structural analysis in the Ansys Workbench software was performed to analyze the performance of each concept design to obtain information on stress and deformation when force existed. A similar setup was used during the analysis so that the result obtained could be compared for every concept design. On the other hand, the information regarding the volume and weight could also be extracted during the analysis in the Ansys software. A baseline CAD modeling is essential in this stage to fulfill the requirement for developing a nanocomposite bracket. For this purpose, a CAD modelling software tool, CATIA V5, was used to set the dimensions of the design. The accuracy of predicting the actual behaviour from the finite element model can be obtained by finite element mesh [73]. Meshing was carried out in the Ansys software to generate structural optimization of each conceptual design. The model is segmented into smaller elements that are subjected to mesh refinement. It is essential to generate mesh to validate the finite element model analysis for the test rig structure. To produce a good mesh, the following criteria must be met to ensure the accuracy of the obtained results [79]: (1) The mesh has to denote the geometrical areas and loads accurately; (2) the mesh should sufficiently represent the large displacement or stress concentration in the generated solution; (3) the mesh must contain elements that are sufficiently small and in an expected ratio. The total number of elements used in the finite element analysis was less because the nanocomposites are symmetrical in design. Subsequently, the mesh grid generation for the model was performed using the mesh function in the Ansys structural analysis. The model is segmented into smaller elements that are subjected to mesh refinement. At the pre-module stage, the subsequent stage in the finite element simulation was the post-module stage, where the overall process of constructing creep test rig was carried out in the Ansys Workbench 16.1. The geometrical model was updated in the form of a shell model. For the static structural module, the creep test rig design was analyzed to determine the structural response in the structures subjected to the external influence of an applied load. Several assumptions were made before performing the analysis [80]: (1) The bracket material is anisotropic because it is made up of hybrid flax/glass fiber composites and considered as homogenous properties; (2) the material has a linearly elastic structure; (3) deformation is continuous and small in the acting force areas. According to Acharya [81], the formulation of anisotropic material is real and complex, which means that the angular variation of the stress and displacement fields can be expressed in infinite ways. Thus, to simplify the finite element simulation, the property of the nanocomposite is considered as a homogenous structural material because these data were used as valuable information on design guides during the selection of the final conceptual design in the design development framework. Further finite element analysis study must be carried out to simulate the properties of the final conceptual design before developing a prototype for the actual application [82]. In this research, each conceptual design was subjected to bending force to mimic the condition of the cross arm when subjected to the working load at 6.347 kN based on Asyraf et al. [27]. In this case, the tie member beam experienced force from cross arm assembly loading around 686.7 N [25], as the composite bracket also experienced this force value. In this stage, the material of the conceptual design was defined based on the material density, which was assumed at 1.62 g/cm^3 based on Marais et al. [83], and the dimensions of the designs, based on actual cross arm size in the 132 kV transmission tower [22]. In the end, the static structural analysis simulated the deformation (stiffness), von Mises stress (strength), and weight (density). The degree of importance for each conceptual design was given according to the structural simulation results by Ansys.

The cost attributes were divided into raw material cost and manufacturing cost. The importance of this attribute is higher than the weight attribute but lower than the performance attribute. To further forecast the cost of raw materials for each concept, the density (weight) criteria were assessed by identifying the mass value of the CAD model. The cost estimation was performed based on the mass of the designs. This is because as the product mass increases, the raw material cost increases. Therefore, it requires more materials. In addition, the shape complexity properties of the concept designs were explained based on low, medium, and high complexity values. The assembly complexity depends on the number of components that form the assembly product. The more components in the bracket, the higher the assembly complexity. The conceptual design that gained the highest score was chosen as the final conceptual design. Table 9 displays the design attributes of all concept designs of the hybrid flax/E-glass nanocomposite bracket installation system.

Table 9. Design attributes for each conceptual design.

Design Features	Equivalent Design Indicator	Design 1	Design 2	Design 3	Design 4
Performance	Max stress (Von Mises stress) (N/m^2)	1.1566×10^{10}	5.0192×10^{10}	1.9842×10^{10}	8.1908×10^{10}
	Total deformation (mm)	0.014482	0.005644	0.037825	0.091776
Weight	Volume (cm^3)	468.3	295.1	120.8	109.6
	Mass (g)	758.65	478.06	195.70	177.56
Cost	Raw material cost	High	Medium	Low	Low
	Shape complexity	Low	Medium	Medium	Medium
Assembly	Assembly complexity	Medium	Low	Low	Low

Note: For comparison purposes, assume that the density of hybrid flax/glass-reinforced unsaturated polyester composite density is 1.62 g/cm^3.

From the ANP selection method, Concept Design 1 reveals an overall good result compared to other concept designs. Therefore, Concept Design 1 was selected as the final concept design of the bracket installation system on the cross arm, as shown in Table 10.

Table 10. Overall ANP results for conceptual design selection.

Configurations	Ideal	Normal	Raw	Graphic
Design 1	1.000000	0.301757	0.030176	
Design 2	0.898487	0.271125	0.027113	
Design 3	0.760617	0.229522	0.022952	
Design 4	0.654817	0.197596	0.019760	

Figure 10 shows the sensitivity analysis conducted in the Super Decision software. Generally, the sensitivity analysis is used to analyze how the priorities of the solutions change when one or more criteria are varied. According to sensitivity analysis, Concept Design 1 was ranked the highest because the design exhibits excellent performance in terms of strength and stiffness, as shown in Figure 10a. Figure 10b also indicates that Concept Design 1 has low manufacturing costs because it can be easily fabricated using the compression molding method. However, Figure 10c shows that Concept Design 1 is the heaviest design among all conceptual designs. Nevertheless, this will not affect the selection because performance was the main vital attribute. Furthermore, the mass of Concept Design 1 was smaller than the current bracket design because the material was replaced from steel with biocomposite. Figure 10d also shows that Concept Design 1 has the highest sensitivity in the sensitivity analysis of the assembly.

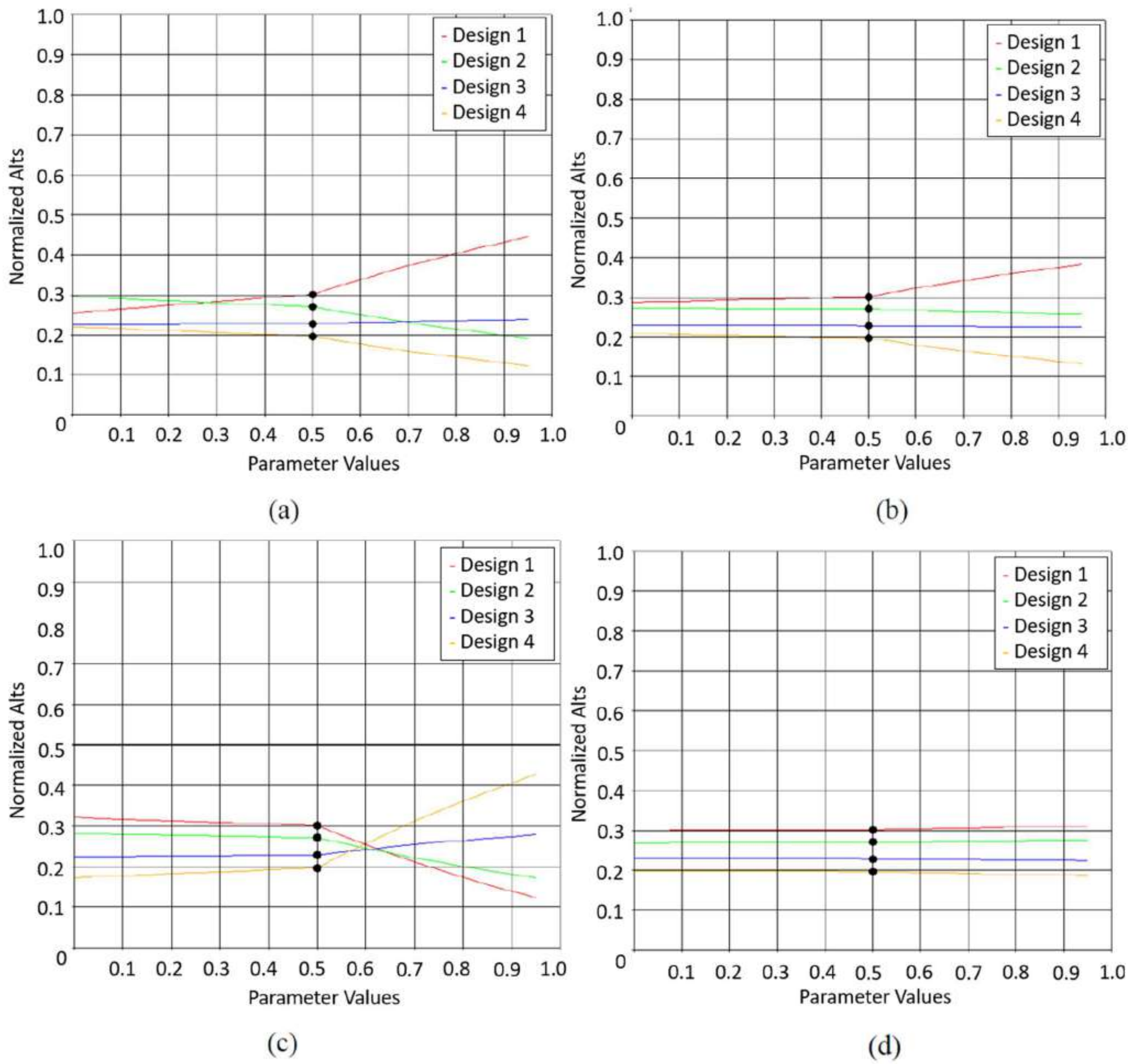


Figure 10. Sensitivity analysis of sub-criteria (**a**) stiffness, (**b**) manufacturing cost, (**c**) density, and (**d**) assembly.

6. Conclusions

In conclusion, this research discussed the conceptual design development process of the bionanocomposite bracket for a braced composite cross arm comprising the TRIZ–morphological chart–ANP technique. The hybrid flax/glass fiber-reinforced polymer biocomposite was proposed as the constituent material in the development of the bracket. In this work, the implementation of the TRIZ 40 inventive principles approach from 39 engineering parameters was established to produce the ideas for the solution based on the identified problem. The identified TRIZ inventive principles were used based on the TRIZ contradiction matrix, which includes "#15 Dynamics", "#35 Parameter Changes", "#2 Taking Out", and "#22 Blessing in disguise". Design strategies were formed from the selected TRIZ solution principles. Later, the strategy was further polished using the morphological chart technique to generate design features for several proposed conceptual designs. Four conceptual designs were developed from the selected design attributes in the morphological method. The selected final design concept was

Concept Design 1, as it shows the highest priority value in the ANP simulation. The design scored the highest value and ranked first in the hybrid engineering approach for sensitive analysis. From the analysis, it can be deduced that the combined technique of TRIZ, morphological chart, and ANP enhanced the practicality, especially in providing a systematic and direct understanding flow of the designing method. For future research, the authors suggest finite element analysis (FEA) research on this final conceptual design to further evaluate the structural and mechanical properties before prototype fabrications.

Author Contributions: Conceptualization, M.R.M.A., M.R.I. and M.R.; Methodology, D.D.C.V.S., A.H.M.H. and M.F.A.R.; Validation, M.R.I.; Formal analysis, A.L.A.; Investigation, M.R.M.A., A.H.M.H. and A.L.A.; Writing—original draft, M.R.M.A., A.H.M.H. and M.R.R.; Writing—review & editing, M.R.M.A., M.F.A.R., M.R., M.N.F.N., M.R.R. and Z.I.; Visualization, M.N.F.N.; Supervision, M.R.I.; Project administration, M.R.I.; Funding acquisition, M.R.R. and Z.I. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest for the article.

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