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Materials Selection for Sustainable Executive Aircraft Interiors

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This study proposes a methodological guide to explore and select materials for executive aircraft interiors, contributing toward a perspective of materials requirements, indicators and strategies to design more environmentally sustainable products. This was motivated by the signs from the aviation industry to reduce its environmental impact and the permanent need to push for cost efficiency. The guide includes a schedule framework of materials requirements for sustainable design, and also aeronautical materials and marketing requirements. It was prepared by mapping sustainability demands for materials selection during product development, supported by a case study. Patented eco-friendly materials solutions for the case study involving the aircraft furniture structural panels were described and analyzed, considering the materials requirements of the aeronautical project. Composites of bio-polymers reinforced with natural fibers, preferably with solid cores, seem to be the most promising solutions to substitute the current panels.

Keywords: *Aircraft interiors, Materials selection, Environment, Sustainability*

1. Introduction

The executive aircraft market is one of the most important segments of the Brazilian aeronautical industry, which is one of the four largest producers in the world[1].

In the executive jet manufacturing industry, the question of sustainability is not sufficiently clear, especially with regard to interior components where materials play an important part in product differentiation. The initiatives to reduce the environmental impact of interior components are the result of government regulations and laws that restrict the materials used. The solutions of the materials used so far have partially solved the problem and the aircraft users hardly ever notice these changes. The procedures are limited to developing material solutions such as water based coatings, low-emission tanning leather, wood veneers from quickly renewable species and the use of natural fiber fabrics.

The executive jet industry has also implemented particular product design and manufacturing practices to minimize the use of environmental resources, with additional cost reduction gains. In this aeronautical segment the cost reduction pressures are due to the strong and growing competitiveness in a relatively small market. The executive aircraft manufacturers and consumer markets are currently concentrated in North America and Europe, but tend to migrate to emerging countries in Latin America, Asia, Middle East and Africa, which have emerging aeronautical industries[1,2]. The current manufacturers, which dominate materials and process technology, will face competition from these new emerging players which also have technology and investment capacity.

It is in this scenario that the technological driving forces of the aviation industry will push for cost efficiency measures and for the reduction of environmental impacts[1-4]. Thus, greener interiors for executive aircrafts gain a competitive advantage as a possible marketing solution.

Most of the new materials currently developed and used to produce aircraft interiors have positive and negative impacts on sustainability and competitiveness. Balancing the properties of materials to simultaneously reach these aspects require better understanding the environmental issues of the material selection process in the product development.

The main decisions in materials selection are usually taken during the product design and have to meet the driving forces such as market demands, cost reduction, legal requirements and societal pressures for environmental sustainability[5-7]. However, there is still a lack of specific studies concerning the subject of aircraft interiors, especially regarding the selection of materials and processes in the context of product development methodologies, as well as sustainability concerns.

The objective of this study is to propose a methodological guide for selecting materials during the development of executive aircraft interior components based on relevant ecodesign strategies and indicators, as well as the critical materials requirements. It is expected that the proposed guide favors an environmental sustainability design while maintaining compliance with marketing and aeronautical demands.

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2. Literature review

Materials selection activities are in almost all product development phases[3,5-7], and concentrated in the preliminary ones in which the product concept is defined and its design is embodied and detailed. The environmental analysis of the product is usually applied during the phase of Embodiment and Detail of the design, which includes assessing the environmental impact and availability of raw materials, as illustrated in Figure 1. It also covers the final phases of product follow-up and product end-of-life to evaluate new materials requirements and executing the disposal plans. The main environmental analytical methodologies generally used are Life Cycle Assessment, Design for Environment, Ecodesign guides and materials selection tools such as Ashby Eco-Audits[8-13]. The materials selection in these phases is supported by environmental indicators.

The materials selection decisions should include the materials sustainability indicators and also the sustainability indicators of economic and social dimensions, taking into account how they influence the product in all life cycle phases, as shown in Figure 2. A single eco-indicator can also be developed for each evaluated material combining all the observed environmental impacts, but it is a challenge due to the complex interferences of the materials used at local, regional and global levels. This normally results in strategies for materials selection that prioritize how the materials impact in only some phases of the product life cycle, for example, the energy consumption impacts and carbon footprint in the Ashby Eco-Audits analytical methodology[8]. Strategies based on Ashby Eco-Audits may not be enough to evaluate the materials selected for products that generally use non recyclable materials and possible toxic substances such as the actual aircraft interiors. Considering environmental issues, materials selection for aeronautical interiors must also include indicators related to how toxic substances impact humans and the environment, as well as the pollution caused by product disposal at the end of the life cycle[14-16]. These complex human safety and environmental issues have to meet chemical product restrictions[17] and regulations for the disposal of products[18-20].

Most of the ecodesign strategies usually chosen for product design directly affect the materials selected, as shown in Table 1. There is a positive relation between product sustainability improvements and manufacturing optimization practices focused on costs reduction, which are frequently limited by the materials initially chosen during product development [4,21,22].

The leading commercial aircraft manufacturers have adopted ecodesign practices and guides that normally emphasize environmental conservation efforts by the optimizing natural resources, water, energy and materials use, in addition to minimizing waste production[14-16]. They also consider the reduction or elimination of materials used for building aircrafts or support during the production processes that include intrinsically toxic properties, which are hazardous to the health and safety of people, and to the environment. Sustainable concepts, technologies and materials for aircraft interiors[23,24] have been developed, although it is still not clear how they are relevant to developing a product with reduced environmental impact and economical benefits due to their compliance with regulatory restrictions.

The interior components such as ceiling, sidewall, furniture, floor and seating are predominantly composite structures. They are composed of a structural material fastened with adhesives and metallic parts, and finished with different materials such as lacquers, paints, wood, synthetic laminates, fabrics and leather.

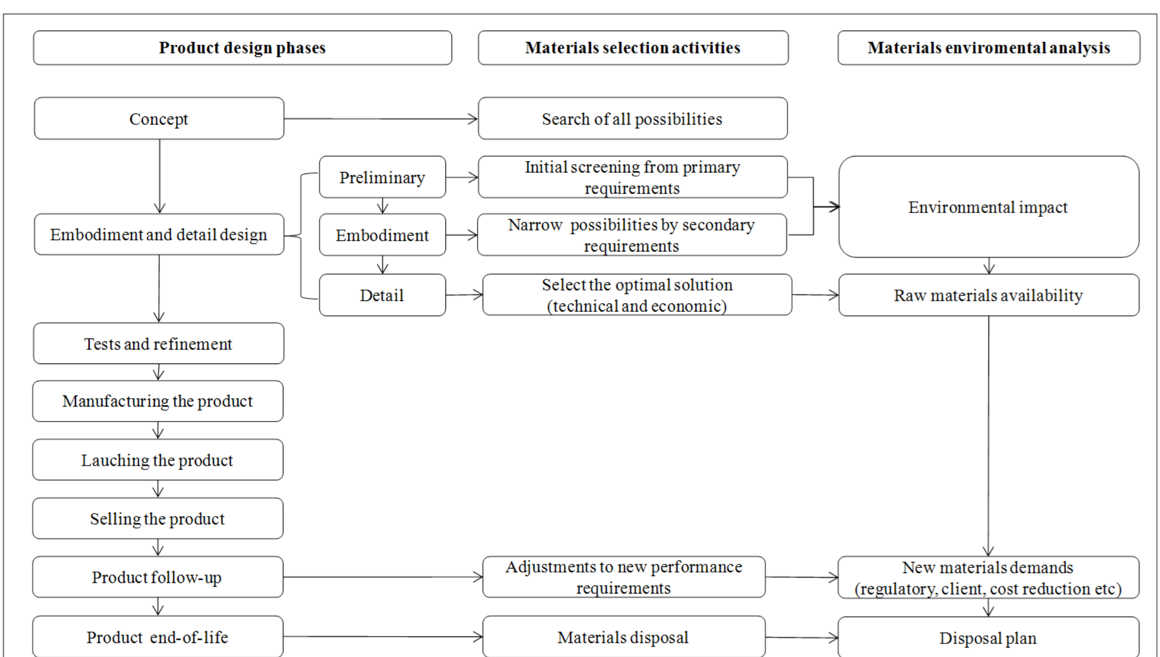

Figure 1: Selection activities and environmental analysis of materials in the product design[3,5,6-13].

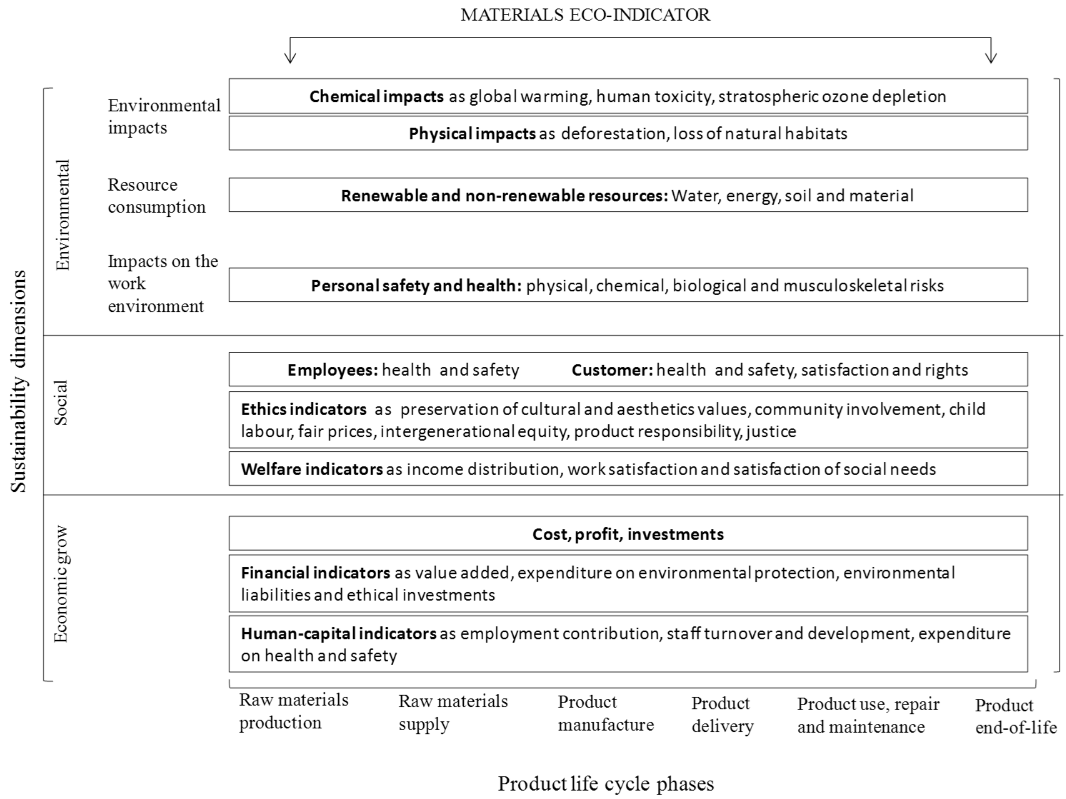

Figure 2: Materials eco-indicator determined by its impact on the product life cycle phases[8,12,47,48].

The selection of materials is generally restricted to those that have a consolidated use, based on strict technical and aeronautical regulations related to fire and smoke resistance, low density and other specific requirements[3,28]. Table 2 shows the materials currently selected to manufacture interiors of executive aircrafts. Although the importance of eco-friendly design and materials is recognized, there is a lack of systematic studies on the environmental issues regarding these materials, and also methodologies to support the product development of aircrafts.

3. Materials and methods

To propose a methodological guide to select materials during the development of components for executive aircrafts, taking into account the environmental issues and the aeronautical and marketing requirements, the following steps were executed:

1- A case study was carried out to fully understand and identify relevant ecodesign strategies, materials requirements and definition of potential eco-indicators for the sustainable design of aircraft interiors;

2- A methodological guide was proposed for the selection of materials, based on materials requirements and indicators for a sustainable design highlighted by the case study, in addition to aeronautical and marketing requirements.

The information was collected from field survey and documentary research. The field survey covered interviews with specialists in the areas of Marketing, Purchasing, Design, Product Design, Materials and Manufacturing Engineering, with experience or relevant knowledge on executive aircraft furniture, in order to identify the factors influencing the decision regarding the materials to be used in the aircraft interior design. The documentary research comprised the relevant technical and scientific publications available in the data bases Web of science, Scopus and Engineering Village, in the bibliographic patent publications data bases Derwent and Espacenet, and the books written by respected authors in the areas of materials selection and product design. It was complemented by available information in the supplier's materials catalogues, web sites of executive jet manufacturers and associations, and also in university thesis and dissertations databases and documents.

The material component selected for the case study was a honeycomb sandwich panel used to produce aircraft interior furniture such as cabinets, doors and dividers. The honeycomb panels represent more than 90% of the total volume of materials used to build the furniture items, which represent a key differentiation in executive jets compared to other aircraft categories. The configuration of these panels is produced from an aramid honeycomb core facing with phenolic and/or epoxy resins, reinforced by glass fiber[29, 52], as shown in Figure 3. These panels are commonly used by interior aircraft manufacturers. They are also essential to the functional performance of the furniture items.

Table 1: Product sustainability strategies that affect materials selection in product design.

Design strategies for product sustainability improvement that influence material choices	Approach techniques references	Ref
Related to reducing resource consumption:		
- Dematerialize products and components	Ecodesign or Design for Environment	8, 13-16
- Reduce amount of materials in the product (reduce material types, thickness of components, integrate functions, combine properties)		
- Reduce materials and energy necessary to use, manufacture, maintain the product		
- Select local materials		
- Select materials which low energy consumption for primary production	Design for Manufacturing and Assembly	21, 26, 46
- Select materials which low CO_2 footprint for primary production		
- Select materials which low water consumption for primary production		
- Reduce energy for transportation and storage of materials		
- Optimize logistics by supplier chain engagement with environmental strategy		
- Minimize production phases	Lean Manufacturing	22
- Select materials to best suit each processing operation		
- Minimize, reuse and recycle production scrap and residues		
- Avoid Packing during product production		
- Reduce energy for production process and select local energy sources		
- Optimize energy use in the production buildings		
- Use recycled processing materials		
- Reduce use and quantities of processing materials and consumables		
- Use processing and consumable materials from renewable sources		
- Remove process waste related to:		
- Defects: that produces scraps		
- Over production: that produces scraps and increase the inventories;		
- Inventories: that produces scraps and consumes stock area and energy;		
- Over processing: that consumes more materials and energy		
- Transport: that consumes more energy		
- Waiting: that produces intermediate stocks and use area, energy and may produce scraps		
- Remove or minimize processing activities required by the actual technological level but that do not add value from the customer point of view and consumes more materials and energy.		
- Reduce energy for product transportation and storage		
- Minimize the quantity of material in product packing		
- Optimize materials and energy consumption during the product usage and maintenance		
Related to reduction of environmental impacts:		
- Avoid using toxic materials in all product life phases		
- Avoid materials that cause depletion of ozone layer and/or global warming		
- Avoid materials with problematic origin (such as deforestation wood)		
- Use recycled, renewable and/or bio-compatible materials		
- Use raw-materials produced from renewable and environmentally compatible energy resources		
- Transport raw-materials to the use point using renewable and bio-compatible energy		
- Extend the product lifespan:		
- Design to improve the reliability, durability and functionality.		
- Use well tried and tested materials for a product with high level of reliability		
- Facilitate upgrading, adaptability, maintenance, repair, reuse, remanufacturing		
- Extending the lifespan materials:		
- Select materials with efficient recycling technologies		
- Facilitate material recycling		
- Facilitate the product end-of-life collection and transportation		
- Minimize different incompatible materials and avoid inseparable composite materials		
- If fasteners cannot be eliminated, minimize and standardize them.		
- Avoid pigments, additives, materials with unknown composition and substances that interfere with the recycling process		
- Avoid processing materials that cause depletion of ozone layer and/or global warming		
- Avoid production of hazardous waste in the process stages		
- Use renewable and bio-compatible energy to manufacture the product		
- Eliminate the source of environmental issues instead of setting up end of pipes treatments in the manufacturing		
- Product delivery using renewable and bio-compatible energy		
- Avoid toxic materials for use, repair and maintain the product		
- Avoid materials that need hazardous waste disposal		
- Ensure easy removal of hazardous material for product disposal		
- Reuse, re-engineer, recycle rather than landfill or burn for heat recovery		

Table 2: The main materials currently used to produce aircraft interiors.

Material use	Materials for typical interior components	References
Interior structures	Ceiling and sidewall: • Phenolic resin panels reinforced with glass or carbon, in solid structures or with honeycomb aramid fiber paper core	28
	Furniture (cabinets, doors and dividers) and floor structures: • Honeycomb sandwich panels: - Facing materials: aluminum alloy, epoxy or phenolic resin reinforced with glass, carbon or aramid fibers - Core materials: aluminum alloy, aramid fiber paper in a honeycomb structure - Edge filling and reinforcing resins: epoxy based	25,28,29
	Seating structures: • Aluminum alloys • High temperature thermoplastics as polyethersulfone and polyphenylsulfone, glass or carbon fiber reinforced	30
Structural jointing	Union of structural components: • Epoxy adhesives • Aluminum and steel alloys (painted, chromed, anodized, gold plated)	31-34
Finishing of structures	Ceiling, sidewall, furniture and seating covers: • Cotton or wool fabric, natural or synthetic leather • Decorative thermoplastics such as polyvinyl chloride and polyvinyl fluoride • Wood veneers and hardwood covered with polyurethane, polyester or acrylic lacquers • High pressure laminates (decorative paper treated with melanin resin on kraft paper sheets impregnated with phenolic resin) • Water or solvent based polyurethane paints • Polyethylene and polyurethane foams Flooring covers: • Nylon and wool carpets, polyvinyl chloride base sheets • Stone veneers	28, 35-44
Paste the finish	• Epoxy, polyurethane, resorcinol or neoprene adhesive systems, water or solvent based	25,29,31,45

Main source: Committee of fire and smoke resistant materials for commercial aircraft interiors, 1995[28]

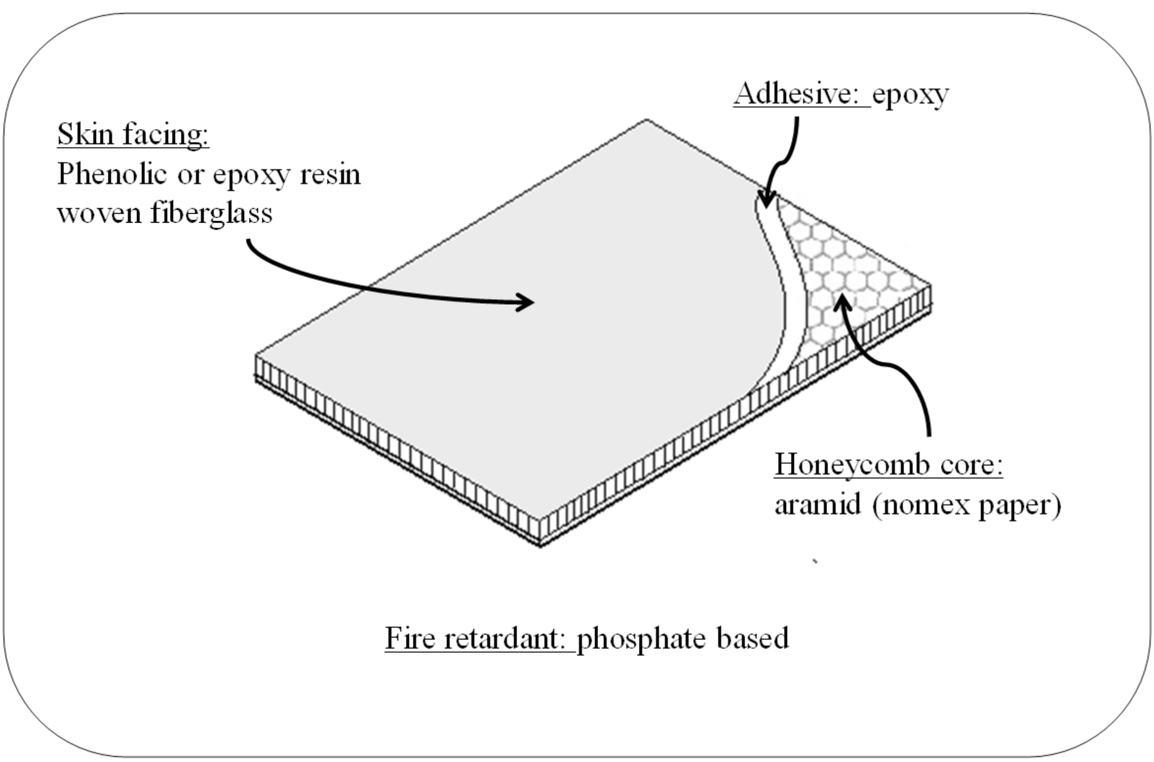

Figure 3: Honeycomb sandwich panels used in the case study.

To understand and identify the relevant ecodesign strategies and materials requirements, the case study was based on the mapping of the sandwich panels route through the furniture life cycle and the main concepts reported in the literature about Ecodesign, Design for environment, Design for manufacturing and assembly, and Lean manufacturing.

4. Results and discussion

4.1. The honeycomb sandwich panel life cycle route in executive aircraft interiors

Figure 4 illustrates the honeycomb sandwich panel route analysis, from the raw materials used to produce the furniture, until their disposal at the end of their life cycle, indicating design strategy opportunities to select more sustainable materials for interior components, as follows:

A) Opportunities related to materials properties:

A1) Reduce or eliminate using materials or substances hazardous to humans and to the environment

A2) Reduce loss of materials and emissions in the manufacturing process

A3) Reduce infrastructure for the material use in manufacturing process

The honeycomb sandwich panels are produced with thermosetting resins that use toxic chemicals and precursors such as phenol, from non-renewable sources. The materials components, although inert in the composite, release hazardous dusts during the furniture manufacturing process in the milling, drilling and sanding activities[25]. These dusts cause skin irritation and respiratory problems if inhaled, and chronic lung disorders with prolonged exposure[52]. Therefore, the use of these materials in the furniture plants, besides requiring the monitoring of human health and use of personal protective equipment, requires special infrastructure in the manufacturing process to collect and dispose of the insalubrious dust. These infrastructures increase energy consumption and CO_2 emissions in the cabinet production system not directly associated to the transformation process, affecting the environmental performance of the product.

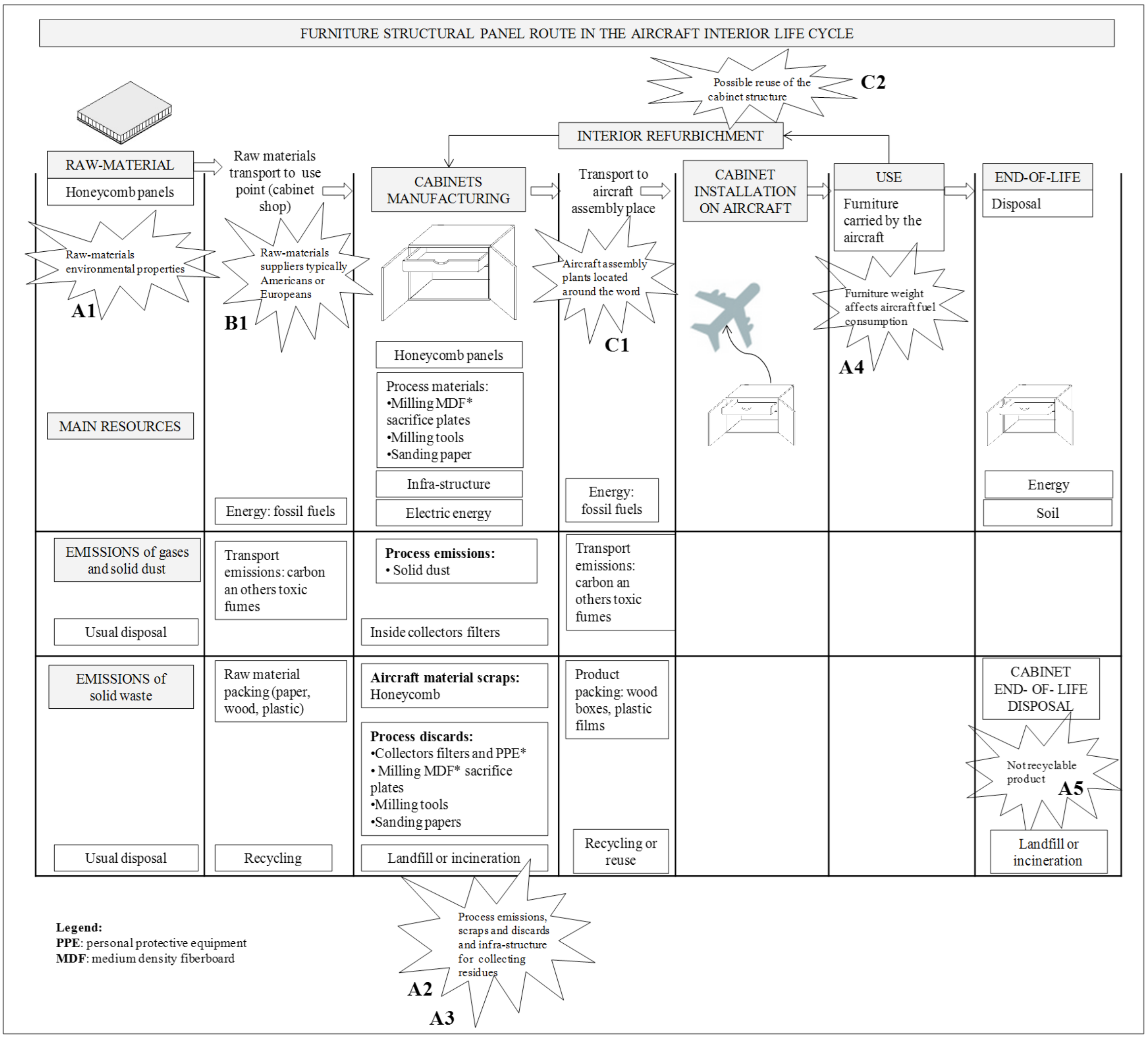

Figure 4: Honeycomb sandwich panel route analysis in the aircraft interior life cycle to produce environmentally friendly furniture.

A4) Use more lightweight materials to minimize aircraft fuel consumption during the product use phase

Weight is one of the most important properties in aircraft design as it affects fuel consumption when the aircraft is flying, consequently more resources used and more pollution[15]. The aircraft's environmental impact in flight represents about 90% of total impact considering the other product life cycle phases due to fuel consumption[49].

A5) Improve end-of-life product disposal

Regarding the disposal of manufactured sandwich panel scraps, and the end-of-life product, the current practice is landfill or incineration, since it is almost impossible to recycle these materials due to its properties.

Notwithstanding the disposal and recycling difficulties related to the use of this type of sandwich panel, its use in aircraft components have been justified by the long life of the product, produced in relatively small numbers[8,50,51], and by the panels lightweight properties.

B) Opportunities related do materials provisioning:

B1) Materials availability and transportation to the plant where they will be used

Regarding the transportation of raw-materials to the use point, most raw-materials manufacturers and suppliers are located in North America or Europe, where the leading aeronautical companies such as Boeing and Airbus are installed. This affects mainly the interior manufacturers not located in North America – Europe axis[14], whose production will require more energy consumption and will release more carbon dioxide to the atmosphere. In addition, material availability is also impacted by the substantial volumes of materials used by the biggest aeronautical companies, which will affect the offer, demand and cost of materials. Furthermore, local suppliers may be particularly relevant to interior manufacturers located outside North America – Europe axis with the possibility to reduce environmental impacts due to the transportation of materials and social benefits by developing local communities.

C) Opportunities related to materials use:

C1) Improve product construction techniques imposed by material properties, which affect the transport of the finished interior to the location where it will be installed in the aircraft in terms of packaging and transported volumes

The most common way to use the sandwich panels to manufacture the aircraft interior cabinets is finalizing the assembly at the plant and transporting big volumes to the location where it will be installed in the aircraft. Since the aircraft production is globalized, big volumes of interior parts are transported across continents. This strategy to produce and transport the cabinets impacts the logistics and energy costs, and also the use of material packaging. Panel joint solutions, strongly related to the composite material properties and structure, could allow using manufacturing and assembly solutions to produce all parts separately and then transport to the client for the on-site assembly, like that used by the residential furniture industry.

C2) Encouraging furniture refurbishing practices

Interior refurbishing is a common practice for executive aircrafts owing to aesthetical obsolescence and wearing out, which occurs within a twenty year period in the average life cycle. This practice could be made easier if the furniture components use materials and manufacturing techniques that facilitate the removal and replacement of finishing materials, retaining the interior structure, thus extending the interior life-time and minimizing the impacts related to the use of composite materials.

The other materials used to produce aircraft furniture (the jointing and finishing materials), and interior components (as ceilings, sidewalls, floors and seating), shown in table 2, have similar properties to the structural panels in terms of the presence of hazardous substances in the composition, production from non-renewable sources, recycling difficulties and use of manufacturing techniques. These similarities allow expanding the use of identified product design strategies from the case study to the interior components.

These product design strategies translated to materials selection requirements and indicators can be used in the first product development phases to survey and select alternative materials.

Table 3 shows the results of these strategies converted into materials requirements and indicators to explore and select materials in the design of sustainable interiors.

Most of the eco-friendly materials solutions for aircraft interiors found in patent documents seem to be focused on compliance with environmental regulations. For example: a) replacement of blowing foams agents with ozone depletion potential[54]; b) elimination of halogenic compounds in fire-retardants and polymers[55]; c) elimination of hydrogen-chloride group gases during the incineration or disposal of decorative sheets[56], and; d) elimination of chromates in paints and coatings[57].

Decorative sheets with reduced emission of volatile organic compounds that improve cabin air quality[58], and production of synthetic leathers, foams and insulators with less organic solvents[59-61], also have been patented at the last ten years. In this most recent period, solutions focused on the incorporation of natural fibers to reinforce polymers, and in the application of bio-plastics to produce composite panels also emerged[62-66]. It agrees with the global tendencies to reduce the dependence on non-renewable material sources and worries about materials recycling encouraged by environmental regulations. In the aerospace industry, programs focused in aircraft recycling are conducted since 2006-2007[18-19].

Specifically for the current panel skins of phenolic and/or epoxy resins, glass fiber reinforced, there are, for example, the following patented solutions: a) substitution of glass fibers to natural fibers, as coir fiber[63]; b) phenolic resins with low free formaldehyde and phenol[64], and; c) polyamide base bio-plastic reinforced with castor plant fibers[67].

Table 3: Exploring materials requirements and indicators to design sustainable aircraft interiors, from mapping strategies.

Design strategy	Materials requirements	Possible materials indicators
A1	Non hazardous (Supported by laws and regulations)	Toxicity
A2	Raw-material shape near to the final shape of the product Reduced emission of dust during mechanical working	Efficiency of materials used: • % of raw materials converted to product Materials energy requirements: • Energy consumed for direct processing of raw-materials x energy consumed for containing and disposing residues • % of energy used from renewable sources
A3	Non specific infrastructure demands for raw material processing	Materials infrastructure costs needed for manufacturing
A4	Low weight	Density
A5	Materials recyclability potential for the product	Amount of materials waste recycled
B1	Use of local materials	Materials energy requirements: • Energy consumed to transport materials to the use point • % of energy used from renewable sources
C1	Materials joining techniques that allow to assemble the interior components at the location where it will be installed in the aircraft	Materials energy requirements: • Energy consumed to transport product to the use point • % of energy used from renewable sources Materials packaging requirements: • Volume and type of packaging materials used
C2	Materials reuse potential for the same use	Amount of reused materials

The two first solutions keep the current materials concept and improve the sustainability by adding a natural material, or reducing the toxicity of the synthetic material. However, they do not solve the issues regarding the material recyclability and end-of life disposal. The third patented solution is more promising in all environmental aspects, since it proposes to reduce the dependence of non-renewable material sources, and to be biodegradable and no-toxic. And it can be combined with solutions for sustainable honeycomb cores as cellulose paper honeycomb[68], as alternative to the current aramid honeycomb cores.

However, the panel solutions should be validated with the aircraft interior project requirements. The main ones are flammability, strength and stiffness, low weight, and resistance to the aircraft environmental operations conditions along the product life cycle (temperature, humidity and pressure). The panel is also required to be physically and chemically compatible with finishing materials, and with joining materials and techniques.

Another important concern involving the use of the natural materials is their tendency to absorb water, mainly the ones containing cellulose in the composition. Make these materials more resistant to water is important do reduce infrastructure energy costs to keep them stable during the manufacturing process. This is also important to avoid product defects as warping, cracks and detachments of finishing materials[69].

The use of natural materials for the aircraft interior application should also consider how to stabilize chemical composition variations, since they can affect the reproducibility of flame retardant properties.

Other promising environmental solutions covering the panel skin and cores, but that also require validation, are the sandwich honeycomb panels produced from polylactide or polylactic acid or corn starch[65], and a balsa wood plate-shaped element with fiber composite reinforced faces[70] There are also the composite solid panels with core and faces of biopolymeric resin containing fibers[66].

Although there are probably material weight concerns of using solid panels, they have the advantage of reducing or eliminating the use of the epoxy resins to reinforce honeycomb panels areas to attach metallic joining elements as inserts, hinges and latches. There is also the advantage of reducing or eliminating the resins use to fill the exposed honeycomb cores on the edge of the aircraft parts.

The resin parts edge filling is a process step required to apply finishing materials as paints and laminates. It can be bypassed through the insertion and gluing of plastic or wood edge close-out elements [25, 71]. However, the available materials for edge close-out are not always adequate to project aesthetic requirements.

4.2. Proposal of a product development guide to select materials for sustainable aircraft interiors

The materials selection process to design an environmentally friendly product requires specific analysis in almost all product development phases, as shown in Figure 5.

In the **Concept phase** of product design, an environmental mapping is suggested to the materials survey, and also to verify environmental regulations and restrictions for the use of materials in countries where the aircraft will potentially be sold and used. Applying a mapping strategy, which can be performed along the lines of that applied in the case study, is the basis for identifying product design strategies to be extended in materials requirements and indicators for the following product design stages. Besides the environmental analysis, the materials survey must also be performed considering a customer analysis. The executive aircraft client analysis should focus on aspects related to the

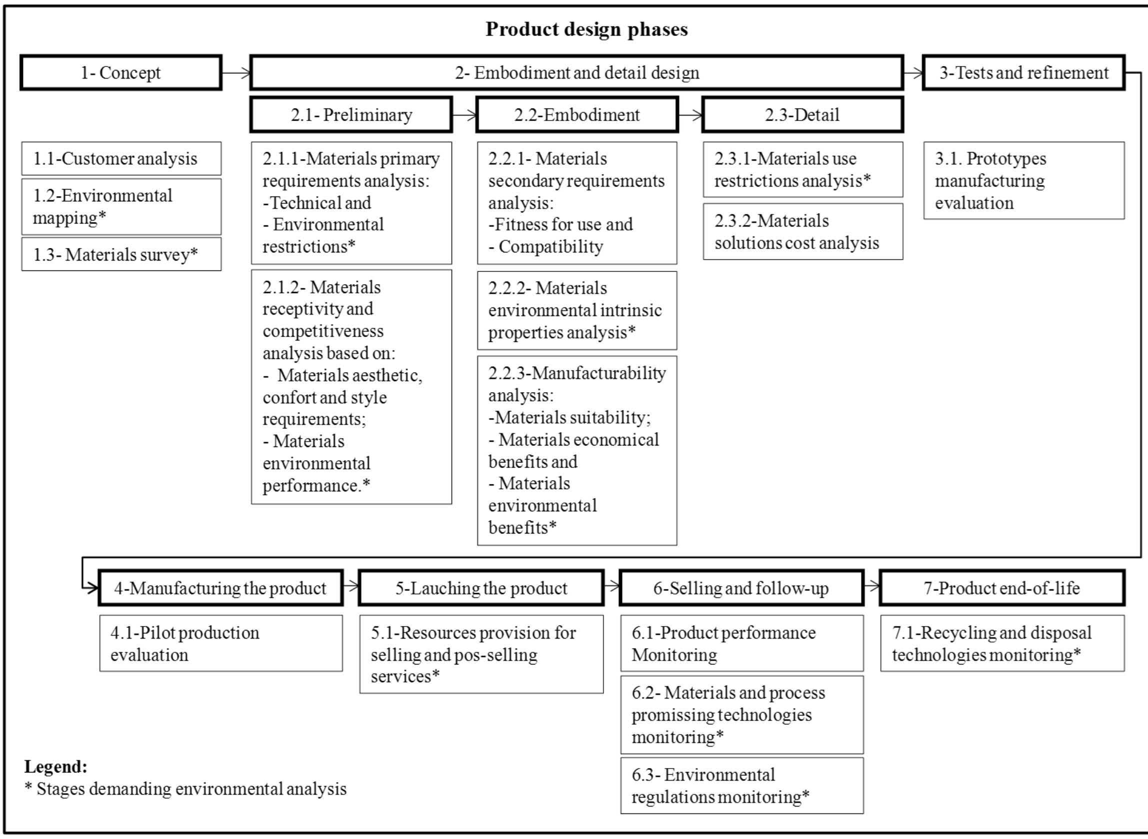

Figure 5: Roadmap of materials selection needed in product development for environmentally friendly design.

aircraft size and use, cultural and regional aspects and the tendencies of products and settings used by the clients. These aspects will be used to determine the relevance of materials requirements such as robustness, durability, functionality, aesthetics, personalization, comfort, and environmental concerns. The Concept activities can be implemented, as shown in Appendix A, to identify materials requirements and to survey materials possibilities.

In the **Embodiment and Detail design** of product development, the analysis of materials primary requirements is proposed at the **Preliminary stage**, including environmental regulations and aeronautical design such as aircraft flammability and structural certification, as shown in Appendix B. Then, from the materials selected, the next choices should evaluate materials receptivity and possible competitive differentiation considering environmental benefits required by regulations, in addition to aesthetics, comfort and style issues.

In the second **Embodiment stage** shown in Appendix B, the materials selection activities should consider the analysis of aeronautical secondary design requirements (for example, substrate-adhesive physical-chemical compatibility) followed by environmental issues. The environmental analysis in this phase should comprise materials requirements such as those for the honeycomb case study shown in Table 3, including non-hazardous, low weight and recyclability/reuse potential, besides environmental improvements during manufacturing. The manufacturing can be improved by reducing the materials used (aircraft and consumables), reducing the use of energy and water, reducing costs and investments in infrastructure, reducing costs to monitor and conserve worker´s health, as well as reducing the need of process scraps and residues disposal.

In the **Detail stage** of the Embodiment and Detail design step shown in Appendix B, the environmental analyses are related to the company's external and internal setting. The evaluation of the external setting should comprise the use of restricted materials related to world market, materials availability and supply conditions in terms of distances (affects energy consumption and carbon emissions) and development possibilities of local suppliers (that affects the social dimension of sustainability). The internal setting should evaluate the experience of the materials used to avoid losses due to low reliability of the manufacturing process and of the product.

Considering the materials foreseen in the product Concept phase, it is believed that most of them will not meet all the main project requirements of the aircraft interior. Then, an environmentally friendly product design should consider investments in materials development. Other investments should be in collecting and organizing non-existing or available information about the environmental performance of these new materials formulated for the aeronautical area, and for those currently used, to compare alternative solutions.

Adapting technologies and materials to the aeronautical context should include identifying organizations and suppliers that have the knowledge and background regarding eco-efficient product development. Thus, considering the complexity of the subject matter and the level of product globalization, the structuring of consortiums among manufacturers and suppliers is seen as achievable to develop and make available sustainable technologies and materials for aircraft interiors[23,24], such as the earlier studies regarding alternative solutions to recycle aircrafts at the end-of-life, PAMELA[18] and AFRA[19].

Notwithstanding the initiatives to build sustainable aircraft interiors with positive impact in terms of competitiveness and attractiveness, and the technologies developed to reduce aircraft fuel consumption, the executive aircraft will continue to be a product of high fuel consumption per capita during the use phase. And minimizing the impacts in this area should occur through emission compensation actions financed by the aircraft owners[53].

The next product design phase for environmental issues regarding materials selection should be the **Launch of Product**, after the Tests and Refinement, and Product Manufacturing, as shown in Appendix C. The launched product should have environmental appeal and be easily to refurbish. The maintenance and repair of interior parts should be simple to perform, consume few resources and use environmentally friendly materials and procedures. If strategies such as carbon emission compensation during product use are offered to the clients[53], it should have a structured program.

In the **Product Selling phase** shown in Appendix C, materials use should be monitored to anticipate any adjustments required by environmental regulations. In this product design phase, and in the next **Product end-of-life**, materials and process technologies that were disregarded during the materials selection process, because they are not sufficiently mature or not applicable for aeronautical use, may be evaluated for possible implementation during the serial production phase. These improvements could be performed to increase environment performance, differentiation or profits.

Additionally, the Product end-of-life phase will require an organized network of receivers of discarded products, as well as interior disposal procedures.

5. Conclusion

This study proposes a methodological guide to explore and select materials for executive aircraft interiors, and strategies, materials requirements and possible indicators for the design of a more sustainable product. Some of the development strategies regard solutions based on light, non hazardous materials, that use a percentage of recycled raw-materials, compatible with the environment, from renewable sources, produced by local suppliers and that result in simple refurbishing practices. Other strategies include manufacturing technological solutions that produce low quantities of scraps and residues, and others which will enable improving the transport of the aircraft interior to the place where it will be installed in the aircraft. Materials toxicity, density, recyclability and reuse potential, energy use efficiency and resource requirements for supply and processing, seem to be the most relevant indicators to be considered during the design of interior components.

Promising materials solutions covering the sustainable indicators for the current honeycomb panels seem to be the bio-polymers composites reinforced with natural fibers, and with solid cores. However, these solutions need validation on the aircraft interior project mainly concerning the materials properties related to flammability, strength and stiffness, low weight, moisture resistance, durability in the aircraft operation conditions, and compatibility with de adjacent materials.

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Appendix A: Activities in the Concept phase of the product development guide to select materials for sustainable aircraft interiors.

Activities in the Concept phase
Customer analysis
A1) Determine the purpose of aircraft use.
A2) Determine aircraft operators.
A3) Determine aircraft category based on its weight, size or range, and average flight duration.
A4) Determine aircraft world region use and cultural aspects of potential clients, to whom the materials should reflect values, perceptions, and quality concepts.
A5) Verify material tendencies in residences, work places, leisure and transport used by the potential clients.
A6) Verify material settings used in competing aircrafts of the same category, to identify competitive differentiation opportunities.
Environmental analysis
A7) Verify environmental regulations and restrictions for materials use in countries where the aircraft will potentially be sold and used.
A8) Map current product systems for aircraft interior to analyze all life cycle phases, comprising economical and environmental issues.
A9) Define targets and strategies for the product from identified restrictions (A8), and other benefits associated to economical and social issues. Define materials requirements and indicators.
Materials survey based on customer and environmental targets
A10) Materials forecasting based on customer definition, identified tendencies, and environmental targets.

Appendix B: Product development guide to select materials for sustainable aircraft interiors in the Embodiment and detail design phase.

Embodiment and detail design phase		Materials requirements	
Phase	**Activities**	**From aeronautical project and clients**	**For sustainable design**
Preliminary	• **A11) 1st Filter:** primary technical requirements and environmental regulations	• Flammability. • Structural certification	• Meet environmental regulations in the countries where the product will be manufactured and sold
	• **A12) 2nd Filter:** materials receptivity and product competitive differentiation; including environmental issues	• Aesthetics, comfort and style	• Environmental appeal for competitiveness and client receptivity
Embodiment	• **A13) 3rd Filter:** secondary requirements of aeronautical design, specifically for materials use, and materials compatibility	• Resistance to: cleaning products and foods, abrasion, U.V. radiation, wear, humidity and temperature variations during aircraft operation	-
	• **A14) 4th Filter:** environmental properties of materials and effect of the materials on the weight of parts	-	• Non hazardous • Environmentally friendly disposal • Low weight
	• **A15) 5th Filter:** manufacturability of parts/ components from selected materials, and their environmental and economical benefits	• Promote a good product and process performance • Promote optimized and profitable manufacture	• Promote environmentally friendly manufacture (ex: reduced raw-materials loses, low hazardous emissions, low infrastructure demands)
Detail	• **A16) 6th Filter:** materials use restrictions	• Materials availability and timely supply conditions • Know-how and existing infrastructure for materials use	• Materials provision from local suppliers
	• **A17) 7th Filter:** detailed solution cost	• Project cost limit	-

• Detailing of activities:

A12) Verify materials receptivity and competitive differentiation, considering aesthetics, comfort and style issues, and environmental performance targets.

A13) Verify materials compliance to the aeronautical design secondary requirements: specifically for applications and materials compatibility.

A14) Evaluate environmental properties of materials related to toxicity, weight, disposal of scraps and residues generated during the manufacturing processes, recycling possibilities at the product end-of-life.

A15) Evaluate the ability to manufacture the parts/components from the selected materials and process, and the environmental and economical benefits of their use.

A16) Evaluate conditions to use pre-selected materials and process from experience, availability, materials supply logistics, possibility to develop local suppliers and infrastructure for product manufacturing.

A17) Detailed cost solution and verification according to the project budget.

Appendix C: Product development guide to select materials for sustainable aircraft interiors in the design phases of Tests and Refinement, Manufacture, Launch, Sell and Product End-of-life.

Product design phase	Activities	Materials requirements:	
		From aeronautical project and clients	For sustainable design
Tests and refinement	• Manufacturing evaluation of prototypes	• Promote product reliability and sturdiness for aircraft use conditions, desirable aesthetics and comfort and certification	-
Manufacture	• Pilot production	• Promote process capability	-
Launch the product	• Resources provision for selling and pos-selling services	• Have competitive appeal • Promote easy maintenance and repair	• Environmental appeal • Easy refurbishing
Product selling and follow-up	• Monitoring product performance • Monitoring promising technologies of Materials and processes • Monitoring environmental regulations	• Maintain competitiveness	Maintain environmental performance
Product end-of-life	• Encourage and facilitate reuse of materials • Monitoring recycling technologies	-	• Extend materials life cycle • Environmentally friendly disposal