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Environmentally Sustainable Raised Access Flooring Product Development

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Abstract: Raised access floors are nowadays widely used in buildings. A novel raised access flooring product is developed by this research, with a set of sustainable features, including less environmental impact and high strength. Its floor panels are made of polyurethane (PU) reinforced with glass fibre, which is light-weight and fire-resistant, replacing the traditional floor panel materials, and the panels are supported by simplified steel stringers to reinforce the strength of the flooring product. Instead of the conventional sandwich design consisting of a core material encapsulated by outer layers, the new floor panel design adopts the reinforced PU as its sole material, which not only simplifies the structure but also reduces floor weight and costs. The sustainable advantage is further approved by the environmental life cycle assessments of the new raised flooring product in comparison to traditional ones made of cement and woodchips, with results showing that the new floor product's total environmental impact is 52% less than cement floor and 47% less than woodchip board floor. Further, the finite element analysis (FEA) was carried out, and the experimental test was conducted to verify the FEA results, indicating that the new product's strength is higher than the requirements of the raised access flooring product standards. There is no raised access flooring product made of PU reinforced with glass fibre available in the market, and, hence, the new product developed by this research is a novel contribution.

Keywords: raised access floor; sustainability; carbon emission; product design; floor panel; composite material; polyurethane; glass fibre; finite element analysis

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1. Introduction

Raised access floors, also known as raised floor or access floor, have gained wide applications in buildings nowadays, such as office buildings, commercial buildings, teaching rooms, experimental laboratories, and telecommunication rooms [1]. Figure 1 shows an example of such a raised access floor. Raised access floors have exhibited various advantages. It enables wire routing and equipment installation (ventilation, fire protection, etc.) via elevating floors to provide convenience for accessibility and re-configurability [2]. Moreover, it allows air to circulate underneath the panels to cool down rooms to a safe operating temperature and offer ventilation [3]. These advantages facilitate the management of wires and equipment, underfloor air distribution, and the installation of water pipes.

In a raised floor system, the panel is a key component which is fixed onto stringers and pedestals with mechanical fastening members, in order to support the load on the floor. The panel can be made of different materials with associated manufacturing technologies, and, hence, the selection of proper materials is vital as it directly affects the structure, function, and cost of the raised flooring system [4,5]. The literature of raised floor panels and their materials shows that wood composition sheet, namely chipboard, is the mostly used panel material, due to wood material's cost-effectiveness and easy-to-manufacture features [6,7]. However, chipboard panels have defects such as inferior issues in fire resistance and strength, and, hence, efforts have been made in both optimising wooden materials' performance and identifying appropriate fabrication materials [8].

Figure 1. A generic raised access floor.

In addition to chipboard, aluminium, steel, concrete/cement, and synthetic materials are also used for panel materials, in order to meet certain requirements. Metal materials, such as aluminium and steel, have good properties for forming a floor panel, because they are relatively light in weight in comparison to concrete-core panels with high strength. With these properties, metal panels can be made to various structures and shapes. For example, flat metal sheets were initially used as reinforcements on the upper and lower sides of floor panels [9]. Hale discussed a type of floor panel using a sandwich structure with an anti-elastic cell core, which provided structural decoupling and noise attenuation between outer sheets for improving the rigidness of floor panels [10]. Also, the advantages of the sandwich structure panel were recognised for panel products [8–14]. The sandwich structure panel is composed of core materials, an edge trim, covering surface, and bottom surface [14]. This type of structure enables the panel core to be filled with different materials, such as chipboard, concrete, vegetable fibre, and so forth [15–19], which are presented in Table 1.

Table 1. Core materials of existing raised floor panels used in sandwich structure.

Core Material	Pros	Cons
Chipboard (Wood) [6,7,15,20]	• Easy to get material • Cost-effective	• Heavy • Limited load capacity • Low fire-resistance
Concrete [8,9]	• High load capacity • High fire-resistance	• Very heavy • Potential safety issue in instalment, replacement, and removal • High environment impact
Vegetable fibre [10,11]	• Natural and sustainable material • Good acoustic properties	• Heavy • Limited load capacity • Low fire-resistance
Hollow steel [12–14]	• Easy to handle • Available in traditional, low-profile floors	• Heavy • Hollow sound may be made when walking
Calcium sulphate	• High fire resistance • High load bearing capacity • Low impact sound and airborne sound	• Very heavy • High transportation cost • High production cost

A major problem of existing raised floor systems is that the panels are usually heavy, which causes manual handling problems and increases the cost of transporting them between sites. According to the results shown in Table 1, the wood-based chipboard panel is superior to other types of panels; however, the weight of a single floor panel is high at around 11 kg–15 kg [20]. In recent years, the chipboard panel has been improved with several methods, such as galvanised steel encapsulation, metal stringer support, edge trimming protection, etc. [15,21]. Although fire resistance and loading capacity are improved via the above methods, the weight of the chipboard floor further increases. A similar situation also exists in other flooring products, such as vegetable fibre floors. While improving the strength and fire-resistance features, the weight of the floor increases too. The weight problem of floor panels causes difficulties of installation and maintenance. When installing/replacing panels (e.g., concrete, steel, etc.), if there is no special tool, it will be difficult to move panels to the installation location, or to remove a panel from the installed floor. A heavy panel is difficult to handle and increases transportation costs, and, hence, a light floor panel is demanded to overcome this problem.

Current floor-panel manufacturing requires complicated processes, which affects the production efficiency. The processes usually involve the fabrication of the covering surfaces and edge trim with galvanised steel coil cutting, which are then followed by the press to form the lids and trays of galvanised steel for the floor panel. Subsequently, a pre-cut chipboard is encapsulated with galvanised steel in the assembly process, to satisfy fire-resistance requirements. As a result, manufacturing processes are complicated and tedious, which results in low productivity.

To overcome the challenges stated above, a new raised access flooring product with a composite material has been developed by this research, which utilises polyurethane reinforced with high-strength glass fibre as the sole material of the panel supported by simplified metal stringers. The new flooring product has several advanced features: it is light-weight and fire-proof with ensured strength, easy to install and replace, has improved production efficiency with a faster manufacturing process than traditional ones, and, most importantly, it is environment friendly and, hence, contributes to reduce the overall environmental impact of buildings.

To address environmental concerns during the development of new flooring products, it is essential to assess environmental impacts (such as use of resources, carbon emission, and the environmental consequences of releases) throughout the flooring product's life cycle. Life cycle assessment (LCA) methodology has been world-widely recognised as an effective way to assess the environmental impact of products [22]. It has also been constantly used in ecolabeling schemes and product environmental declarations [23]. In this research, LCA is applied to assess the design concept of the sustainable flooring product by identifying the total environmental impact and "hot spots" through its life cycle [24,25]. In addition, two conventional raised flooring products are assessed for the purpose of comparison.

This research is part of the international collaborative project supported by China Ministry of Science and Technology, and the new flooring product has been manufactured by the industrial partner of the project (see the Acknowledgements section). The sustainable product methods developed by this research can be expanded to other products, such as the second-life batteries being implemented in the Horizon Europe REBELION project [26].

As a sustainable product for buildings, the new flooring product not only has reduced the environmental impact confirmed by the LCA assessment results but also meets the required strength verified by the strength assessment results, along with other prominent features stated in the Section 5 of this paper. In the rest of the sections, the design of the new flooring product is presented first, followed by the detailed LCA assessment and strength investigation including finite element analysis and experimental tests, and then the novelties of this research are discussed.

2. Structural Design of the New Raised Flooring Product

A raised access floor consists of three elements: panels, stringers, and pedestals [4]. Stringers are located between the pedestals and panel, in order to provide supports to the system via de-centralising the pressure on the panel and enhancing the yielding resistance of the panel. The pedestal, which is usually made of metal, is a rigid adjustable column placed underneath the panel and stringers at the corners, in order to provide support for the floor assembly. The pedestal's height may vary, usually between 40 mm and 150 mm, which offers flexibility in the height of the flooring product. Also, such a design has the advantage of providing different load-bearing capacities [3].

The new raised flooring product developed by this research is shown in Figure 2. In the new product, the pedestal is a standard one, while the panel and stringers are novel as detailed below.

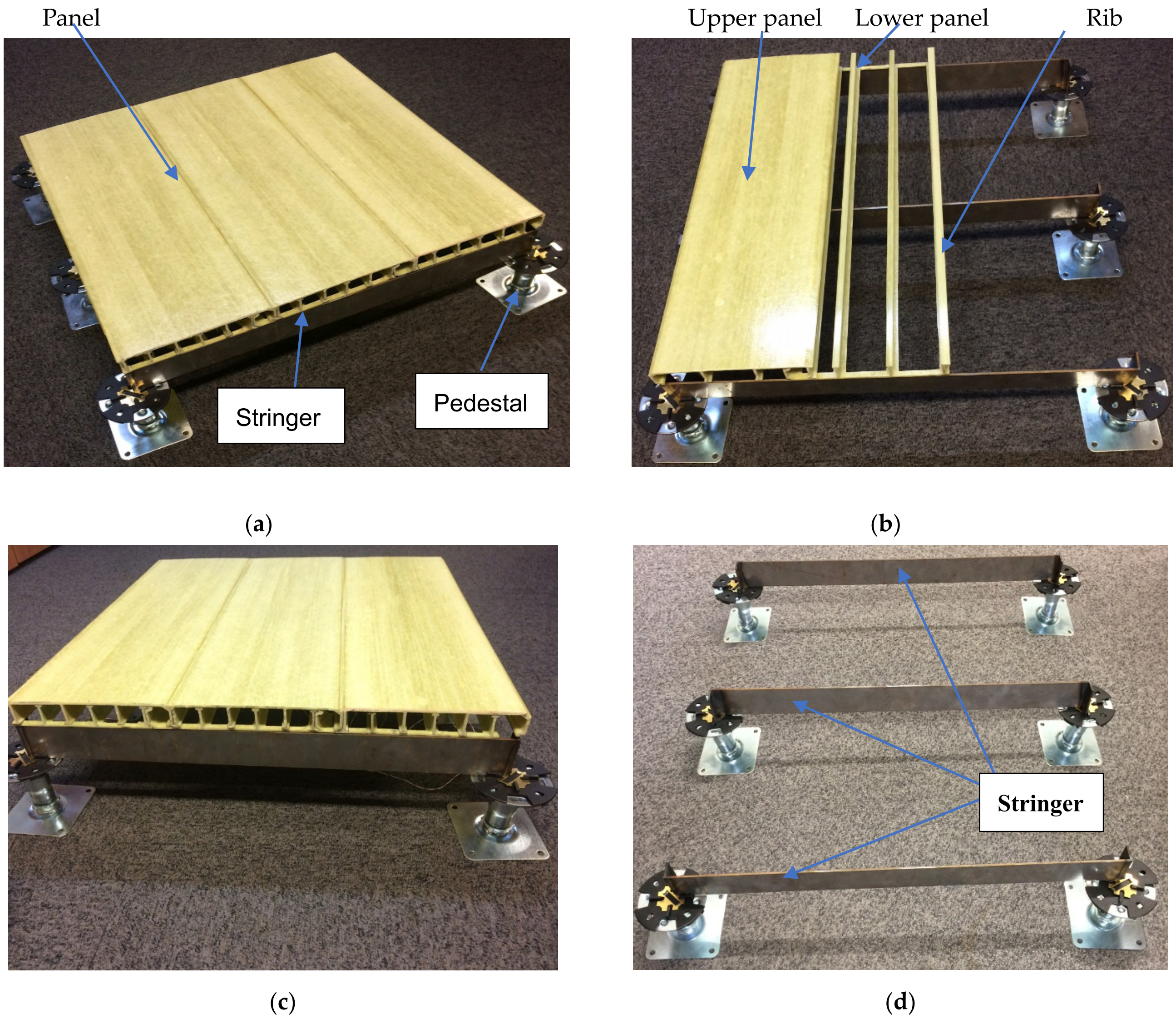
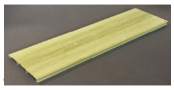


Figure 2. New raised flooring product. (**a**) Overview of the raised floor; (**b**) Assembly of an upper piece and a lower piece; (**c**) Assembly of three upper pieces and three lower pieces to form the panel; (**d**) Stringers and pedestals supporting the panel.

Panel design of the new flooring product. Different from the existing panel which is a single piece with a size of 600 mm × 600 mm [see Figure 1], the panel of the new floor product contains six pieces with dimensions of 200 mm × 600 mm per piece, including three upper pieces and three lower pieces which are assembled together to form the panel with the overall size of 600 mm × 600 mm. The upper piece is shaped with a flat sheet and four equally spaced ribs (see Figure 2b) to enhance the strength of the panel along the longitudinal direction, as shown in Figure 2c. The lower piece is processed from the same one as upper piece by cutting-off some parts of the flat sheet, leaving the ribs as shown in Figure 2b,c, to reduce the weight of the panel while achieving the required strength.

The panel is made of a glass fibre-reinforced PU composite material, consisting of 70% PU material and 30% glass fibre. The material properties are shown in Table 2. The panel piece is manufactured by the pultrusion processing method. In order to ensure the surface flatness and to meet the dimension requirement of the panel, the width of 200 mm is confirmed for the panel piece, because the required surface flatness would not be achievable by the pultrusion method for a wider width dimension.

Table 2. Properties of materials.

Property	Panel	Stringer
	PU2500-12.3 (Glass Fibre-Reinforced PU Composites) 	**AISI 1045 (Carbon Steel)** 
Mass Density	2070 kg/m^3	7850 kg/m^3
Poisson's Ratio	0.3	0.29
Yielding Strength	220 MPa	530 MPa
Tensile Strength	70 MPa	625 MPa
Elastic Modulus	20.5 GPa	205 GPa
Fire resistance	Yes (UL94-V1)	Yes
Water Absorption	<0.09%	Paint required for corrosion resistance

Stringer design of the new flooring product. Three stringers are placed underneath the lower panel pieces in a horizontal direction as shown in Figure 2d, where one stringer is located underneath the middle of the panel and the other two stringers are at the two ends of the panel. The stringers are supported by pedestals, and there are three stringers and six pedestals in total as shown in Figure 2d. The stringers are made of carbon steel and the material property is shown in Table 2.

In the design, the ribs enhance the strength in the longitudinal direction of the panel piece, and three stringers are placed underneath the lower panels in a horizontal direction, in order to improve the yield resistance (deformability) capability and to reduce the stress on the floor panel.

The new design enables the product's number of sustainable features which are further discussed in Section 5.

3. Environmental Life Cycle Assessment

This section is to assess the environmental impact of the flooring product through its life cycle, in order to address environmental concerns during the development of the new flooring product.

3.1. Goal and Scope

The goal of this study is to evaluate the environmental performance (the finally categorized impacts on human health, resources, and the ecosystem) of the flooring product, to find out the key environmental impact stages or processes, and to compare the environmental performance with existing flooring products. The final design concept of the sustainable flooring product is assessed to identify the total environmental impact and hot spots through its life cycle; two existing raised flooring products are also assessed for comparison and further analysis.

In the LCA conducted in this research, the professional software tool openLCA (version 1.11) [24] was utilised in conjunction with the Ecoinvent 3.5 database [25].

3.2. System Boundary

The study aims to conduct a cradle-to-grave life cycle assessment. Stages throughout a flooring product's life cycle including raw material acquisition, manufacturing, packaging, distribution (transportation), and end-of-life treatment are within the system boundary. The use phase along with maintenance during useful time are excluded from the assessment boundary, because information about these stages and activities are out of reach. The system boundary of this study is illustrated in Figure 3.

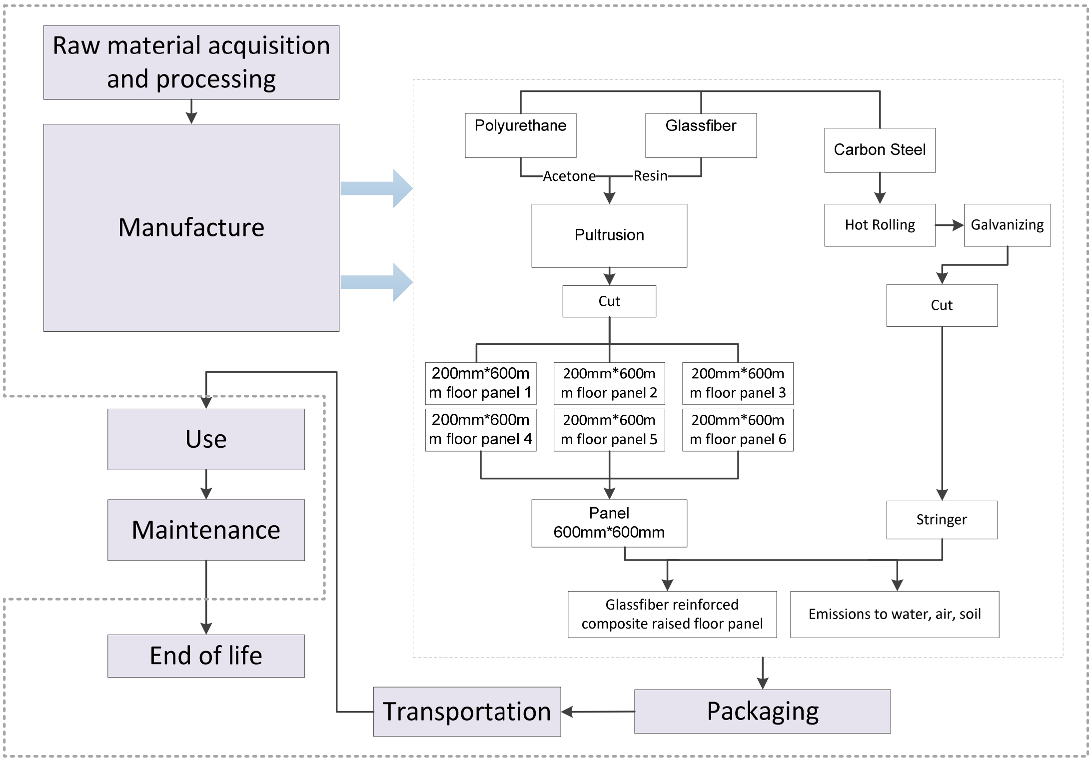


Figure 3. System boundary of the flooring product.

Raw material acquisition (including chemical use during pre-treatment, energy consumption, and transportation from extraction to site–mill–distribution) was taken into consideration in the manufacturing stage. Procedure-related environmental impacts throughout the fabrication of the proposed flooring product (F1), such as the use of materials, electricity, waste during manufacturing, and emissions, are considered and assessed, and the transportation during the manufacturing phase is also considered within the boundary. Nevertheless, the production of pedestals was not included, because the height of the pedestals are supposed to be chosen by the customer and the unsureness of height may result in inaccuracy of the assessment.

In the packaging stage, materials and dimensions are assumed with reference to international transportation methods. It is assumed that the flooring products are packaged with folding boxboard, plastic, as well as wooden pallets for mass transportation.

The transportation mainly focused on the transport activity through product distribution. In this case, the flooring products are assumed to be manufactured and packaged in China (Chongqing) then transported to the retailer in the UK (London). The total delivery distance between the two countries is 11,477 km via a direct freight train.

The end-of-life scenario of flooring systems, such as F1, is hard to predict, as it depends on the user's preferences on treating wasted floors. Yet, the material/waste recycle rate is relatively high in the UK and will be up to 65% by 2030 (http://ec.europa.eu/environment/waste/target_review.htm (accessed on 12 June 2024); in addition, it is the assumed that, for the end-of-life (EoL) scenario, after the service life, the EoL floor panel will be sent to remanufacturers to make cement products (the major route for reuse and remanufacture of post-consumer composite materials). The other parts of the floor system are steel, which will take the normal recycle/reuse route of steel waste.

3.3. Inventory Data

Inventory data in F1's life cycle are listed in Table 3. The floor panel sample was manufactured by Chongqing International Composite Material Co. LTD (CPIC) in Chongqing, China, thus input data such as material use and energy consumption during the composite floor panel production were acquired in the factory of this company. In order to collect data as well as learn the manufacturing procedure, a field study was conducted that included interviewing engineers and staff at the plant and measuring the product on site. Transport data were assumed according to the direct distance from Chongqing (China) to the UK (London); EoL treatment data were obtained with the assumption that 80% of panel materials may be sent to be recycled and 20% shall be taken to landfills, and all stringer material will be reused; other data were obtained by utilizing the Ecoinvent 3.5 database.

Table 3. Inventory data per function unit of the new flooring product (F1).

Inputs		Output	
Materials		*Product*	
Polyurethane	2.16 kg	Floor panel	9.78 kg
Glass fibre	8.66 kg	Stringer	4.6 kg
Acetone	1.2 L	*Waste*	
Resin	0.5 L	Solid waste	1.71 kg
Carbon steel	5.2 kg		
Plastic	0.07 kg		
Paper cardboard	1.24 kg		
Energy		End-of-life treatment	
Electricity	0.48 kw/h	Recycle (composite material)	7.82 kg
Transport		Reuse (carbon steel)	4 kg
Road transport (material delivery)	2517 km	Landfill	4.27 kg
Railway (product transport)	11,477 km		

3.4. Environmental Impact Assessment

Environmental impact assessment is conducted using openLCA 1.11 software and the Ecoinvent 3.5 (Consequential) database. The choice of openLCA instead of other software tools was made because, other than paying expensive fees to access an LCA tool like Simapro, openLCA is an open-source tool which is more accessible for companies or practitioners, especially for small companies; moreover, it has been proved that the evaluation results are very similar between these two software packages, even though the underlying matrices are different, and openLCA has been widely used around the world especially in institutions and environmental impact evaluation-related activities. Ecoinvent 3.5 was used as the LCA data source, and Consequential System Model was utilised for the study since it emphasizes more on assessing the consequences of different suppliers in product systems which fits better to the study.

The life cycle model of F1 was developed to simulate the input and output throughout F1's life cycle; ReCiPe (Endpoint Hierarchist) was chosen as the evaluation method according to the assessment goal. The environmental impacts are finally categorized in three endpoint impacts: Ecosystem, Human Health, and Resources.

3.5. Assessment Results

Table 4 and Figures 4 and 5 show the Life cycle impact assessment (LCIA) results of 100 flooring products. The total impact is 2795.9 points, and impacts to Resources contribute the most (1226.4) followed by impacts to Human Health (922.3) and to Ecosystem Quality (647.2) throughout F1's life cycle.

Table 4. LCIA results of 100 flooring products.

Impact Category	Result	Reference Unit
Ecosystem Quality	647.2	Points
Human Health	922.3	Points
Resources	1226.4	Points
Total	2795.9	Points

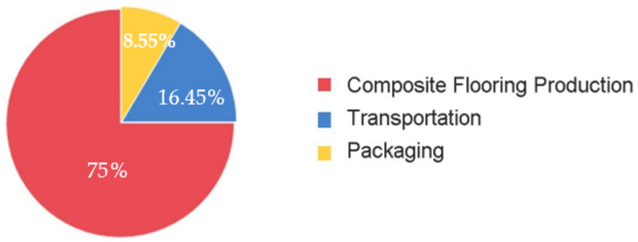


Figure 4. Pie chart of impact distribution in F1's life cycle stages.

Figure 4 shows the total impact distribution of different life cycle stages (end-of-life stage produces a positive environmental performance which is not present in the impact pie chart) in the flooring product's life cycle, which reveals the following:

- The production stage presents the highest environmental impact which accounts for 75.52% of F1's total impact; this is because the production stage is an input–output intensive stage where the majority of the consumption of materials and energy takes place (within production possesses).
- A long transportation distance together with fossil fuel consumption are the main ascriptions to the Transportation stage, which contributes 16.45% of the negative impacts of the total impacts.
- A total of 8.55% of the negative impact was contributed by the packaging stage.
- For the end-of-life stage, the result shows that it produces about −15 points of total impact; this indicates that the chosen waste scenario (discussed in the Section 3.2) may produce a positive environmental performance.

Figure 5 illustrates the Sankey diagram with an 8% cut-off, which pointed out the key environmental impact processes. As shown in the diagram, the wider and redder the line is, the greater the process's environmental impact is. The result reveals that the following:

- In the manufacturing stage, the production of the glass fibre-reinforced floor panels is the key process affecting environmental impact (hot spot), as it accounts for about 72% of the total impact. The environmental impact is mainly allocated in the preparation of materials, which are the following: (1) fabrication of glass fibre including primary chemical extraction and prefabricate (39%), (2) production of polyurethane (20%), (3) acetone production (6.59%), (4) other manufacturing-related inputs, namely production of resin, transport-related activities, and electricity usage (3.2%, 2.48%, and 0.62%, respectively), and the manufacturing of stringers only contributes 3.11% of the total impact.
- The transport of flooring products presents as the second highest impact life cycle stage (about 459.8 point). All the impact comes from the freight train transport from China to the UK, which is mainly due to the usage of fossil fuel, resulting in a high negative impact on the fossil depletion (Resources) and climate change (Human Health) categories.
- The packaging stage contributes a lower environmental impact (8.55%).
- Finally, the end-of-life treatment phase produced a positive effect.

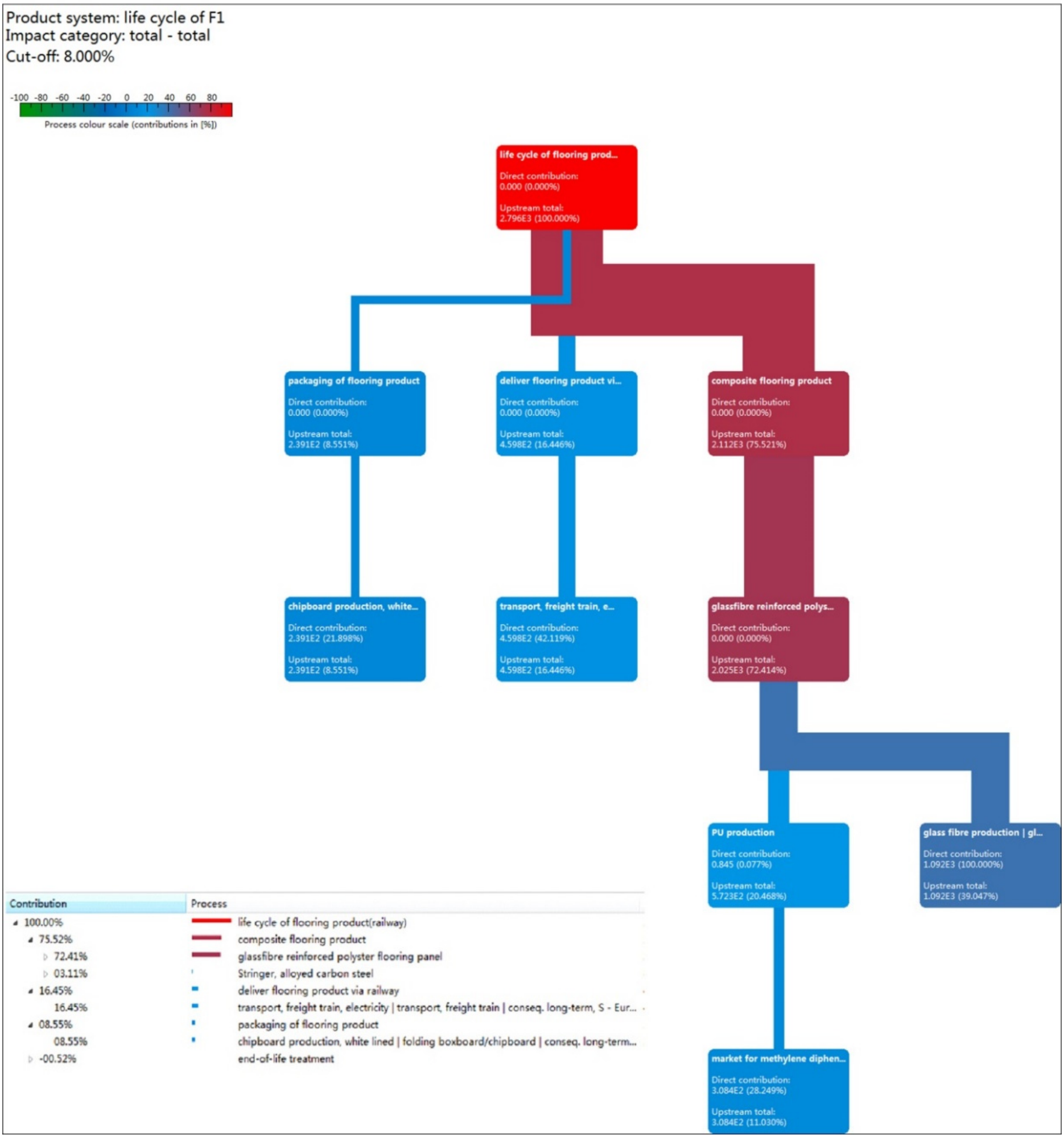


Figure 5. Sankey diagram (8% cut-off) and process contribution tree.

3.6. Comparative Study

In the LCA study of F1, environmental performance has been informed, and key environmental issues and impacts in life cycle stages are identified. However, there is no standard or guideline to check whether the flooring product is environmentally sustainable or not. Therefore, a comparative study needs to be conducted in order to have a better evaluation of the flooring product's sustainability, as well to have a better understanding of the environmental performance of products of this kind.

Two additional raised floor products were introduced and assessed to compare the environmental performance with F1. The two products are cement-injected steel sandwich raised floor (F2) and wood chip-based raised floor (F3). Both of the flooring products have been in the market for years. They are manufactured in Changzhou (China) where most Chinese raised floor producers are located.

As shown as Figure 6, F2 consists of a sandwich structured panel, a stringer, fastening members, and pedestals. The panel is made of cement core wrapped with steel sheets and PVC finishing. The stringer is made of steel in a square shape to support the panel as well as enhance the strength. There are three kinds of stringers with different materials and heights which can be chosen by customers with their preference.

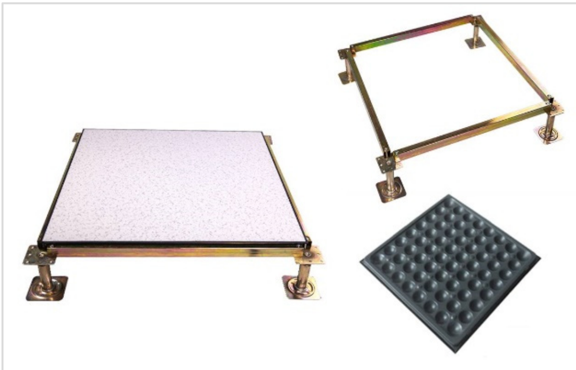


Figure 6. Cement-injected steel sandwich raised floor (F2).

The components of F3 are the same as its counterpart F2, see Figure 7. However, this type of flooring panel is mainly made of wood fibre pressed board in a special thickness (about 40 mm). In order to ensure the fire resistance and strength performance, steel sheets are placed (glued) on the top of the chipboard and underneath it, a printed PVC sheet is added, and the four edges are sealed with conductive rubber. For stringers and pedestals, the material used is steel.

Figure 7. Wood chip-based raised floor (F3).

Technical specifications of the three products are shown in Table 5.

The system boundary of the comparative LCA comprises life cycle stages such as raw material acquisition, manufacturing, packaging, distribution (transportation), and end-of-life treatment. The use phase along with maintenance activities are still excluded for the same reason as stated earlier. In addition, stringers and pedestals also have been excluded from the boundary, because as described in the previous section, the material and structure of the two parts are nearly as same as F1; in this case, the study only focus on the LCIA comparison of flooring panels between F1, F2, and F3.

Table 5. Technical parameters of flooring products under comparison.

	F1	F2	F3
Weight (kg)	9.78	12.6	12.2
Dimension (mm)	600 × 600 × 33	600 × 600 × 35	600 × 600 × 40
Material	glass fibre-reinforced polymer	cement (core), steel sheet, PVC, rubber	wood (fibreboard), steel sheet, PVC, rubber
Concentrated load	≥3000 N	≤3000 N	≥3000 N
Uniform load		11,760 N	23,000 N
Ultimate loads	≥8000 N	≤8000 N	≥8000 N
Fire resistance	V1	V1	V1

The bill of materials used in all three flooring products is shown in Table 6. The data used in F1 were described in a former section (Inventory Data), and the rest of the flooring products' material and process data were selected from the Ecoinvent 3.3 database.

Table 6. Bill of materials (F1, F2, and F3).

F1		F2		F3	
Inputs		Inputs		Inputs	
Materials		*Materials*		*Materials*	
Polyurethane	2.16 kg	Steel (Pressed Steel Sheet)	3.49 kg	High-Density Fibreboard	9.85 kg
Glass Fiber	8.66 kg	Cement	8.52 kg	Steel Sheet	1.51 kg
Acetone	1.20 L	PVC	0.66 kg	PVC	0.05 kg
Resin	0.50 L	Adhesive	0.04 kg	Adhesive	0.002 kg
Carbon Steel	5.20 kg	Medium-Density Particleboard	6.77 kg	Rubber	0.79 kg
Plastic	0.07 kg	Plastic	0.11 kg	Plastic	0.01 kg
Paperboard	1.10 kg	*Transport*		Wood	0.03 M^3
Energy		Freight Road Transportation	3541 km	Paperboard	0.87 kg
Electricity	0.48 kw/h	Freight Railway Transportation	12,451 km	*Transport*	
Transport				Freight Road Transportation	3541 km
Road Transport (Material Delivery)	2517 km			Freight Railway Transportation	12,451 km
Railway (Product Transport)	11,477 km				
Output		Output		Output	
Product		*Product*		*Product*	
Floor Panel	9.78 kg	Sandwich Steel Panel (Cement Injected)	12.60 kg	Wood-Based Raised Floor Panel	12.20 kg
Stringer	4.60 kg				
Waste		End-Of-Life Treatment		End-Of-Life Treatment	
Solid Waste	1.71 kg	Landfill	12.60 kg	Incineration	12.20 kg
End-Of-Life Treatment					
Recycle (Composite Material)	7.82 kg				
Reuse (Carbon Steel)	4.00 kg				
Landfill	4.27 kg				

A total of 100 items for each of the three variants (F1, F2, and F3) are assessed using the same method (ReCiPe endpoint H) to compare their environmental performance. The results are presented below.

As shown in Figure 8, F2 presents the highest environmental impacts of the three variants (1055 points), F3 has the second highest impacts (960 points), and F1 has the lowest impacts (513 points), which are 52% less than F2 and 47% less than F3.

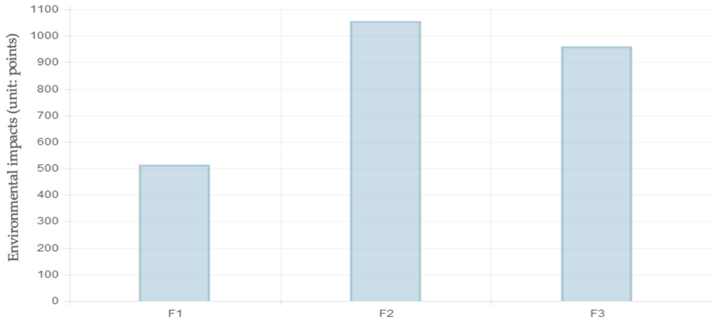


Figure 8. Total impacts of three flooring products.

Figure 9 illustrates the relative impacts in percentage of F1, F2, and F3. In the endpoint perspective, F1 presents the smallest percentage (about 25%) of impact on Ecosystem Quality, whilst F2 is about 90% and F3 is almost 100%. This is because F1 (panel) is fully made of composite material, which has relatively less water involved in production processes and thus has less of an effect on ecosystems; in contrast, wood-based materials are naturally grown materials which are majorly used in F2 (packaging material) and F3 (panel material), and it could result in a large amount of potential impacts on Ecosystem Quality such as climate change and terrestrial acidification. In the Human Health category, the impacts were majorly affected by the complexity of the material used in product or product systems, including the chemicals used and the amount of material used, etc. Again, affected by the packaging material, particleboard, F2 scores the most amongst the three flooring products (100%), and F1 still has the lowest score (40%) in this endpoint category. In category of Resources, F2 has the highest impact as well because of the packaging and transportation stage, while F3 has the second highest impact (80%). F1 presents a slightly higher percentage (70%) of impact compared to the impacts on other categories, and this may be ascribed to the glass fibre fabrication requiring raw fossil extraction, which has the potential of causing fossil depletion.

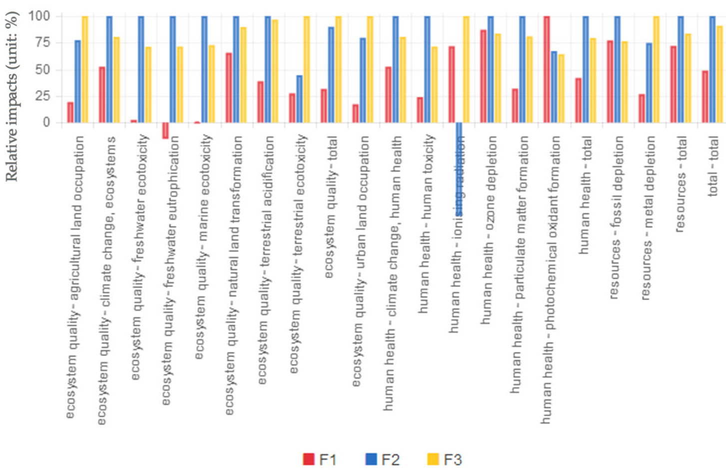


Figure 9. Relative impacts of three flooring products.

The key environmental impact stages are varied among the three flooring products. Contribution trees indicate that in F1, the hot spot stages were the same as the one assessed earlier (F1 with stringer) but in a different percentage (production 78.8%, transportation 13.87%, and packaging 9.3%). For F2, packaging is the highest environmental impact stage which contributes 54.64% of the total impact, and the second highest impact stage is transportation (23.27%). The reason behind this is, according to the producer, every panel was going to be packaged with wooden (particleboard) materials to ensure product safety during transportation; nevertheless, the material use and mass-related factors were increased in the impacts of different categories, consequently increasing the total impact. The production stage of F2 just produced 22.06% of its total impact. In F3, the production stage is the key environmental impact stage (71.57%), and fibreboard production is the key environmental process. Transportation and packaging contribute 17.6% and 10.76%, respectively, of F3's total impacts.

4. Strength Assessment

The methods implemented to assess the product's strength include finite element analysis (FEA) and experimental tests. The strength assessment criteria are set up first, and then, based on the criteria, the FEA is carried out and confirmed with the experimental test.

4.1. Strength Assessment Criteria

According to the EU/UK Standard BSEN 12825:2001 [16] and PSA (MOB PF2 PS/SPU) [17], when applying a 3000 N working load within a 25 mm^2 square area of the panel surface, the strength (yielding stress and deflection) of the floor panel must meet the requirements within the standards. Because the working load multiplied by the safety factor is equal to the ultimate load, the safety factor can be obtained via the working load and ultimate load. Based on the EU/UK BESN and PSA standards, the strength assessment criteria for the new raised access flooring product is established, including the following: (1) working load: 3000 N; (2) ultimate load: 9000 N; (3) safety factor: 3.0 (Class 3), which shows the very strong floor panel under the BSEN certification with a high safety factor; and (4) deflection under the working load: 2.5 mm (Class A) under the BSEN certification.

According to the "Maximum von Mises stress criterion", also called "Maximum distortion energy theory", the von Mises stress $\boldsymbol{\sigma}$ of the flooring product is required not to be bigger than the allowable yielding stress $[\boldsymbol{\sigma}]$, which is expressed as follows: $\boldsymbol{\sigma} \leq [\boldsymbol{\sigma}]$

Where

$$[\boldsymbol{\sigma}] = \boldsymbol{\sigma}_{\text{yield}}/\text{Safety Factor}$$

The yielding strength $\boldsymbol{\sigma}_{\text{yield}}$ of the panel and stringer can be obtained from Table 2, and the safety factor is 3. Then the allowable yielding stresses $[\boldsymbol{\sigma}]$ of the panel and stringer are expressed as follows:

$$\text{PU panel reinforced by glass fibre: } [\boldsymbol{\sigma}]_{\textbf{PUG}} = 220/3.0 = 73.3 \text{ MPa},$$

$$\text{Stringer: } [\boldsymbol{\sigma}]_{\textbf{steel}} = 530/3.0 = 176.7 \text{ MPa}$$

Therefore, the von Mises stresses $\boldsymbol{\sigma}$ of the panel and stringer must meet the following conditions:

$$\text{PU panel reinforced by glass fibre: } \boldsymbol{\sigma}_{\textbf{PUG}} \leq 73.3 \text{ MPa},$$

$$\text{Stringer: } \boldsymbol{\sigma}_{\textbf{steel}} \leq 176.7 \text{ MPa}$$

In addition to the stress requirement, the British Standard PSA MOB PF2 PS [17] also formulates the requirement with regards to the deflection/deformation of the flooring product. The deflection **D** of the floor must meet the following conditions:

$$\text{PU panel reinforced by glass fibre: } \mathbf{D}_{\textbf{PUG}} < 2.5 \text{ mm},$$

$$\text{Stringer: } \mathbf{D}_{\textbf{steel}} < 2.5 \text{ mm}$$

The above conditions apply when a 3000 N working load is applied on the surface of the floor panel.

4.2. Finite Element Analysis (FEA)

4.2.1. Assessment Scenario

Figure 10 shows the CAD model of an upper panel piece, a lower panel piece, and a stringer. Within the upper panel piece, the four ribs with a height of 15 mm are located at equal intervals, which provide support for a 3 mm thick flat sheet as shown in Figure 3a,b. As mentioned in Section 2, the lower panel piece is made from the one of the same shape as the upper panel piece, but some parts of the flat sheet are cut off while keeping the ribs and the connections between the ribs, as detailed in Figure 10c,d. The stringer's dimensions and shape are shown in Figure 10e.

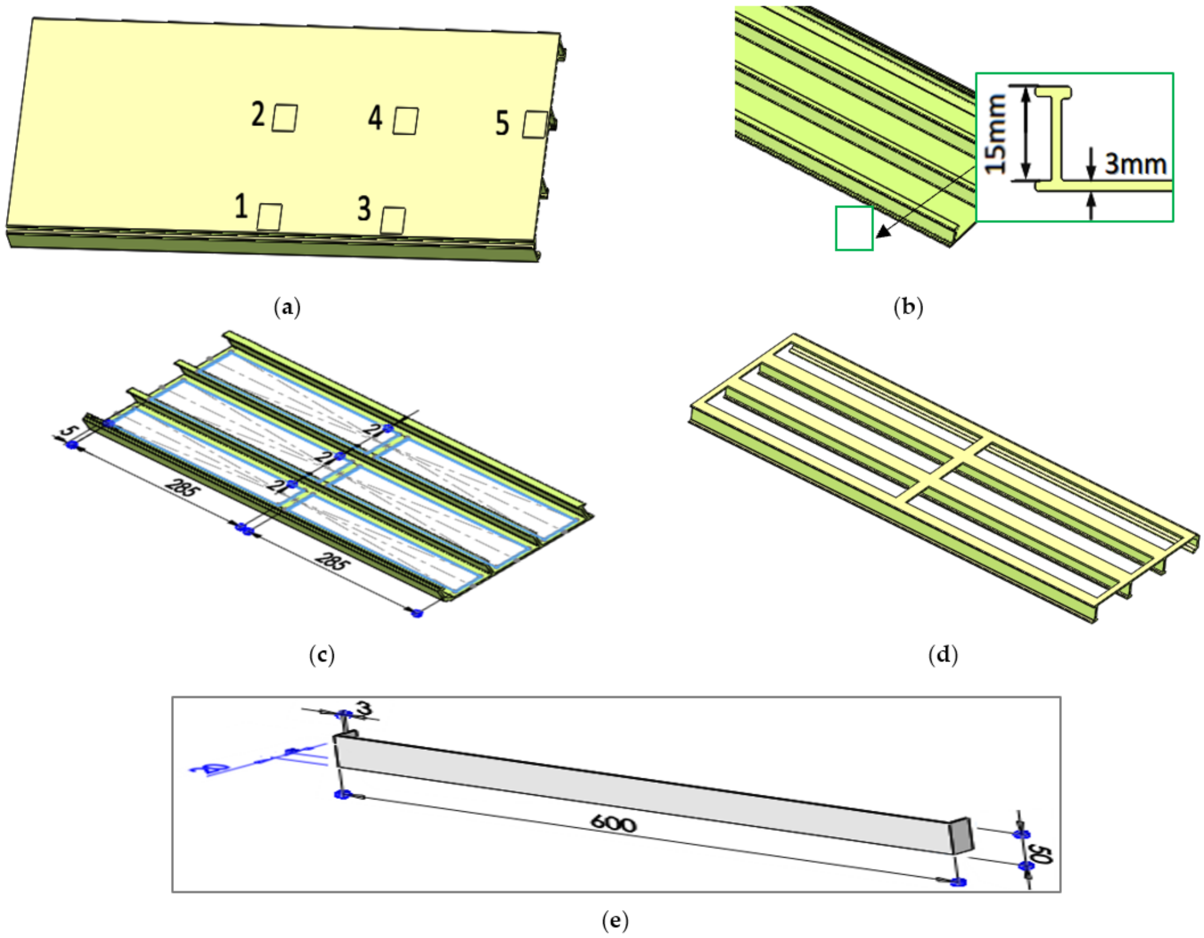


Figure 10. Components of the raised flooring product (units: mm). (**a**) Upper panel (top view); (**b**) upper panel (back view); (**c**) lower panel (top view); (**d**) lower panel (back view); (**e**) stringer.

The strength of the floor panel must meet the requirement of the composites' floor standards [18], and hence, a strength test of the floor panel is required. Figure 10a shows the testing locations marked with numbers 1, 2, 3, 4, and 5, where the loads are to be applied on the panel.

The finite element analysis is conducted with a professional FEA software tool (version 2021) based on the parameters of material properties, which are shown in Table 2. The finite element model has been developed for the loading capacity analysis of the panel. The main material parameters involved in the modelling process include the elastic modulus (E), yielding strength, density, and Poisson's ratio. For more information about the strength analysis with the finite element method, please see Section 4.2.2.

To confirm the FEA results, the experimental tests have been conducted by utilising an Instron testing system and strain gauges to assess the strength of the two types of panel materials. The test items include deflection, strain, and stress. For more information about the experimental tests, please see Section 3.3.

4.2.2. The FEA Model

The full flooring system includes three panel pairs, and each pair consists of an upper piece and a lower piece, as shown in Figure 2a. The middle pair is in the weakest location, and, hence, the strength assessment is focused on the middle pair. The FEA model of the raised floor product contains two floor panel pieces, three parallel stringers, and six pedestals. The 3000 N forces are applied to five test positions indicated as Load 1, 2, 3, 4, and 5 (see Figure 11a), each of which is a 25 mm^2 square area on the upper panel surface, the same as the experimental test presented in Section 3.3.

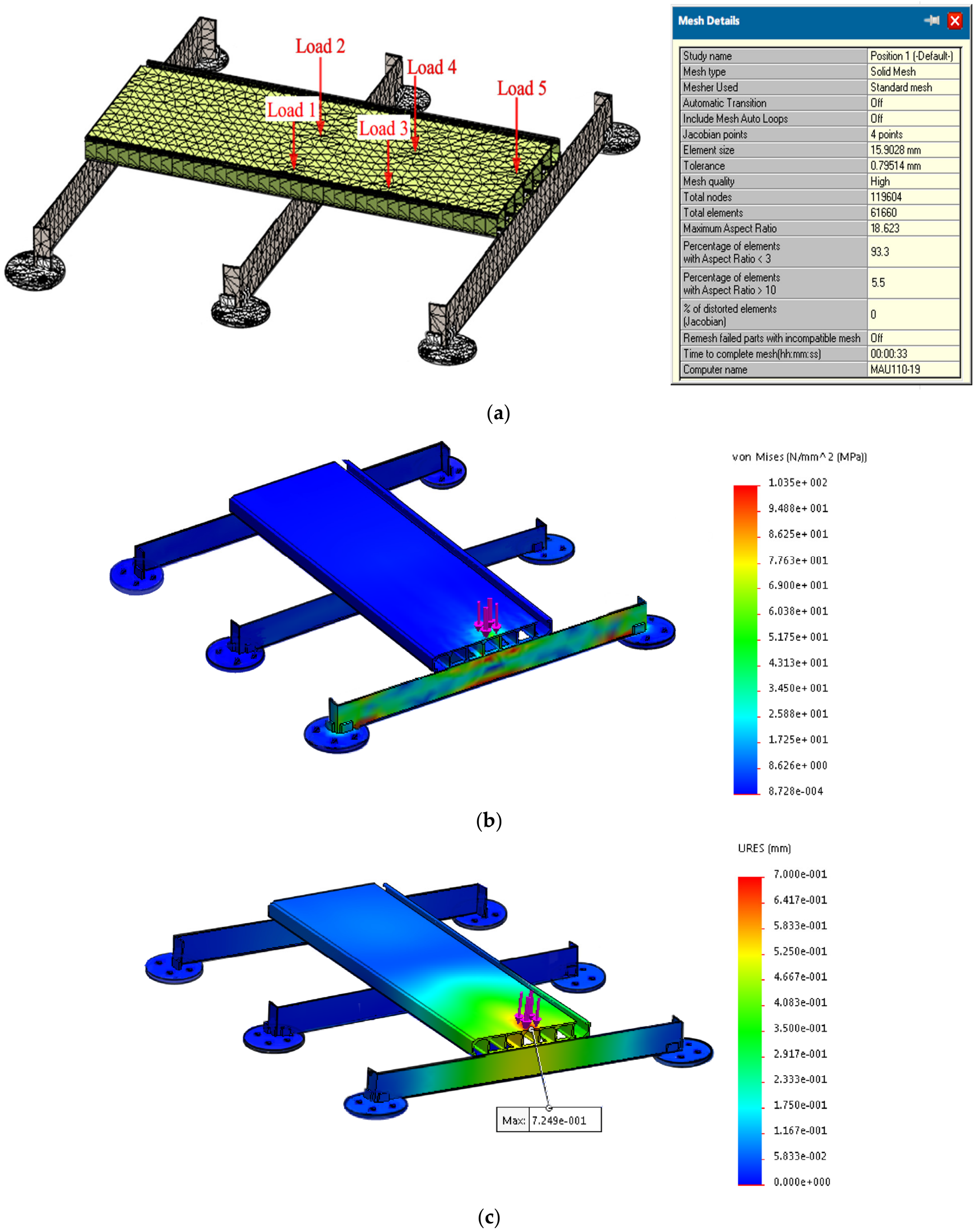


Figure 11. Finite element analysis. (**a**) FEA model with element mesh; (**b**) FEA results of yielding stress of glass fibre-reinforced PU panel; (**c**) FEA results of deflection of glass fibre-reinforced PU panel.

The FEA mesh details are shown in Figure 11a. As indicated in this figure, the FEA model of the flooring product system is meshed with 61,600 elements and 119,604 nodes. In the FEA model of the flooring product system, the maximum aspect ratio of elements is 18.62. The elements with an aspect ratio less than 3 account for 93.3%, and the elements with an aspect ratio greater than 10 account for 5.5%. There is no distortion element generated during the modelling process. Based on the above analysis, the floor model has been divided into several high-quality finite elements.

The key parameters of the strength analysis include the elastic modulus (E), yielding strength, density, and Poisson's ratio. According to the maximum distortion energy theory mentioned in Section 4, the maximum allowed yielding stress of the PU panel with glass fibre is 73.3 MPa. The maximum allowed deflection of the panel is 2.5 mm subject to the safety factor.

An example of the FEA results of deflection and yielding stress is shown in Figure 11b,c, where the load is applied at loading position 5 (see Figure 11a) that is one of the weakest points.

According to the FEA outcome shown in Section 4.3.3, the deflection of the panel is more than that of the stringer, while the yielding stress of the panel is less than that of the stringer, which can be observed at each loading position. The maximum deflection took place at position 3 on the panel (2.03 mm), and the maximum yielding stress occurred at position 3 on the stringer (143.4 Mpa).

4.3. Experimental Investigation

The experimental test conducted is to ensure that the new flooring product complies with the requirements of the raised floor standards stated in Section 4.1 and to confirm the FEA results. In this section, the experimental test system is presented first, followed by the test conducted using the experimental system.

4.3.1. The Experimental Test System

In the experimental test, the Instron testing system shown in Figure 12a is utilised to apply working loads on the panel surface and to monitor the change in the deflection of the panel.

Based on the Standard BSEN 12825:2001 [16], it is required to apply a 3000 N working load within a 25 mm^2 square area on the surface of the floor panel. Hence, a steel cube with 25 mm^2 square sides is used to confirm the location of loading (test position), as shown in Figure 12b. The deflection values of the panel are obtained by the Instron measurement instrument. The base for the experimental test consists of five I-shape beams, which are used for mounting the panels and stringers with six pedestals.

According to the requirement of the PSA MOB PF2 PS/SPU standard [17], the test positions are in the middle and outer edges of the upper panel piece (see Figure 11), where the five strain gauges are installed on the back.

The strain gauges are used to capture strain values of the panel, which can be read by a strain reader, a strain measurement device shown in Figure 12a. Based on the strain values, the stress values of the panel are then calculated using the Hooke theory [19].

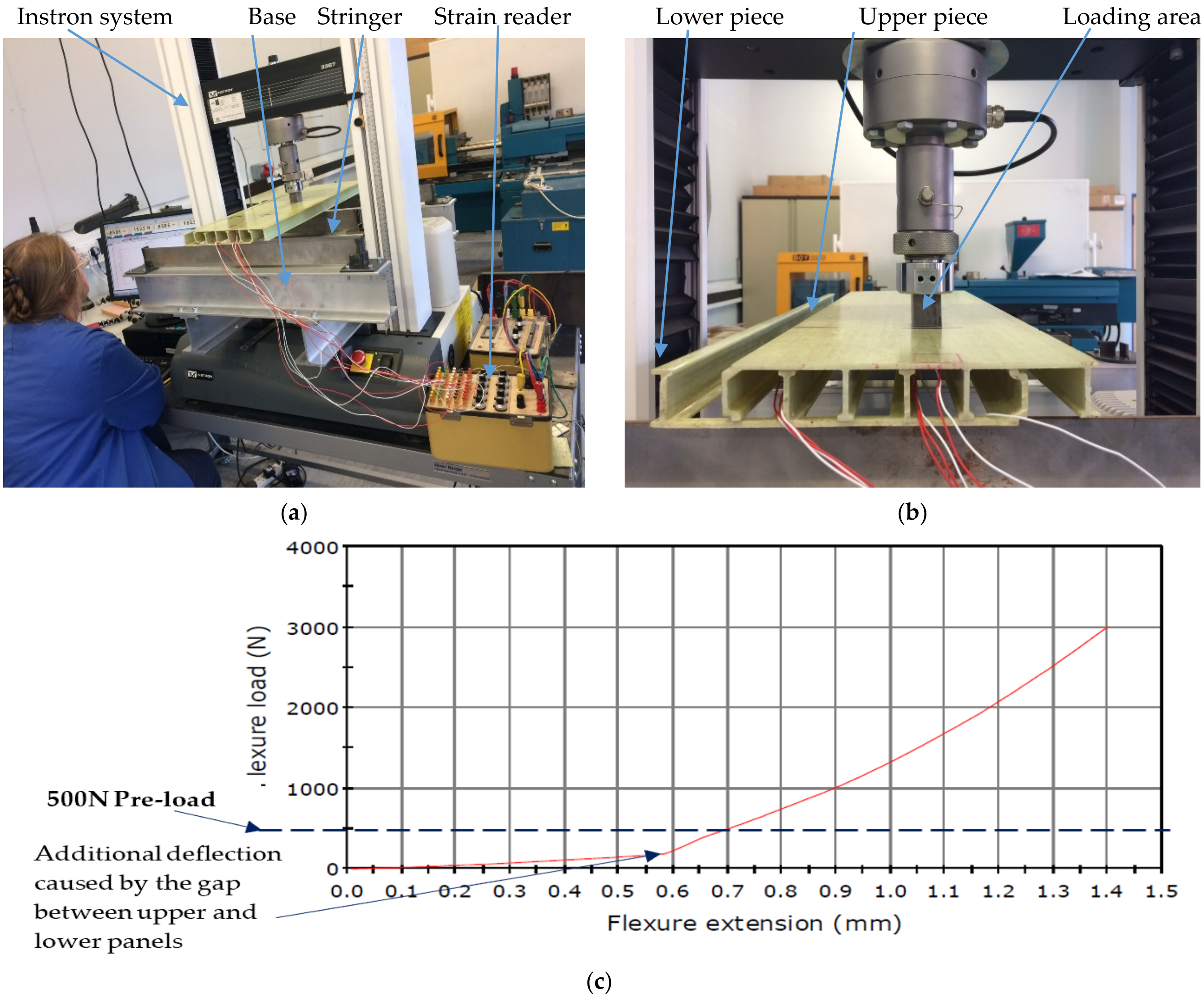


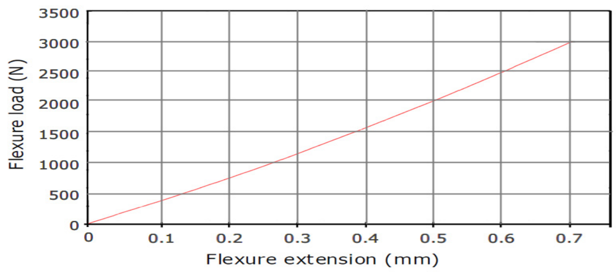
Figure 12. The experimental test system. (**a**) Test overview; (**b**) panel test; (**c**) pre-loads applied to ensure the panels are contacted without gap.

4.3.2. Experimental Test

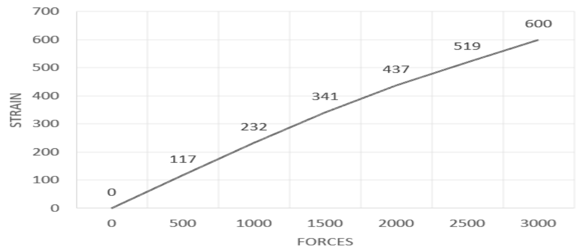
The experiment is conducted to measure the values of deflection and strain of the panel. To do so, the monitoring device is applied for tracking the load process and displaying deflection values, and the strain measurement device is used to read strain values out of the strain gauges.

Before the start of the experiment, pre-loading is conducted. The upper panel piece is placed on the lower panel piece without connection (like adhesion or gluing), and, hence, there is a small gap between the upper panel piece and the lower panel piece, which may generate additional deflection. Therefore, it is vital to apply pre-loads, to ensure both the upper and lower panels are in full contact. Figure 12c shows a 500 N pre-load being applied, which eliminates the gap between the panel pieces.

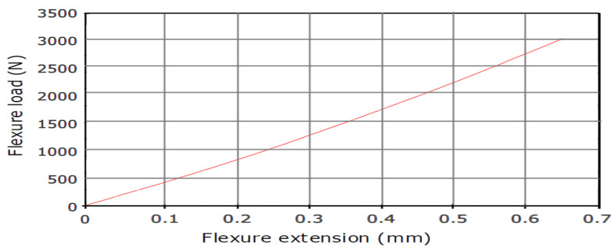
In order to apply the working load, five positions have been selected for the measurement of the deflection and strain of the panels and the stringers. At each test position, the 3000 N working load was gradually loaded onto the upper panel piece (load step interval value is 1 N). When the working load applied was 3000 N, both the strain and deflection of the panels reach the maximum values, as shown in Figure 13.



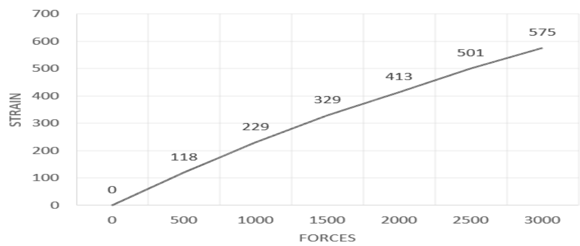
(**a1**) Deflection at position 1



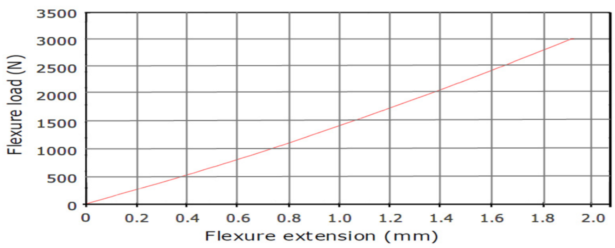
(**a2**) Strain at position 1



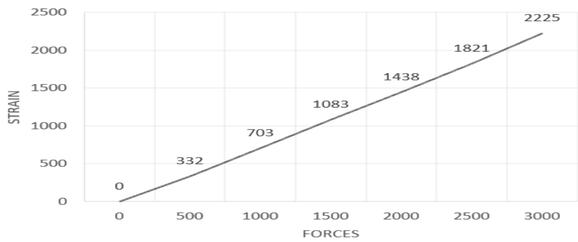
(**b1**) Deflection at position 2



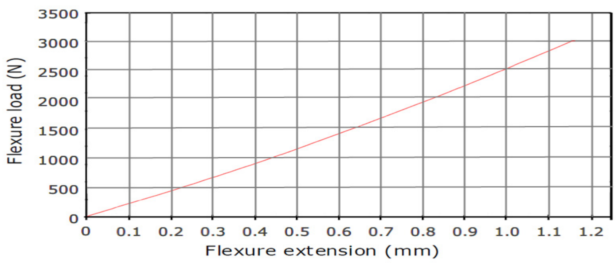
(**b2**) Strain at position 2



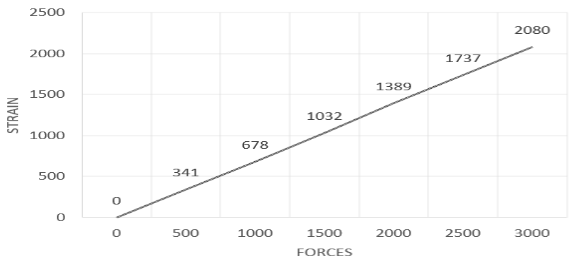
(**c1**) Deflection at position 3



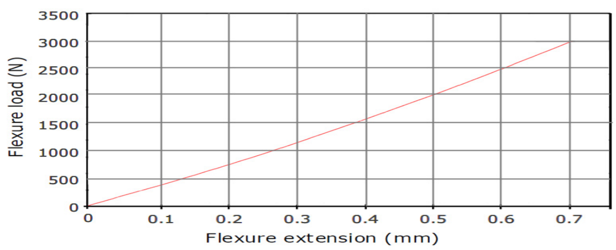
(**c2**) Strain at position 3



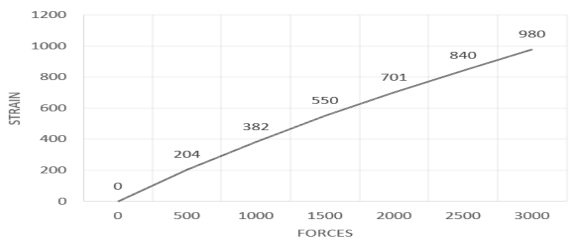
(**d1**) Deflection at position 4



(**d2**) Strain at position 4



(**e1**) Deflection at position 5



(**e2**) Strain at position 5

Figure 13. Experimental outcome of deflection and strain of glass fibre-reinforced floor panel.

The deflection values of the panels were measured by the Instron system, which generated a trending curve reflecting the deflection changes corresponding to the workload changes. The strain values of the panels were captured by the strain gauges installed at the testing points, which were read from the strain measurement device (strain reader) every

500 N, and hence, seven strain values were obtained when the workload was applied up to 3000 N at each testing point.

Figure 6 shows the experimental results of deflections and strains of the glass fibre-reinforced floor panel, where the graphs record the trending curves that represent the deflections and strains captured at the five testing positions.

With the Hooke theory [21], stress values can be calculated using strain values and the panel's elastic modulus (E = 20.5 GPa). The panel's strain values (unit: micro) at five loading positions (see Figure 11a) were measured: 600, 575, 2225, 2080, and 980; and then, the corresponding stress values (unit: MPa) were calculated and obtained: 12.3, 11.8, 45.62, 42.65, and 20.1. The deflection values (unit: mm) at the loading positions were 0.70, 0.65, 1.90, 1.13, and 0.70, respectively.

4.3.3. Confirmation of FEA with the Experimental Test

The experimental results are applied to confirm the correctness of the FEA results of the glass fibre-reinforced PU material panel. The results of deflection and yielding stress of both FEA and experimental tests are summarised below:

Deflections at the five locations shown in Figure 11a:

Position 1: experimental test result 0.70 mm, FEA result 0.71 mm, difference 1.0%;
Position 2: experimental test result 0.65 mm, FEA result 0.62 mm, difference 4.6%;
Position 3: experimental test result 1.90 mm, FEA result 2.03 mm, difference 6.4%;
Position 4: experimental test result 1.13 mm, FEA result 1.08 mm, difference 4.4%;
Position 5: experimental test result 0.70 mm, FEA result 0.70 mm, difference 0.0%.

Yielding stresses at the five locations shown in Figure 11a:

Position 1: experimental test result 12.3 MPa, FEA result 11.45 MPa, difference 6.9%;
Position 2: experimental test result 11.8 MPa, FEA result 11.05 MPa, difference 6.3%;
Position 3: experimental test result 45.6 MPa, FEA result 48.34 MPa, difference 5.6%;
Position 4: experimental test result 42.6 MPa, FEA result 40.45 MPa, difference 5.2%;
Position 5: experimental test result 20.1 MPa, FEA result 21.55 MPa, difference 6.7%.

As shown above, the FEA results are in accordance with the experimental results, which proves that the experimental results are correct.

When a 3000 N working load is applied to the panel, the deflection of the panel is less than 2.5 mm, and the yielding stress of the panel is less than 73.3 MPa, which complies with the composite floor standards and the strength assessment conditions presented in Section 4.1. Therefore, the glass fibre-reinforced PU composite material is selected as the material of the panel, because it has high load-bearing performance and meets all the requirements within the composite material flooring product standards.

5. Discussion

As a sustainable product for buildings, the new raised flooring product developed by this research not only reduces environmental impacts but also facilitates manufacturing efficiency and a light product weight, while meeting the required strength and fire resistance standards, which are discussed below.

5.1. Product Environmental Sustainability

In comparison with traditional flooring products, the new floor product has much lower environmental impacts. As indicated in the LCA results shown in Section 3, the environmental impact of the new floor is half of that of the existing ones.

In addition to the LCA assessment, the following also contribute to the environmental sustainability:

- The panel materials used, polyurethane and glass fibre, do not contain chlorine and formaldehyde emissions. Therefore, the materials are environmentally friendly, in accordance with the requirements of the standard ISO14001:2004 [27] and British Standard EN 12825:2001 [16].

- The panel is made of a sole material which facilitates the recycling of the materials when the product reaches its end-of-life stage (EoL). This is another advantage in comparison with traditional raised floor panels, such as the chipboard panel which requires the separation of the outer cover metal sheet from the woodchips in order to recycle it when it reaches the EoL stage.
- The stringers and pedestals are made of metal materials, which are easy for recycling and reuse.
- The new raised flooring product does not generate any harmful emissions, like formaldehyde and chlorine, avoiding polluting the environment and damaging human health.
- As stated in the section below, the new floor panel is much lighter than the traditional products, which reduces the transportation costs including fuel consumption, and hence reduces carbon emissions.

5.2. Light Product Weight

Currently, the floor panels used in the traditional raised access floor systems are heavy and costly. Although the existing wood-based chipboard panels outperform other types of panels in weight and cost, they still lead to considerable difficulty in manual handling and transportation [20]. Further, the chipboard panel must utilise steel encapsulation and edge trimming to improve fire resistance and load-bearing capability, and hence, the weight of the panel is further increased.

In contrast, the new raised access flooring product utilises Polyurethane (PU) as the panel's core material and high-strength glass fibre for reinforcement, which is light-weight and fire-proof and replaces the conventional chipboard material in order to overcome the problem of the weight of floor panels. The glass fibre and steel stringers adopted ensure that the strength of the floor panel complies with the industrial standards that are required for bending (yielding) stress and deformation, such as the British Standard BSEN 12825: 2001 [16] and PSA (MOB PF2 PS/SPU) 1992 [17].

The weight of panel pieces was measured with results showing that the upper piece weighs 1.3 kg and the lower piece weighs 0.84 kg, and, hence, the weight of the full panel of 600 mm $\times$ 600 mm is 6.45 kg, while traditional floor panels are much heavier; for example, a chipboard panel weighs more than 11 kg, which means that the new designed flooring product is 40~50% lighter than existing flooring products. The light weight makes it easier for workers to install the product and conduct maintenance services. Also, the 600 mm $\times$ 600 mm panel is broken into six pieces as shown in Sections 2 and 4.1, which further enhances product's easy installation.

5.3. Product Strength

Within the conventional design of a raised flooring system, the floor panel contains a core encapsulated with the outer layers (steel encapsulated and edge trimming). The outer layers are used to improve the loading capacity and fire resistance of the floor panel, which increases the weight and manufacturing complexity. In the new floor panel, the outer layers are not required because it is made of a sole composite material, and, therefore, the weight of the panel can be further reduced but the strength is still ensured as proved by the FEA and experimental results. In addition, the strength of the floor panel is improved via applying the stringers and panel ribs with the particular structure and dimensions detailed in Sections 2 and 4.1.

The strength of ordinary PU material is 124 MPa, while the strength of glass fibre-reinforced PU composite material is 220 MPa. Hence, the use of PU composite material significantly improves the overall mechanical performance of the floor.

5.4. Simplified Manufacturing Process

The traditional floor panel manufacturing method is complicated [14], requiring complicated processes (coil cutting, forming press, and assembly), which affects the production efficiency. Such processes usually involve the fabrication of the covering/bottom surfaces and edge trim with galvanised steel coil cutting, which are then followed by the forming press to form the lids and trays of galvanised steel for the floor panel. Subsequently, a pre-cut chipboard must be encapsulated with the galvanised steel in the assembly process, to satisfy the fire resistance requirements. As a result, manufacturing processes are complicated and tedious, which results in low productivity.

In contrast, the manufacturing of the floor panel developed in this research utilises the pultrusion method, which is faster than the traditional processing methods of floor panels, such as compression modelling. Moreover, because the panel surface is formed during the pultrusion process of the panel material without additional treatment being required, the outer layers are not needed for manufacturing, which simplifies the processes, and, hence, accelerates manufacturing and decreases the cost.

5.5. Fire Resistance

The fire resistance is important for flooring products as stated in the **EU/UK standards BS 476-4:1970 [16] and BS 476-6:1989 [17]**. Since the traditional chipboard material is not fire resistant, it has to be modified or improved by metal protections to meet fire resistance requirements; however, the weight and cost of the chipboard floor also increase. Compared to the traditional panel materials, the composite materials used in the new flooring product have the inherent advantage in fire protection.

The new floor panel meets the fire resistance standard [15]. The UL94 (Underwriters Laboratories) standard has been applied to check the safety of the flammability of plastic materials [18]. The composite material panel pieces used in this research have met Class V1 of the UL94 standard with the high-level rating ignition characteristics of plastic materials [21], and, hence, the floor panel complies with the fire resistance requirement.

The flooring panel developed in this research uses a glass fibre-reinforced polyurethane thermoset material. As most thermoset materials have similar characteristics in terms of fire resistance, the material used in the flooring product presented in this paper is not easily flammable, does not support the burning process, and the fire turns the thermoset material into char (it does not provide the fuel to the fire but just turns the material into char). Therefore, the new raised flooring product is fire safe.

Due to time constraints, we are unable to cover all tests in this paper. Further investigations will be conducted to confirm the material's characteristics, according to relevant standards, such as BS476, ASTM E119, ISO 834, or NFPA 251, and, if necessary, further work will be conducted in order to meet the standards.

6. Conclusions

A new type of raised access flooring product has been developed by this research to overcome the weight, cost, and handling problems of current raised flooring products. The performance of the product was assessed via life cycle assessment, finite element analysis, and experimental tests, indicating that the flooring product developed meets the requirement of raised flooring product standards as well as other prominent features.

The research made the following major contributions to the knowledge:

(1) Contribution to reduce the weight and cost of raised floor products. Currently, the raised floor products are heavy, which makes them difficult to handle and increases the transportation costs. To address this issue, a new type of raised floor product using a light composite material and design with a sole material is developed, which overcomes the weight problem of raised floor products. The assessment results show that the weight of the developed composite material panel is almost half the weight of the traditional chipboard material panel. Benefiting from the light-weight floor panel and simple design structure, less labour and manufacturing materials are required.

(2) Contribution to reduce the environmental impact. The LCA has been carried out to evaluate the environmental performance of the proposed raised flooring product. Overall, the proposed floor has lower environmental impacts than other products, i.e., the total impact of the proposed floor (F1) is 52% less than the cement floor (F2)

and 47% less than the woodchip floor (F3). Key environmental impact stages are investigated, which involve production, packaging, and transportation: (i) For F1 and F3, the production stage, including the material extraction and prefabrication, is considered a critical stage in the environmental impact of the entire life cycle. (ii) For F2, packaging and transportation are identified as the biggest environmental issue stages due to the improper selection of packaging materials. The environmental performance of F2 can be improved by the eco-design of the packaging. The LCA study indicates that, with the consideration of environmental issues at an early stage of product development, the proposed floor product embraced several eco-features which have proven to have superior environmental performance.

(3) Contribution to improve the installation and maintenance of raised access floors. The existing floor panels all consist of a single piece per panel which creates difficulty in handling and maintenance services [20]. The panel developed in this research breaks the single panel into six removable panel pieces, which are easy for workers to dismantle and install.

(4) Improvement in productivity and sustainability of raised floor products. Traditional floor manufacturing requires complicated processes, such as steel coil cutting, forming press, and assembly, which significantly affect the production efficiency of products. To address this, a rapid manufacturing method and design with a sole material are utilised for the new product, which accelerates production and simplifies the development process. In addition, the new product's stringers and pedestal are made of metal materials, which are easy for recycling and reuse, and polyurethane and glass fibre are used for the panel which do not contain chlorine, and hence there are no formaldehyde emissions.

This paper illustrates a novel instance of effectively integrating interdisciplinary methods and techniques in the development of raised flooring products. Through the utilisation of such flooring products, the environmental impact can be substantially reduced, consequently improving the overall environmental performance of a building. The methods developed in this research are valuable for sustainable product development, which is currently being further developed in the REBELION project [26] for the repurposing of second-life batteries.

As stated in the Section 5, the floor panel will be further tested according to the relevant standards, such as BS476, ASTM E119, ISO 834, or NFPA 251 [28], and, if necessary, further work should be conducted in order to meet the standards.

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Data Availability Statement: The raw/processed data required to reproduce the findings, such as experimental data and FEA results, are available from this paper. The design files include CAD drawings and the FEA model (see Figures 3 and 4, and Table 2) conducted in SolidWorks (Dassault Systèmes SolidWorks Corporation, Waltham, MA, USA) and experimental tests (see Figure 5) conducted via the Instron measurement system (Illinois Tool Works Inc., Crawley, UK). This work is licensed under the Creative Commons Attribution 4.0 International CC BY 4.0) License. To view a copy of this license, please visit https://creativecommons.org/licenses/by/4.0/ (accessed on 12 June 2024).

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Conflicts of Interest: Author Shuyi Wang was employed by the company CECEP Eco-Product Development and Research Center Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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