Designing Sustainable Furniture Systems - The knowledge base and know-how for Furniture Product and Product-Service System Design for Environmental Sustainability

Dongfang Yang

Supervisor: Prof. Carlo Vezzoli

Co-supervisor: Prof. Francesco Scullica

Politecnico di Milano

March 2024

Acknowledgment

I would like to express my gratitude to the people who accompanied me during this research journey.

First of all, I would like to thank Carlo, for his insightful guidance and his invaluable support throughout this research. His enthusiasm and contribution to design for sustainability community, his efforts to his lectures, his social concern for non-privileged people/community, affect me a lot, and encourage me to be a researcher, a teacher and a mentor like him.

I would like to thank my co-supervisor, Francesco, for his support, insights, and discussions during the research.

I would like to thank the people who were engaged in the GIOTTO project, Carlo, Francesco, Lena, Luca, Alfonso, Lara, and Mariah, for their knowledge contribution.

I would like to thank all reviewers through the research for their insights and encouragement, a special thanks goes to Maria, Lucia, and Cindy, for their constructive comments and precious advice.

I would like to thank people who contributed their insights and knowledge on sustainable furniture system design and this thesis, especially, Diane, Atle, Laura, Pål, Svein-Erik, Dominique, Shuai, Mengmeng, Fangyuan, Aguinaldo, Jun Zhang and his energetic group, Hang, Alessandra, Ning, Luoheng, Martina and many others during interviews.

I would like to thank my family, my friends, and Zhao for their continuous support, encouragement, trust, and companionship during this long and meaningful journey, which means a lot to me.

Table of Contents

Summary

It is widely acknowledged that the furniture production and consumption system have a significant environmental impact and is one of the key sectors for improving sustainability. However, there is a lack of comprehensive, scientifically based, furniture-specific knowledge base and know-how, including a theoretical framework, approaches, guidelines, methods, and tools to guide the furniture industry toward sustainability. A growing international scientific community is working to fill the gap. This Ph.D. research is framed into this research area, focusing on product eco-design (or better Life Cycle Design (LCD)) and Sustainable Product-Service System Design (S.PSSD). The LeNS network[1], which connects nearly 150 design Universities distributed worldwide, is the primary scientific community for reference. The research aims to develop a furniture-specific knowledge base and know-how to support the diffusion of Sustainable Furniture System Design (SFSD).

Introduction (Chapter 1-2)

Sustainable development refers to systemic conditions where, on a planetary and regional level, both social and productive development takes place (i) respecting the limits of environmental resilience, i.e., within its capacity to absorb the effects of human impact without causing any irreversible degradation; (ii) without compromising the ability of future generations to meet their own needs, i.e., preserving resources, or natural capital, which will be passed on to future generations; (iii) on the grounds of equal redistribution of resources following the principle that everyone has the same rights to environmental space, i.e. the same access to global natural resources (Vezzoli, Conti, et al., 2022). The 2030 Agenda for Sustainable Development announced 17 Sustainable Development Goals (SDGs) as a shared blueprint for sustainability in three dimensions- economic prosperity, social equity and inclusion, and environmental protection (United Nations, 2015). However, much evidence indicates that our current growth is incompatible with these SDGs considering the environmental aspects.

Overproduction and overconsumption on the system level, as well as the heavy environmental impacts of a single piece of furniture on the product level, are among the environmental challenges for the furniture sector. According to the estimation of Centre for Industrial Study (CSIL), On a global scale, the furniture industry has doubled its volume from 2000 to 2021, reaching a worldwide volume of about $500 billion, which

[1] Learning Network on Sustainability, is an international open and multipolar network to diffuse Design for Sustainability.

is seeing an increase in the next year (CSIL, 2021), resulting in significant resource consumption, harmful emissions, and waste generation. For example, each year, 10.5 million tons of furniture are produced, and 10 million tons of furniture waste are generated, accounting for more than 4% of municipal solid waste in the European Union (Forrest et al., 2017). These impacts, among others, could also be seen throughout the furniture's life cycle, during pre-production, production, distribution, use, and disposal (González-García et al., 2019). As a result, furniture has recently been identified as one of the key sectors that should be addressed and improved to achieve more sustainable development (European Commission, 2020).

The design was recognized as a significant area in the transition to more responsible and sustainable production and consumption models (Bhamra & Hernandez, 2021). To be specific, more than 80% of a product's environmental impact is determined at the design stage (Design Council, 2022; European Commission, 2020), it is necessary to change the way we think about products, processes, or services from the earliest stages of design (Barbero & Ferrulli, 2023). Actually, The focus of Design for Sustainability has expanded the level of innovation from low-impact material and energy selection to product design[2], to Product-Service System design[3], to Spatio-Social innovation[4], and more recently to socio-technical systems innovation[5] (Ceschin & Gaziulusoy, 2019). On the other hand, DfS has expanded its scope from the environmental dimension of sustainability to the economic one to the socio-ethical one[6] (L. I. Chaves, 2018; Vezzoli, Conti, et al., 2022). Referring to the Design for Sustainability (DfS) framework, this research places its emphasis on the environmental and economic dimensions of sustainability. It addresses these dimensions at two crucial levels: the furniture product level, which includes aspects such as Life Cycle Design (LCD) (or eco-design[7]), and the innovation level involving furniture Product-Service Systems (Sustainable Product-Service System, S.PSS). It is

[2] The product innovation level focuses on improving existing products or developing new products by considering the whole product life cycle, from material extraction to disposal (Ceschin & Gaziulusoy, 2019).

[3] The product-service system innovation level focus goes beyond individual products towards integrated combinations of products, services, stakeholder value chains, and business models (Ceschin & Gaziulusoy, 2019).

[4] The spatio-social innovation level innovates on human settlements and the spatio-social conditions of their communities; this can be addressed on different scales, ranging from neighborhoods to cities (Ceschin & Gaziulusoy, 2019).

[5] The socio-technical system innovation level encompasses design interventions that focus on promoting radical changes in how societal needs (such as nutrition and mobility) are fulfilled and thus focus on supporting transitions to new socio-technical systems (Ceschin & Gaziulusoy, 2019).

[6] Social equity and inclusion dimension focuses on social equity and cohesion, see Chapter 2.1 for a deeper description.

[7] Product eco-design or Life Cycle Design have the same meanings and implications, and in this research, the LCD terminology is used.

important to note that both levels exhibit a noticeable knowledge gap that calls for comprehensive and scientifically grounded insights to enrich the design context.

LCD approaches innovate at the product level, using a Life cycle approach and a functional approach (Hemel, 1997; Giudice et al., 2006; Keoleian & Menerey, 1993; Pigosso et al., 2015; Tischner, 2001; Vezzoli, 2018a). Sustainable Product-Service System Design (S.PSSD) approaches innovate at the system level regarding the offering/business model, which is frequently modeled after the satisfaction system, stakeholder configuration, and system sustainability approaches (UNEP & Delft University of Technology, 2017; Van Halen et al., 2006; Vezzoli et al., 2015). According to findings from the literature review, the furniture industry is currently focusing on single-indicator innovation, such as reducing material content (Ika Rinawati et al., 2018) and selecting resources with lower environmental impacts (Iritani et al., 2015), which are insufficient. Although some furniture product LCD strategies have been proposed (Krystofik et al., 2018), there is a lack of comprehensive furniture-specific approaches, strategies, and guidelines. Furthermore, little research provides solutions to the trade-offs among different LCD strategies, i.e., furniture-specific LCD strategy priorities.

Regarding furniture S.PSSD, a limited number of studies focus on either environmental sustainability or economic prosperity, with no considerations for win-win economic and environmental benefits (Park et al., 2016). Knowledge base and know-how are required to generate sustainable win-win furniture S.PSS solutions. In conclusion, the critical importance of design and the emphasis on complementary products and Product-Service Systems innovation are duly recognized. Nevertheless, the established knowledge base and practical know-how of Design for Sustainability (DfS) as applied to the furniture sector remain relatively limited at this time.

On the other side, furniture refers to a broad set of products used daily in both domestic and non-domestic spaces for functions such as storage, hanging, supporting, lying, sitting, working, and eating (Cordella & Hidalgo, 2016). The scope of this research focuses on office and household furniture because they account for more than 60% of furniture production (Renda et al., 2014), and they are the primary focus of interdisciplinary fields such as furniture and environmental science, as well as furniture and design for sustainability.

Furthermore, the study has evidenced (through a series of Life Cycle Assessment studies, chapter 5.1) that these two subcategories of furniture have similar life cycle environmental performance. Thus, similar approaches to improve sustainability could be used. Second, the boundary between office and household furniture is vanishing in use contexts as modern organizations increasingly rely on engaging work environments that blur the lines between home and office to boost employees’ motivation and productivity (Leclercq-

Vandelannoitte, 2021). As a result, the application contexts for these two types of furniture are becoming and have been evaluated as more comparable.

Research questions (Chapter 3)

According to the former considerations, the main research questions for this research are:

RQ1: What are the framework and characteristics of environmentally Sustainable Furniture Systems?

RQ1.1 What are the innovation requirements and characteristics of environmentally sustainable furniture products (product level)?

RQ1.2 What are the characteristics of environmentally and economically sustainable win-win furniture Product-Service Systems (PSS level)?

RQ2: What new knowledge is needed to design environmentally Sustainable Furniture Systems?

RQ2.1 What new competencies, skills, methods, and tools are needed for environmentally sustainable furniture Life Cycle Design (product level)?

RQ2.2 What new competencies, skills, methods, and tools are needed for environmentally Sustainable furniture Product-Service System Design (PSS level)?

Methods (Chapter 4)

This research aligns with the constructivism paradigm, which posits the existence of a tangible reality encompassing sustainable furniture systems, comprising both furniture products and Product-Service Systems. The researcher actively collaborated with other experts from the sustainable furniture community to collectively construct a deeper understanding of the nature of sustainable furniture systems. This collaborative effort aimed to facilitate the practical application of these insights within the furniture sector. The interactions between researchers, designers, and the furniture system itself play a pivotal role in this constructive process. It's important to note that the LeNS Network serves as the primary scientific community of reference in this endeavor.

This Ph.D. research primarily adopted a qualitative research approach, employing a flexible design strategy and an inductive approach. It's worth noting that a small portion of this research utilized a mixed strategy. Given the complexity of the research and the variety of strategies, approaches, and planned activities, a Design-Based Research (DBR) methodology framework was chosen to guide the entire process. DBR consists of four primary stages (Barab & Squire, 2004; Brown, 1992; Collins, 1992; F. Wang & Hannafin, 2005): (1) Analysis of practical problems, (2) development of solutions informed by existing design principles, (3) iterative cycles of testing and refinement of solutions in practice, and (4) reflection to produce design principles and enhance solution implementation (Herrington et al., 2007; Reeves et al., 2005). It's worth mentioning that some researchers followed a three-stage research process involving preliminary research, prototyping and assessment, and reflection (Ceschin, 2012; Diehl, 2010). These two research processes essentially align, with the latter combining the steps of prototyping and assessment while the former keeps them separate.

Research stage I: Analysis of practical problems_preliminary research (Chapter 1-2, Chapter 5-6)

The initial phase of the design-based research process encompasses fundamental tasks such as problem identification, conducting a comprehensive literature survey, and defining the research problem (Bannan-Ritland, 2003). In this research, the initial stage entailed a comprehensive exploration surrounding design for sustainable furniture systems. This exploration encompassed various aspects, including an examination of the environmental issues stemming from the furniture system (from furniture products and Product-Service Systems) and the general knowledge base and know-how related to design for sustainability. Building on the foundational understanding acquired, the research proceeded to identify specific research problems, gaps in existing knowledge, and overarching research goals (Chapter 1-2).

In the second step of the research process, further investigation was conducted to address Research Question 1 (Chapter 5-6): a qualitative research strategy was employed, complemented by one research activity utilizing a quantitative strategy. This stage embraced an inductive approach. The activities undertaken to address RQ 1 were as follows.

Exploring aspects including the innovations and characteristics of environmentally sustainable furniture products (addressing Research Question 1.1): Reviewing the literature on furniture life cycle activities and other researcher’s Life Cycle Assessment (LCA) on furniture, assessing the environmental impact of 25 pieces of furniture through a comprehensive LCA in the study, analyzing best practices, conducting semi-structured interviews, all with the goal of constructing a furniture life cycle profile and identifying sustainability-oriented interventions and characteristics. The design insights gained in this phase were employed in the subsequent stage to formulate furniture-specific Life Cycle Design (LCD) guidelines (Chapter 7.1). The detailed life cycle data served to establish priorities for furniture LCD strategies (Chapter 7.1) and as a comprehensive database for furniture designers. (Chapter 5)

Furthermore, the investigation delved into the attributes of economically viable and environmentally sustainable furniture Product-Service Systems (addressing Research Question 1.2). This involved a comprehensive review of literature, analysis of best practices, and conducting semi-structured interviews with the objective of identifying characteristics of furniture S.PSS (classification, definition, key elements, and features). This process resulted in the creation of a furniture system profile and the development of an archetypal furniture S.PSS map. Subsequently, these furniture S.PSS characteristics were utilized in the subsequent stage to formulate furniture-specific S.PSSD guidelines in Chapter 7.2. (Chapter 6)

Concluding this stage, the conceptual framework for the Sustainable Furniture System was developed, taking into consideration the characteristics of S.PSS furniture offerings. Additionally, the framework acknowledges the mutually beneficial economic and environmental advantages of Furniture S.PSS in facilitating furniture Life Cycle Design (LCD).

Research stage II: Development of solutions informed by existing principles _prototyping (Chapter 7-8)

The second phase of design-based research involved developing solutions to the problems identified in the first research stage. Theory plays a crucial role in informing practical design guidelines. Design-based research advocates for a pragmatic philosophical foundation, where the value of a theory is measured by its capacity to bring about changes in the real world (Barab & Squire, 2004).

In this stage, the new role of design in shaping environmentally sustainable furniture systems at both the product and Sustainable Product-service System (S.PSS) levels was defined. The framework developed in the first phase has served as a guide for conducting the second stage of the research, aimed at addressing Research Question 2 (RQ 2). To answer RQ 2, a qualitative strategy was employed, adopting a mixed inductive approach.

To address Research Question 2, building upon the design insights and sustainable characteristics identified in Research Question 1, preliminary guidelines for sustainable furniture system design were developed. This process involved integrating experts' knowledge in furniture design and design for sustainability through two workshops, employing a consolidated method (see Figure 8). Subsequently, these guidelines were evaluated by experts for comprehensibility and practical utility. This iterative process facilitated the creation of comprehensive sustainable furniture-specific design guidelines at both the product and Product-Service System (PSS) levels, encompassing three levels of detail: strategy, sub-strategy, and guideline.

At the same time, drawing on these design guidelines, a series of furniture-specific sustainable design tools were created and evaluated through workshops, focus groups, interviews, and questionnaires, employing a deductive-inductive approach. The evaluation process is detailed in the next paragraph.

Research stage III: Iterative cycles of testing and refinement of solutions in practice _assessing (Chapter 9)

This research stage was dedicated to iterative processes of empirically applying, evaluating, updating, and redesigning/improving the furniture-specific design method and tools. The primary goal of this stage was to validate the developed knowledge base and know-how for their comprehensibility, usability, and effectiveness (success). The main methods employed during this stage include a workshop, a focus group, interviews, and questionnaires.

Three strategies were employed to validate the sustainable furniture system design tools: The first strategy involved the implementation and evaluation of these tools in real projects. These tools underwent validation within the GIOTTO project[8], with peer feedback providing valuable insights. The second strategy included the implementation and assessment of the approach in a design workshop, a focus group, and interviews with (young) furniture designers and/or experts in design for sustainability. The sustainable furniture system design tools were applied and evaluated by 30 master's students (young designers) in furniture design during a workshop. The third strategy was centered on engaging furniture designers, experts, and practitioners in the fields of design for sustainability and furniture design to assess the potential of these tools. This involved interviews with a total of 19 furniture designers, experts, and professors with a background in furniture design for sustainability from the LeNS Network. Lastly, a questionnaire was distributed to 21 LeNS Network members for the final evaluation of these tools. After each evaluation activity, these tools were refined or improved.

Participants were selected based on specific criteria: 1) their involvement in sustainable furniture-related projects; 2) their affiliation with furniture design institutions/studios or their experience in furniture design or other product design; 3) their association with the LeNS network and focus on design for sustainability and/or furniture design. The continuous application and evaluation of these tools resulted in continual improvement.

[8] "The Circular Economy for the Competitiveness of the Made in Italy Industry - GIOTTO." This project, conducted in collaboration with eleven national organizations and funded by the Italian Ministry of Education and Research (MIUR), sought to develop and disseminate innovative design guidelines and tools, to foster a sustainable and circular economy within the competitive value chains of the Made in Italy industries, including furniture, food, and fashion. Through a multidisciplinary and collaborative research consortium, GIOTTO empowered small and medium enterprises with innovative approaches to minimize the environmental impact of their products across their entire life cycle.

Research stage IV: reflection to produce design principles and enhance solution implementation (Chapter 10)

The objective of this research stage was to conduct a retrospective analysis of the entire study, with a particular focus on the research outcomes and the research methodology employed. This stage led to the following outcomes:

- Specification of the primary contributions made to both theory and practice.
- Identification and discussion of research limitations.
- Reflection on the potential generalizability of the results.
- Formulation of recommendations for future research and practice.

Leveraging the knowledge base and know-how developed within this research, I am currently in the process of creating an open-access course (comprising videos, slides, and textual content) and an open-access book to disseminate this valuable knowledge base and know-how. The overall aim is to share the knowledge base and know-how on Sustainable Furniture System design with an open-access approach.

List of Tables

List of Figures

Part I Designing Sustainable Furniture System - Why, What, When and How?

This section offers insights derived from a two-stage review of the literature. The first stage delves into the contexts of sustainable furniture systems (Chapter 1), while the second explores the role of design in contributing to sustainable furniture systems (Chapter 2). Furthermore, Chapter 4 explains the research design and explains the rationale behind the selection of the methodology employed to structure this investigation. Specifically:

In Chapter 1, the environmental impact of the furniture system is investigated, encompassing the production and consumption system (chapter 1.1) as well as the life cycle of furniture products (chapter 1.2). The chapter further identifies potential opportunities for fostering sustainability within the furniture system (chapter 1.3) and examines the policy contexts surrounding sustainable furniture (chapter 1.4).

Chapter 2 explores the role of design in shaping Sustainable Furniture Systems. It critically defines the research scope across three key aspects. Firstly, within the three sustainable dimensions, this research specifically emphasizes the environmental dimension with economic consideration. Secondly, among various Design for Sustainability approaches, the focus lies in Life Cycle Design and Sustainable Product-Service System Design. Lastly, the investigation concentrates on the household and office furniture categories.

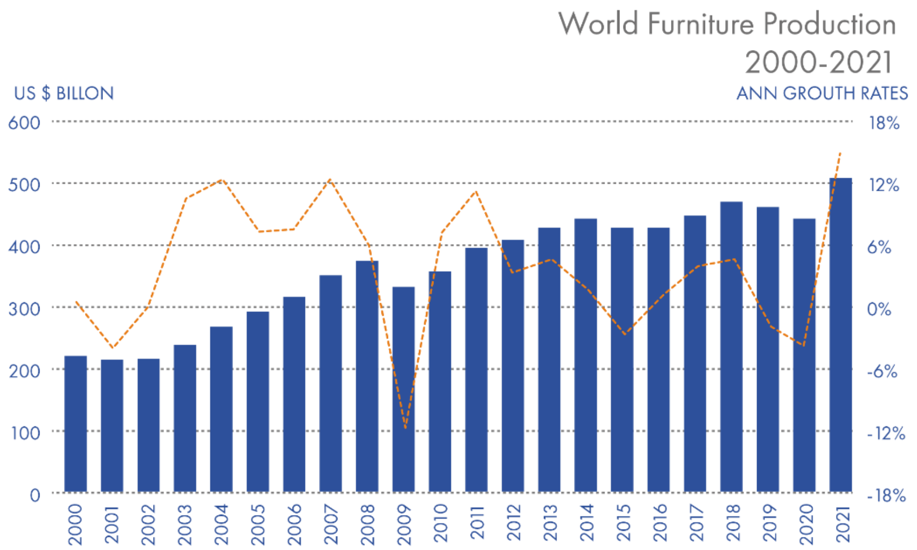
Chapter 4 presents the roadmap to address the research questions. It describes elements for the research design of the paradigm, purpose, strategies, approaches, methodology, and the rationale of this roadmap. It clarifies how this design research is designed.

Chapter 1 Introduction: the furniture system and its sustainable challenges

1.1 The environmental unsustainability of the furniture sector

The furniture sector is important not only due to its close relationship with humans (Xiong et al., 2020) but also its significant contribution to employment, the economy, and its impact on the environment. For instance, in EU-27, the furniture sector employs more than 1 million workers across 130,000 companies, generating an annual turnover of around 95 billion Euros in 2010 (European Commission, 2013a, 2013b). On a global scale, the furniture industry has doubled its volume from 2000 to 2021, reaching a worldwide volume of about $500 billion (Table 1), which is seeing an increase in the next year (CSIL, 2021).

Table 1 The world furniture production value (year 2000-2021) (CSIL, 2021).



However, these data translates to approximately 58.64 million tons of furniture consumed and 56 million tons discarded each year worldwide (calculated based on data from (CSIL, 2021; Forrest et al., 2017)). When examining the main materials used in furniture production, wood furniture accounts for 57% of the EU furniture production value, followed by 20% for soft furniture and 12% for metal furniture (Renda et al., 2014).

If comparing the furniture sector with other industries, research conducted by the European Union ranked the Furniture sector as the second highest scoring group after textile and footwear (among 12 products which are absorbent, hygienic products, bed mattresses, cosmetics, ceramic products, detergents, fishing gears, furniture, lubricants, paints, textiles and footwear, toys, tires) both in terms of its environmental impact and the improvement potential. For the environmental impact, European research considers the environmental categories, including water effects, air effects, soil effects, biodiversity effects, waste generation and management, climate change, life-cycle energy consumption, and human toxicity. For the improvement potential, the research considers the potential to improve material efficiency and lifetime extension.

Data from the Consumption Footprint Platform (European Commission, 2023) show that since 2018, furniture has been the most impacting sector (with 27.79 mpt consumption Footprint per capita) among all household products, which are furniture, clothes, paper products, detergents, plastic products, footwear, sanitary products, bed mattresses, and personal care, see Table 2..

If compared with larger amounts of product groups, it is still possible to see the importance of furniture in a total of 55 sectors from 5 groups (food, housing, mobility, household goods, and appliances). The furniture sector ranked as the 9th most impacting sector for consumption Footprint per capita, after meat (food), dairy (food), single-family houses_moderate (housing), Passenger cars_gasoline (mobility), Passenger cars_diesel (mobility), Multi-family houses_moderate (housing), Beverages (food), Multi-family house_warm (housing), see Table 3.

Table 2 The consumption footprint per capita of household products from year 2018 to 2021, data from the Consumption Footprint Platform, data from (European Commission, 2023)

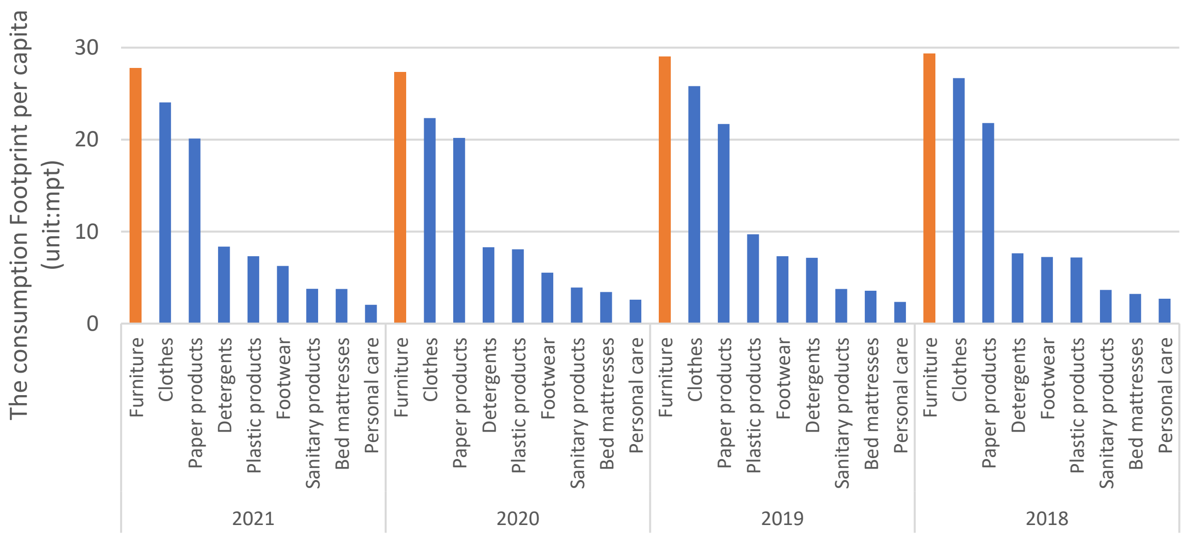
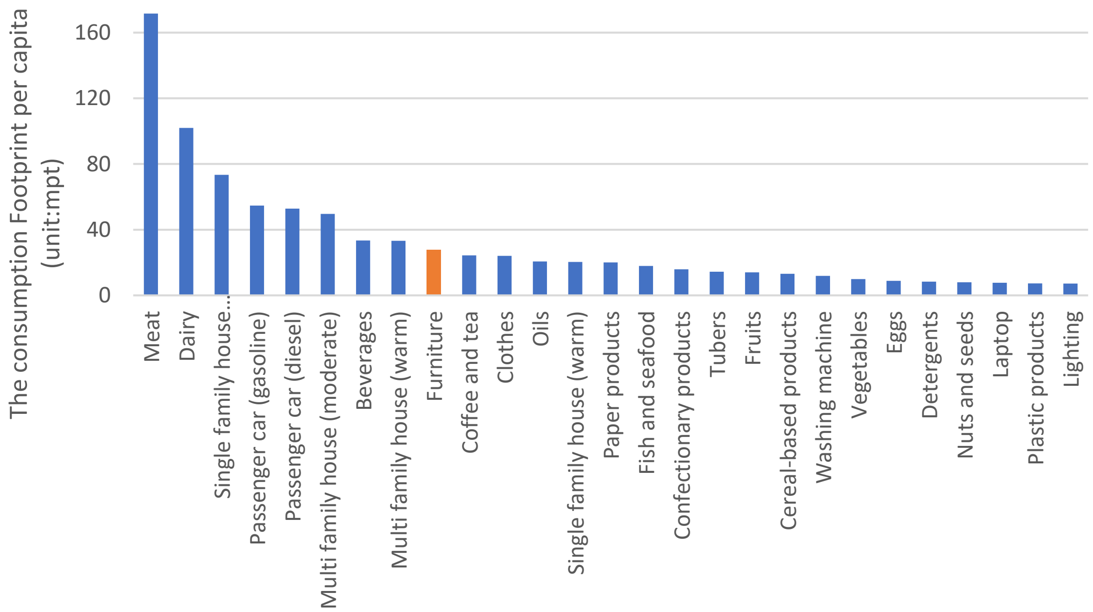


Table 3 The consumption footprint per capita of products, data from the Consumption Footprint Platform, data from (European Commission, 2023)



In conclusion, furniture has been identified as a crucial area that requires proactive measures and improvements to promote sustainability, considering its serious environmental impact and great potential for sustainability (European Commission, 2020; Joint Research Center of the European Commission, 2023). Addressing the environmental impact and resource consumption within the furniture sector is imperative for fostering a more sustainable future.

1.2 The environmental unsustainability of the furniture product along its life cycle phases

1.2.1 An overall environmental impact of furniture in each life cycle stage

As stated before, overproduction and overconsumption on the system level represent heavy environmental challenges for the furniture sector since the huge amount of furniture production and consumption results in significant resource consumption, harmful emissions, and waste generation. On the other hand, these impacts, among others, could also be seen on the product level, throughout the furniture's life cycle, during pre-production, production, distribution, use, and disposal (González-García et al., 2019).

"When examining the furniture's life cycle at a micro level, we can gain detailed insights into the sources of environmental burdens. In the **pre-production stage**, environmental impacts primarily arise from the preparation of raw materials, such as wood-based materials, various metals (e.g., aluminum, steel), plastics, fabrics, leather, glass, and various chemicals, as well as the subsequent consumption of resources. For instance, in the production of approximately 1 m3 of particleboard (weighing around 650 kg), the consumption of dry wood-based materials amounts to approximately 687 kg, Urea-formaldehyde resin (100% solid content) around 72 kg, lubricants around 18 g, and comprehensive energy input of about 507 MJ, along with other resources (Clean Production

Standard-Wood-based Panel Industry (Particle Board), 2010; González-García et al., 2019)[9]. The over-extraction of wood resources has significant negative consequences, including habitat destruction leading to reduced biodiversity, drought causing desertification, and deforestation contributing to climate change. Wood-made furniture accounts for a substantial portion of the furniture sector, and the production of wood-based panels (e.g., particle board, fiberboard, etc.) is a critical source of hazardous emissions due to the use of formaldehyde-emitting resins to bind wood chips or fibers (Donatello et al., 2017). Formaldehyde is a common indoor air contaminant known to cause sensory irritation and, depending on the concentration and exposure time, lead to health issues such as allergic reactions in the eyes, skin, and respiratory system (Liu et al., 2012). The production of other materials like steel and plastics also generates various impacts, such as CO2 emissions contributing to global climate change.

In the **production** stage, manufacturing, assembly, and treatment of components contribute significantly to environmental impacts due to the generation of residues, consumption of chemical mixtures, and electricity usage (European Commission. Joint Research Centre, 2017). These processes can result in the creation of solid waste, air pollution, and water pollution. For example, the edge banding process involves the application of adhesives such as Ethylene Vinyl Acetate (EVA), Urea-formaldehyde (UF), phenol-formaldehyde resin (PFR), and Melamine Formaldehyde (MF) to the board's edge. Painting and finishing solid wood or metal components require coatings, while the injection/ extrusion/ blow molding process for plastic components consumes resin particles and additives like blow agents for foaming. Additionally, upholstery assembly and padding

[9] To be specifically, it consumes wood based materials 687 kg, UFR 72 kg, lubricants 18 g, energy 507 MJ and other resources in a brazil case (González-García et al., 2019); it consumes wood based materials 600-750 kg, UFR 65-75 kg, energy 80-260 kg standard coal and other resources in China (Clean Production Standard-Wood-based Panel Industry (Particle Board), 2010).

involve the use of latex and Polyurethane (PUR) foams. These processes, which consume resins, pigments, solvents, additives, and diluents, can generate Volatile Organic Compounds (VOC) emissions such as alcohols, olefins, ethers, alkanes, and aldehydes, as well as wastewater containing sulfide, chlorine (Cl), alcohols, olefins, and alkanes (Cheung et al., 2017). These emissions can have negative impacts on the environment and human health (Berrios et al., 2005). VOCs emitted into the atmosphere contribute to acid rain and the greenhouse effect. In the presence of sunlight, they react with oxides of nitrogen to form ozone in the lower atmosphere, leading to photochemical smog, a persistent air quality issue in many regions. Smog's environmental impact can affect both health and property, causing respiratory irritation, plant damage, and reduced visibility. Waste generation is another significant impact occurring during production (Ulrich & Eppinger, 2012). Manufacturing processes like cutting, punching (or drilling), and sanding (or trimming) generate solid waste, including sawdust, metal, and plastic residues. Sawdust, for example, can contribute to smog formation and negatively impact air quality and human health.

Environmental impacts in the **distribution** stage primarily arise from transportation, packaging, and storage facilities. This includes the resources used for transportation, the life cycle impacts of packaging materials, and the overall environmental effects of warehouses. Air pollution is a harmful consequence resulting from non-renewable fossil fuel consumption during the transportation of furniture products. Additionally, the centralized economic structure may lead to irrational long-distance logistics, causing high energy consumption during distribution. The storage of furniture also contributes to environmental impact, mainly due to electricity consumption. Constructing storage facilities involves the consumption of resources and the emission of pollutants, making it a complex process. Moreover, packaging waste is generated to protect furniture during transportation. Various types of packaging are used, including primary, secondary, and tertiary packaging. These packaging materials can include corrugated board boxes, PE and other types of plastics, and sometimes even wood and metals.

Although the **use** phase may not be the most critical in terms of environmental impacts (European Commission. Joint Research Centre, 2017), it still requires careful consideration. Potential environmental impacts can arise from the operation and cleaning of furniture products. For instance, electrically adjustable furniture consumes electricity during use. Cleaning furniture typically involves wiping surfaces with a damp cloth, vacuuming upholstery, and machine-washing textile covers for chairs and other seating or laying products. These cleaning processes may require water, detergent, and electricity. The use of detergent and the emission of wastewater has the potential to cause acidification, such as acid rain in terrestrial and freshwater environments. While the use phase of furniture might appear to have a relatively low environmental impact on furniture Life Cycle Assessments (LCAs), it is essential to recognize that irresponsible furniture use can lead to premature obsolescence before the actual end of its functional lifetime. This, in turn, results in additional materials and energy consumption as well as increased waste generation.

The end-of-life stage of furniture encompasses various scenarios. In the EU, furniture waste constitutes over 4% of the total municipal solid waste (MSW) annually, with 80-90% being incinerated or landfilled and only 10% being recycled (European Commission. Joint Research Centre, 2017). Unfortunately, much furniture becomes obsolete before reaching its actual functional lifetime due to reasons such as office relocations, inadequate furniture after renovations, expansion of premises or staff, and changes in interior or corporate design. Consequently, perfectly functional furniture is often discarded for aesthetic reasons. Reuse in the furniture sector is also limited, primarily occurring through commercial second-hand shops or social enterprises (European Commission. Joint Research Centre, 2017). Frequent replacement of office furniture contributes to the growing volume of solid waste, leading to increased landfill usage (Besch, 2005). Landfill disposal can generate methane and groundwater pollutants, while incineration produces air pollution and toxic ash (Ulrich & Eppinger, 2012). These environmental issues emphasize the need for more efficient furniture use to reduce emissions and waste generation. Another end-of-life scenario involves incineration for energy recovery, but incinerating plastics, in particular, has a high environmental impact. For instance, the combustion of plastics releases noxious fumes into the atmosphere, posing serious threats to both human health and the environment.

Last but not least, the entire life cycle of furniture involves electricity consumption and transportation. Firstly, the overuse of non-renewable resources may lead to resource depletion. The consumption of non-renewable fossil fuels, such as coal, natural gas, and diesel oil, occurs during production activities, transportation, and electricity generation, resulting in the release of CO2, CH4, CF4, C2F6, SO2, HF, HC, NOx, CO, particulate matter (PM), among others. These emissions may contribute to Global Warming (CO2, CH4, CF4, C2F6), Acidification (SO2, HF, NOx), Photochemical Ozone Creation (SO2, CO, NOx, HC), and winter smog (PM). Some of these emissions have been proven to have a negative effect on human health. For instance, SO2 and NOX are linked to skin, lung, bladder, liver, and stomach cancers, while PM and NOx can cause respiratory problems.” (D. Yang & Vezzoli, 2023)

1.2.2 The detailed environmental impact of furniture

To obtain detailed data on the environmental impacts of furniture, several authors conducted a Life Cycle Assessment (LCA), which is one of the most commonly used tools for systematically assessing environmental impacts (Panameño et al., 2019).

Some researchers evaluated or compared the environmental impact of various processes, materials, or components. A study comparing different types of wood-based panels found that standard particleboard has a lower environmental impact (72%) compared to standard fiberboard (Çinar, 2005). This finding was further supported by another environmental analysis of three types of wood-based boards, which demonstrated that particleboard with low formaldehyde content exhibited better environmental performance than standard particleboard, while fiberboard had the highest impact (Bovea & Vidal, 2004). In addition to traditional boards, bio-composites made from hemp fiber and polylactide demonstrated good environmental performance with lower resource consumption and biocompatibility, among other benefits (Smoca, 2019).

Crucial processes for wood boards involve surface and edge treatments. An evaluation of four different wood surface coatings (two wax-based coatings and two UV lacquers that use ultraviolet light for hardening) showed that the 100% UV lacquer is the most environmentally friendly alternative (Gustafsson & Börjesson, 2007). Another technique involves using laminate for surface and edge treatments, and the evaluation revealed that low-density laminate is preferred over high-density laminate, resulting in a 36% improvement in environmental impact (Çinar, 2005).

In terms of wood production processes, the milling saw step was found to have the highest environmental impact on Para-rubber wood (Phungrassami & Usubharatana, 2015). When considering wood extraction techniques, the choice of technological options should be based on the geomorphology, topography, and site-specific characteristics of the area investigated. Neither advanced nor traditional mechanization can be considered the most suitable for all conditions (Mirabella et al., 2014). Furthermore, a Life Cycle Inventory (LCI) data investigation of five timber production lines in Ghana provided average national data for the timber industry (Eshun et al., 2010).

Processes for metal and leather were assessed. An evaluation of two powder coating solutions verified that substituting the epoxy-based coating with a polyester-based alternative reduces both health risks and environmental impacts (Askham, 2011). Compared with the traditional chrome tanning process, the novel wet-white tanning process has lower ADP (Abiotic Depletion Potential), GWP (Global Warming Potential), and HTP (Human Toxicity Potential) but higher GWP excluding biogenic carbon and energy consumption. The tanning process is the main contributor to environmental impact (Shi et al., 2016).

Some LCAs evaluate the life cycle data for a single piece of furniture and identify hot spots in the furniture system, which can help determine improvement alternatives. The environmental profile of a set of wood furniture (a convertible baby cot, a study desk, and a bedside table) was evaluated, and two processes (the production of wooden boards and electricity) were identified as hot spots. Based on this, several improvement alternatives were proposed to reduce the environmental profile (González-García et al., 2012). Mirabella et al. assessed the environmental impacts of a school desk and highlighted that solid wood panel production and iron parts processing had the greatest environmental burdens (Mirabella et al., 2014). An assessment of a wardrobe showed that the most significant environmental impact of the furniture life cycle was due to the distances covered and the production of the main raw material, medium-density particleboard (MDP) made of wood (Medeiros et al., 2017). These trials help assess the environmental profile of a single piece of furniture and propose targeted suggestions for improvement.

There have been several LCAs conducted to compare different furniture models and define better ones. Panameño et al. compared the environmental impacts of a basic chair and a redesigned chair to provide insights into the implementation of cleaner production (Panameño et al., 2019). In the case of wardrobes, those made from hybrid-modified ammonium lignosulfonate/wood fiber composites (HWC) showed better environmental performance than conventional medium-density fiberboard wardrobes (Li et al., 2019). The hotspots over the life cycle of the HWC wardrobe were found to be raw materials supply, energy requirements, and transportation (Li et al., 2019). Another study evaluated two LIFE office chairs and found that the model with an aluminum base had a higher GWP100 impact. The main hotspot in the life cycle of these chairs was the raw material extraction/refinement stage (Babarenda Gamage et al., 2008). In a comparison of 11 seating solutions, it was observed that energy and materials minimization improved environmental performance, and higher recycled material content and the use of renewable energy resources were beneficial (Askham et al., 2012)

In addition to assessing the environmental impacts of furniture products, processes, and materials, one study evaluated the environmental performance of varying models. Adaptive remanufacturing was verified to be both an environmentally preferable and economically viable business strategy (Krystofik et al., 2018).

1.3 The potential to improve furniture system's environmental performance

The importance of design in innovating furniture products for sustainability is becoming more widely recognized. Up to 80% of a product's environmental impacts are determined during the design phase (Design Council, 2022; European Commission, 2020), emphasizing the importance of sustainable design knowledge in addressing major environmental issues associated with the furniture system. Indeed, addressing environmental concerns early in the design process is more efficient than retroactive actions, as it avoids costly and dangerous operations to reverse or limit the damage.

In terms of the furniture sector, there is great potential to improve its sustainability through design. In the framework of the Paris Agreement, the furniture sector can contribute to the goal of limiting global warming to 2 ◦C by 2050 (Geng et al., 2019). In the case, for example, of sales of office chairs and desks in the EU, they are associated with greenhouse gas emissions of more than 2 Mt CO2 eq per year. According to studies, it is possible to improve the carbon footprint by up to 10% by increasing, for example, the proportion of recycled metals (Heinemann & Arsenio, 2022). Impacts at the end of life vary considerably depending on what materials are used in the furniture. Recycling furniture components or recovering energy from furniture waste is often complicated due to difficulties in separating components (Geng et al., 2019). If the furniture is well-designed, such as easily separated structures or using easily recycled materials, it is possible to avoid this waste.

The first thing is about life extension. The durability of products can dramatically influence the environmental impacts of furniture products. It was observed that many furniture products become obsolete despite still being perfectly functional or in need of only minor repair (e.g., due to office relocations, changes in interior design of public buildings, etc.) (European Commission. Joint Research Centre., 2017).

Illustrative estimates show that within the EU, a one-year extension of the useful life of office desks and tables, from 15 to 16 years, could save 65,000 tons of CO2eq each year, and 100,000 tons of CO2eq could be saved if office chairs lasted 11 years instead of 10 years. Combined, this is as much as burning over 60 million liters of diesel (Heinemann & Arsenio, 2022). According to the European Federation of Furniture Manufacturers' statistics, 80% to 90% of the EU furniture waste in municipal solid waste is incinerated or sent to landfill, with less than 10% recycled (Mirabella et al., 2014). Furniture waste in the EU accounts for more than 4% of the total municipal solid waste stream. Additionally, household furniture alone represents between 2% and 5% of municipal solid waste in the EU-28 (Mirabella et al., 2014).

Data for France suggests that 2.3% of all furniture on the French market is not sold, of which 46% is directly destroyed or 'recycled' (ADEME et al., 2021). On a global scale, the estimated value of furniture production in 2019 was US$ 490 billion, with US$ 160 billion in exports and US$ 477 billion in consumption (CSIL & CNFA, 2020), with 2.65% of all furniture unsold. This equals 1.52 million tons of furniture unsold, and a big portion is destroyed or recycled. To avoid the impact caused by early end-of-life furniture or unsold inventory, different design measures could be taken on furniture products or furniture business models to achieve sustainable development in the furniture sector.

Furniture is made of various materials, such as wood and wood-based materials, metal (e.g., aluminum, steel, etc.), plastics, textiles, leather, glass, various chemicals, and so on (European Commission, 2013b; Renda et al., 2014). Each year, approximately 58.64 million tons of furniture are consumed worldwide, which represents huge amounts of materials consumed. For example, for an average production of 1 m^3 particle board (around 650 kg), it consumes dry wood-based materials around 687 kg, Urea formaldehyde resin (100% solid content) around 72 kg, lubricants around 18 g, and comprehensive energy consumption is about 507 MJ with other resources. The production of 1000 kg of primary Aluminum consumes 5168 kg of bauxite, 186 kg of coal, 251 kg of oil, 308 m^3 of natural gas, and 15711 KWH electricity (International Aluminum Institute, 2003). The production of 1000 kg of steel consumes 1239 kg of iron ores and 800 kg of mineral inputs like limestone, dolomite, iron scrap, and so on. The electricity consumption is about 186 KWH, and fossil fuels like Coke consumption is about 509 kg (Burchart-Korol, 2013). The reduction of materials consumption for furniture means a huge impact reduction in the original raw materials and, thus, environmental impact reduction.

The furniture sector has other impacts, such as Biodiversity Effects and Soil Effects, which are closely related to the consumption of wood-made raw materials. Carefully sourcing the legal timber for furniture production would avoid these impacts. Another impact is the air effect since furniture production involves different chemical sources, biocidal products, flame retardants, adhesives, resins, paints, varnishes, inks, dyes, plasticizers, and foaming agents, which affect the indoor environment releasing mainly VOC (Geng et al., 2019). The improvement potential of the furniture sector lies in addressing the composition of furniture elements, reducing the addition of harmful substances, and using low-emission materials and low-VOC-emission furniture (Braulio-Gonzalo & Bovea, 2020).

Furniture exhibited a high improvement potential in terms of waste generation and lifetime extension, which could be improved by performance requirements on design for durability, design for reliability, e.g., resistance to stress or weathering), design for disassembly, design for refurbishing and/or recyclability, availability of spare parts and mandatory minimum recycled content materials. These circularity measures have the potential to extend the lifetime of the product or its component, potentially saving on new resources and, therefore, influencing other categories such as air, soil, and biodiversity.

1.4 The context of environmentally sustainable furniture

Until 2013, there was no specific EU regulation for furniture (European Commission, 2013b) or furniture sectorial legislation (Joint Research Center of the European Commission, 2023) existing at the moment addressing its environmental performance. However, there are some legislation, policy requirements and standards for environment, chemical, health, and safety that affect the furniture sector.

Some initiatives show concerns about the furniture sector’s sustainable development (e.g., circular economy action plan). Some regulations are general and relevant to the furniture sector (e.g., REACH). Some certification systems are proposing sustainability, like the EcoLable or GPP criteria, which are voluntary certifications. There are some technical committees on furniture in some areas/countries, such as the EU, China which develop standards on terminology issues, safety issues (e.g., test methods on flammability and fire behavior), test methods, and requirements for end products, components, surfaces as well as standards on dimensional coordination (European Commission, 2013b).

The circular economy action plan (European Commission, 2020) gives priority to furniture as one of the most important sectors to be improved for sustainability, considering its environmental impact and sustainability potential. The plan proposed improving products' circulation through product improvement and business models. It gives some common directions for different sectors, such as improving products' durability, reusability, upgradability, etc., and proposing some measures to facilitate the process from the point of view of the European Commission, such as developing a certification system.

Regulation (EU) 995/2010 of the European Parliament and of the Council lays down the obligations of operators who place timber and timber products on the market (European Commission, 2013b). This regulation is relevant to the furniture sector since the most common material used in the furniture sector is wood (56% of the pieces of furniture produced in the EU 27 in 2011 are based on wood, which represents 56% of the production value) (European Commission, 2013b).

REACH regulation requires appropriate registration for chemical substances by each company that manufactures or imports from outside of the European Union substances on their own, in preparations, or in articles in quantities of 1 tonne or above per year. Certain substances that may cause serious and often irreversible effects on human health and the environment can be identified as Substances of Very High Concern (SVHC). REACH aims to ensure that the risks resulting from the use of SVHCs are controlled and that the substances are replaced where possible. A Member State, or European Chemicals Agency (ECHA), on request of the European Commission, can propose a substance to be identified as an SVHC (European Commission, 2013b).

EU Ecolabel criteria. Ecolabelling is a simple and cost-effective way to communicate environmental aspects and commitment to purchasers and consumers (European Commission, 2013b). However, there is a lack of furniture products (1,550 out of 88,045 products till March 2023) that are verified. It is in part due to the exclusion of both non-wooden furniture and wooden furniture with less than 90% solid wood or wood-based materials.

EU Green Public Procurement (GPP) criteria aim at facilitating public authorities' purchase of products, services, and works with reduced environmental impacts (European Commission, 2018). This criterion lists detailed information on how to purchase refurbishment services for existing used furniture, new furniture items, and furniture end-of-life services for public authorities.

There are other regulations about the limits on volatile organic compounds emissions, pollution prevention and control, leather production, sale of consumer goods and associated guarantees, waste management, packaging and packaging waste, classification, packaging and labeling of dangerous substances, classification, labeling and packaging of substances and mixtures, etc. Different European standards are of relevance for the furniture sector, such as CEN Committee CEN TC 207 Furniture, CEN Committee CEN TC 38 Durability of wood and wood-based products. The objective of CEN/TC 207 is to prepare European standards in the field of furniture, concentrating more particularly on terminology, safety, test methods, and dimensional co-ordination, and guarantee the "Internal market" for furniture (CEN Committee, 2018), which is not about sustainability.

Within this context, there is an upcoming European regulation, the Eco-Design for Sustainable Products Regulation (Joint Research Center of the European Commission, 2023), scheduled for release in April 2024. The Joint Research Center of the European Commission conducted an evaluation of the environmental impact and improvement potential (see Figure

1_right top image) across 12 distinct product categories, as illustrated in Figure 1_right bottom image. Remarkably, the furniture sector emerged as the second most critical category, following the textile and footwear sector (see Figure 1, right bottom image). This underscores the significant environmental impact of the furniture sector and its substantial potential for improvement towards sustainability. Additionally, it highlights the pressing need for prompt action in the furniture sector.

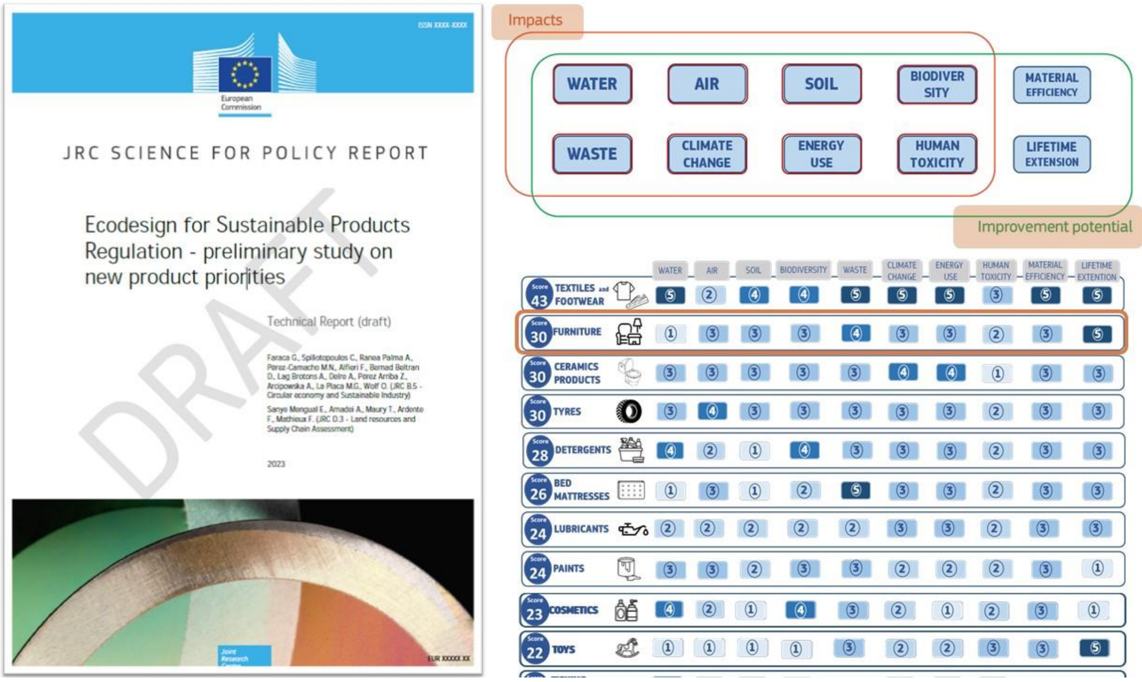


Figure 1 The rationale to design a sustainable furniture system (Joint Research Center of the European Commission, 2023).

1.5 Definition of furniture in this research[10]

Furniture refers to a broad set of products used daily in both domestic and non-domestic spaces for functions such as storage, hanging, supporting, lying, sitting, working, and eating (Cordella & Hidalgo, 2016). The scope of this research is specifically centered on office and household furniture, given that they collectively constitute more than 60% of furniture production (Renda et al., 2014). This focus is reinforced by the findings of another study that emphasized household and office furniture as the primary categories of interest (Feil et al., 2022). Furthermore, these furniture types represent the central focus of interdisciplinary fields such as furniture and environmental science, as well as furniture and sustainable design.

This study assumed that these two categories of furniture, namely office and household furniture, exhibit similar life cycle environmental performance. Consequently, it was inferred that similar approaches for enhancing sustainability could be applied to both types. This assumption was validated through a Life Cycle Assessment conducted by the author, as detailed in Chapter 5.1. Moreover, the distinction between office and household furniture is gradually blurring in terms of usage, as contemporary organizations increasingly embrace dynamic work environments that transcend traditional boundaries between home and office settings, aiming to enhance employee motivation and productivity (Leclercq-Vandelannoitte, 2021). The rise of home offices, a trend further accelerated by the pandemic, underscores the growing comparability of application contexts for these two categories of furniture.

[10] This chapter, 1.5, refers to the publication of the author entitled "Design for Environmentally sustainable furniture systems – the knowledge and know-how of furniture life cycle design and furniture sustainable product-service system design" (D. Yang, 2023).

Chapter 2 The potential role of design towards sustainable furniture systems

2.1 Sustainable development: call for a radical change and system innovation

For a comprehensive understanding of sustainability and its implications, it is common to represent it as three interconnected dimensions (United Nations, 2015):

- The Environmental Dimension: This dimension focuses on ensuring that human activities do not surpass the "resilience" of the biosphere-geosphere. In other words, it strives to avoid triggering irreversible processes of degradation, such as climate change, acidification, and land use, etc.
- The Social Dimension: This dimension focuses on social equity and cohesion. A critical aspect of this dimension is the equal redistribution of resources, guided by the principle that everyone should have equal access to global natural resources.
- The Economic Dimension: This dimension aims to promote inclusive and sustainable economic growth. It underscores the importance of generating employment opportunities and ensuring decent work for all members of society.

Environmental dimension

The **environmental dimension** of sustainability is centered on safeguarding the planet from degradation. This involves promoting sustainable consumption and production practices, responsibly managing natural resources, and taking immediate action to combat climate change. The overarching goal is to ensure that the Earth can adequately meet the needs of both current and future generations.

Efforts to assess the impact of our existing production and consumption systems on the environment, as well as the potential for a global ecosystem collapse, have been ongoing since the 1970s (United Nations & World Commission on Environment and Development, 1987). Presently, we possess well-documented information and scientific evidence that highlights humanity's role in ecosystem deterioration and the severe consequences. In 2023, Earth Overshoot Day fell on August 2nd (Global Footprint Network, 2023). This date signifies the point at which humanity's consumption of natural resources for the year surpasses the Earth's capacity to regenerate those resources within that same year. It is crucial to note that there has been a significant shift over time, with Earth Overshoot Day moving approximately 150 days earlier from 1970 to 2023.

Additionally, it's worth highlighting that certain countries contribute more significantly to this ecological imbalance than others. Figure 2 illustrates when Earth Overshoot Day would occur if the entire world population adopted the consumption patterns of various representative countries. This aspect is also relevant to the issue of social equity, which will be further explored in the subsequent section of this chapter.

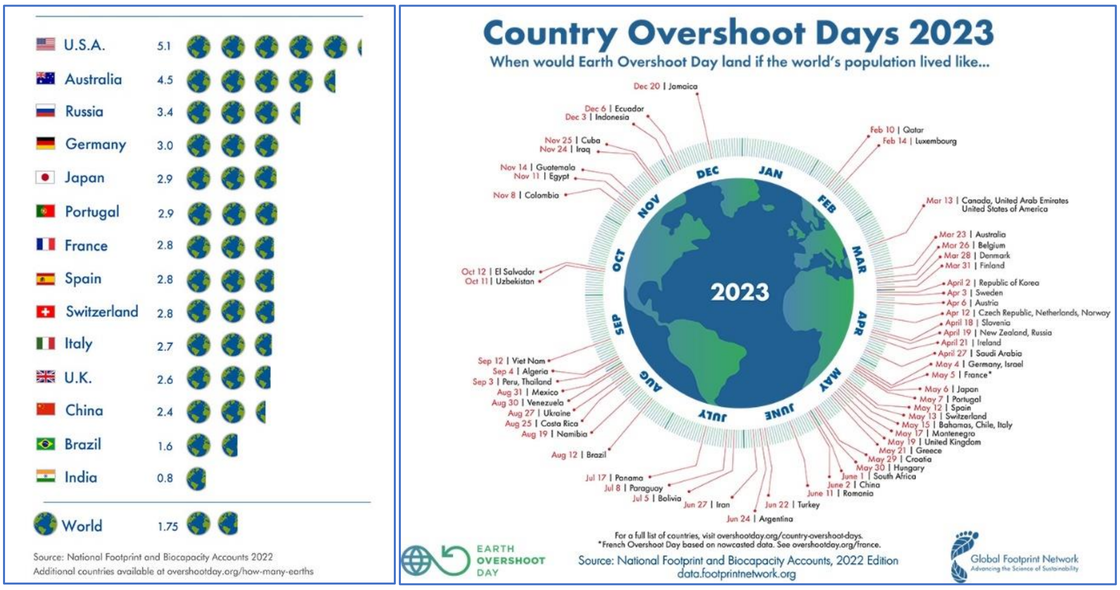


Figure 2 The number of earth we need if we live in the current way (left); Earth Overshoot Days in some countries (right) (Global Footprint Network, 2023)

When examining the relationships between the human world and nature as a whole, we can identify three fundamental scenarios for reducing environmental impact (Vezzoli, Macrì, et al., 2022):

Biocompatibility - Scenario of Biological Cycles: In this scenario, the flows of resources and emissions involved in producing goods and services are aligned with the natural system, including the biosphere and geosphere. This alignment is achieved by using renewable resources and disposing of emissions and waste that are biodegradable and compatible with the natural environment. However, in industrialized settings, this approach may not be suitable for all activities.

Non-Interference - Scenario of Technical Cycles: The non-interference scenario involves no longer extracting resources or emissions from nature. Instead, it focuses on extending the lifespan of products and components within the Technosphere. This is achieved through strategies such as optimizing product/component life, reusing materials, sharing resources, maintenance, repair, upgrading, remanufacturing, recycling, and energy recovery. This approach has been recognized by the European Union since 2014 as an economic system that aims to maintain the value of products, materials, and resources by returning them to the product cycle at the end of their use while minimizing waste generation.

Dematerialization Scenario - Demand for Well-Being: In the dematerialization scenario, both the input and output flows of resources and emissions are quantitatively reduced in response to society's demand for needs and wants. These needs and wants are satisfied through combinations of products and services that are designed to be more resource efficient.

The transition toward environmental sustainability will likely involve a combination of these scenarios, depending on the specific conditions and contexts. It's important to note that sustainable development intersects with socio-ethical sustainability, leading to a broader range of implications and responsibilities that encompass various issues and considerations. (United Nations, 2023):

- SDG 9: Industry, innovation and infrastructure
- SDG 11: Sustainable cities and communities
- SDG 12: Responsible consumption and production
- SDG 13: Climate action
- SDG 14: Life below water
- SDG 15: Life on land

Socio-ethical dimension

The **socio-ethical dimension of sustainability** places a central focus on the equity principle, which asserts that every individual should have access to a fair distribution of resources. Socio-ethical sustainability goes beyond just addressing poverty; it aims to enhance the overall quality of life and foster social cohesion.

Socio-ethical sustainability can be achieved by promoting a high-employment economy that delivers economic, social, and territorial cohesion. This would empower individuals with high-quality employment opportunities, skill development, poverty alleviation, and modern labor markets. It also includes enhancing training and social protection systems to enable people to anticipate and manage changes and contribute to the development of a cohesive society.

When the concept of sustainable development intersects with socio-ethical sustainability, it extends the spectrum of implications and responsibilities to encompass a range of critical issues, including (United Nations, 2023):

- SDG 1: No poverty
- SDG 2: Zero hunger
- SDG 3: Good health and well-being

- SDG 4: Quality education
- SDG 5: Gender equality
- SDG 6: Clean water and sanitation
- SDG 7: Affordable and clean energy
- SDG 10: Reduced inequalities
- SDG 11: Sustainable cities and communities
- SDG 16: Peace, justice, and strong institutions

Economic dimension

The **economic dimension of sustainability** involves promoting models of production and consumption that are environmentally and socio-ethically sustainable while remaining economically viable and fostering economic prosperity. Within this dimension, three main scenarios can be identified (Vezzoli, Macrì, et al., 2022):

Internalization of Costs: Internalization of costs entails including both direct and indirect costs in the purchase price of goods or services. This scenario focuses on addressing the issue of resources having low market costs that do not reflect their actual societal impact. For instance, the extraction of wood from tropical forests may lead to erosion and biodiversity loss, but these negative consequences are not factored into the purchase price of the wood. Some indirect costs arise when resources are consumed by products, generating environmental and economic costs throughout their life cycle. This strategy encourages innovation aimed at minimizing environmental impacts. For example, if the true costs of a car's emissions during its use phase were reflected in its price, it would incentivize manufacturers to develop environmentally friendly alternatives. Achieving cost internalization is primarily a political and legislative challenge.

Reorienting Ongoing Transitions: This scenario involves directing ongoing societal transitions, such as interconnection, globalization, information, and services, toward sustainable solutions. For example, exploiting the potential for dematerialization offered by new information and communication technologies (ICT) and email systems compared to traditional postal services. This approach focuses on steering existing trends and systems toward more effective and sustainable outcomes rather than attempting to revert to previous production-consumption models.

Promoting Niche Economic Models: In this scenario, the emphasis is on promoting and expanding promising economic models that currently have a niche market share. Some of these models align with environmental, socio-ethical, and economic sustainability principles. Examples include Sustainable Product-Service Systems and Distributed Economies. The goal is to mainstream these models and make them more widely accessible, thereby fostering sustainable economic practices.

In summary, the economic dimension of sustainability seeks to align economic activities with environmental and social objectives. The sustainable development goals regarding economic sustainability are (United Nations, 2023):

- SDG 8: Decent work and economic growth
- SDG 9: Industry, innovation, and infrastructure
- SDG 11: Sustainable cities and communities

The transition to system innovation

During the second half of the 1990s, a series of studies and analyses led to a more precise comprehension of the magnitude of change required to attain a society that is effectively sustainable for all (Stahel, 1997). It became evident that sustainability can only be achieved by significantly reducing: the extraction of environmental resources and the emissions released to the geosphere and biosphere from the production and consumption systems of the fully industrialized society.

These studies, considering demographic growth forecasts and assuming a rise in the demand for well-being in both disadvantaged and affluent contexts, yield astonishing results.

They indicate that within 50 years, achieving conditions for sustainability would require an increase of the eco-efficiency of the production-consumption system by a factor of ten. In other words, the use of environmental resources per satisfaction/service rendered should be reduced 90% of the current industrial societies to achieve sustainability.

If the objective in the 1970s was to slow down before reaching the limits, the current imperative is to descend below these limits without causing severe damage to the planet. For instance, if the ongoing trends of overfishing and pollution continue, there is a risk of a complete collapse of all seafood stocks by 2048. By the middle of the 21st century, 7 billion people across 60 countries could potentially face water scarcity. In light of these circumstances, it becomes evident why some authors (Diamond & Morlino, 2004), begin to assert that global society is close to the collapse of ecosystems.

These estimates, while still a subject of scientific discussion, hold enough validity to underscore the magnitude of change required. A profound and radical transformation of our development model is necessary. The production and consumption system in a sustainable society will be quite different from what we have previously taken for granted. In essence, the transition to sustainability requires radical changes in how we produce, consume, and, more broadly, how we live.

In the forthcoming decades, we must transition from a society where well-being and economic health are measured in terms of growth in production and material consumption, to a context where economic growth can be disconnected with resources consumption.

It is certain that it will entail discontinuity across all facets of society. Given the nature and the dimension of this change, the transition towards sustainability, particularly sustainable ways of living, must be seen as a comprehensive social learning process that demands system-level discontinuity. In fact, the debate on more sustainable consumption patterns has gained prominence in the agendas of major international governmental institutions in recent years, with the United Nations establishing the Sustainable Consumption Unit in May 2000.

This complex debate can be summarized in the following question: how can we adopt a new perspective that separate the social wellbeing from a direct relationship with increased resource consumption and environmentally detrimental emissions, thereby moving away from characteristics typical of high-income industrialized societies?

Considering the significant differences across different contexts, it has been emphasized earlier that for the concept of a sustainable society to be taken seriously, we need a wide-reaching social learning process in which a system discontinuity is catalyzed. Therefore, when taking this to the implementation level, it becomes evident that a system innovation approach is required. System innovation refers to a transformation that occurs within the broader societal contexts, leading to fundamental structural changes. This encompasses alterations in user practice, markets, policies, regulations, cultural norms, infrastructure, lifestyles, as well as the structures of companies and organizations. Moreover, it involves changing their interactions within the various production and consumption systems (Ceschin & Gaziulusoy, 2019; Frantzeskaki & Haan, 2009, 2009; Geels, 2006; Kemp & Rotmans, 2004; Vezzoli et al., 2014)

At the level of system innovation, optimization goes beyond products, services, and production systems that exist within current institutional frameworks and infrastructures. It also involves the development and implementation of new infrastructures, spatial planning, and incentive systems aimed at promoting more sustainable lifestyles.

System innovations encompass significant changes in the predominant "socio-technical regimes" and how societal functions are carried out. These are complex processes that intersect the social, economic, technological, and policy domains.

Within the extensive discourse on how to encourage and facilitate system innovation, the Sustainable Product-Service Systems (S.PSS) offer model appears as a promising approach to uncouple resource consumption and environmentally impacting emissions from value creation.

2.2 The evolution of design for sustainability approaches and its relevance within the furniture sector

It is now widely acknowledged that design can and should play a crucial role in driving societal transformations towards sustainability. Design has the potential to serve as a catalyst to trigger and support innovation and it can influence and mold the world. In a broader perspective, researchers highlight that the scope of design interventions for sustainability approaches has enlarged from single indicator innovations to systematic innovation, i.e., from materials and components, products, product-service systems (L. iten Chaves, 2009), local communities, socio-technical systems, to socio-technical-ecological systems. Accordingly, the framing of design problems has evolved from being technology-centered to a more human-centered approach, and further towards an earth-centered perspective (Ceschin & Gaziulusoy, 2019).

These approaches can be categorized into two main groups. The first group focuses on reducing the impacts of current consumption patterns through improved knowledge, technology, or organizational changes. This approach is often referred to as techno-centric or innovation-centered. The second category involves changing consumption patterns to reduce their environmental impact. This approach is referred to as eco-centric or, alternatively, human need-centered (Grover et al., 2019; O’Riordan, 1989; Rawles, 1995).

Ceschin and Gaziulusoy's classification aligns with those proposed by Grover et al. (2019), O'Riordan (1989), and Rawles (1995). In addition, Ceschin and Gaziulusoy's classification steps further by incorporating the concept of sustainable social innovations, reflecting a more comprehensive view of sustainability that considers not only technological and ecological aspects but also the social dimension of innovation.

2.2.1 Materials/energy selection with low environmental impact

In the early stages of green design practices, the primary emphasis was on reducing environmental impact through the redesign of individual qualities of individual products (Ceschin & Gaziulusoy, 2019), such as materials or components. Typical examples of such practices included optimizing the quantity of materials used in a product, utilizing recyclable materials, renewable materials, or energy sources, substituting virgin materials with recycled alternatives, and replacing hazardous or toxic materials with non-hazardous ones.

These design principles are fundamental in the context of furniture, and they remain a central focus in contemporary furniture design practices. However, a common misconception in the furniture sector regarding environmental requirements is the belief that the selection of material with lower environmental impact could be the best leads to a product with a reduced environmental impact (L. I. Chaves, 2008). An illustrative example is Kartell's Chair_Rechair, crafted from recycled thermoplastic sourced from used Illy coffee capsules. However, it's important to note that in order to meet quality standards and necessary mechanical requirements, additives are often incorporated into such designs, which can hinder further recycling at the end of the product's lifecycle. While these innovations are significant steps in the realm of furniture design, they fall short of achieving full sustainability.

Regulations like REACH and Ecolabel are dedicated to overseeing and encouraging green design. REACH specifically governs the use of chemical substances in products. For Ecolabel, criteria are predominantly focused on the materials used in furniture products, given that this is the predominant source of life cycle impacts (European Commission. Joint Research Centre, 2017). Indeed, while materials are an important aspect to regulate in order to enhance the life cycle environmental performance of furniture, it's essential to recognize that some other factors (such as life extension) even play a more significant role, as will be elaborated in the following paragraphs.

In the academic field, green design is also the focus of sustainable furniture system research, like materials choice (Badiu et al., 2015; Bovea & Vidal, 2004; Estrada et al., 2019; Kumar R. et al., 2019; Li et al., 2019; Lovarelli et al., 2018; Montagna & Carvalho, 2018), packaging volume optimization (Wever, 2011), labels, certification standards (Santos et al., 2012), waste management (Daian & Ozarska, 2009), component choice (Iritani et al., 2015), and so on.

2.2.2 Product design for environmental sustainability

Product Eco-design or Life Cycle Design

Eco-design represents a design approach aimed at reducing the environmental impacts of products and services throughout their entire life cycle while ensuring similar or improved performance for the end customer (ISO/TR 14062, 2002). Different from green design which improves an individual aspect of a product, eco-design puts emphasis on the whole life cycle of the product, ranging from the extraction of raw materials through manufacturing, distribution, and use to final disposal (Boks & McAloone, 2009; Brezet & Hemel, 1997;

Charter & Tischner, 2001; Giudice et al., 2006; Keoleian & Menerey, 1993; Pigosso et al., 2015; Tischner, 2001; Vezzoli & Manzini, 2008). Eco-design is also referred to as Life Cycle Design (LCD), Circular Design, or Design for the environment (L. I. Chaves, 2008; Ljungberg, 2007; Vezzoli, 2018). However, it's important to note that sometimes, Design for the Environment is used to describe a broader scope of design considerations. This research used the “Life Cycle Design” terminology.

While Life Cycle Design (or eco-design) have been extensively discussed in the literature, the environmental practices related to eco-design have a generic shape and are difficult to fit into specific product projects and industrial processes (Borchardt et al., 2009). Moreover, it's crucial to acknowledge that the efficiency gains on a single-product basis did not resolve the impacts associated with the ever-increasing consumption of products, which outpaced the improvements in unit efficiency (Brookes, 2000; Ryan, 2003).

In the furniture sector, Life Cycle Design (LCD) is quite a relevant topic in the pursuit of sustainability. Relevant researches include defining the eco-design criteria into Scandinavian wooden furniture industries (Lähtinen et al., 2014), defining the design strategies for office furniture (L. I. Chaves, 2007) which is one of the earliest work on furniture Life cycle Design that focus on office furniture, evaluating the energy and economic saving potential of remanufacturing/refurbishing/reusing furniture (Michelsen et al., 2006), or a methodology to understand and measure the eco-efficiency in extended supply chains (Michelsen et al., 2006). However, with the ongoing development of design for sustainability and furniture design research, numerous new insights have emerged. These include updated Life Cycle Design guidelines (Vezzoli, 2018), new furniture cases such as Orangebox (Orangebox, 2019), and insights from furniture companies, such as (D. Ewen, personal communication, 2022). In light of these developments, there is a pressing need to establish a new, comprehensive, and furniture-specific Life Cycle Design (LCD) knowledge base and know-how that are developed to be universally applicable and adaptable for all furniture categories and practitioners.

Emotionally durable design

Emotionally Durable Design is a call to propose the emergence of a new genre of sustainable design that reduces consumption and waste by increasing the durability of relationships established between users and products (Chapman, 2012). Emotionally Durable Design is a paradigm that focus on increasing resource productivity and reducing waste by extending the lifespan of products (Chapman, 2005). To support the designer engaging in emotionally durable design, a six-point experiential framework was developed comprising narrative, detachment, surface, attachment, exploration, and consciousness (Chapman, 2009). In addition, four main determinants of the detailed design of product meanings have been identified as factors that can enhance product attachment: Self-expression, Group affiliation, Memories, and Pleasure (Mugge, 2007).

In the context of the furniture industry, many furniture products become obsolete for various reasons, including office relocations, inadequate furniture following renovations, office expansions, changes in interior or corporate design, among others. As a result, perfectly functional furniture is often discarded early. In fact, approximately 10 million tons of furniture are discarded by businesses and consumers in EU Member States each year, with the majority of it ending up in landfills or incineration (Forrest et al., 2017). This presents an opportunity for furniture product design to apply the emotionally durable design approach. However, the emotionally durable design approach does have its limitations. It can be challenging to effectively stimulate product attachment since it is a personal, subjective, culturally and socially dependent phenomenon (Ceschin & Gaziulusoy, 2019). Additionally, manufacturers may be reluctant to adopt product attachment strategies, fearing that this could slow down the replacement rate of products and potentially reduce sales (Mugge et al., 2005).

These problems can be addressed by furniture product life cycle design and furniture Product-service system design.

Design for sustainable behavior

Design for Sustainable Behavior (DfSB) is an emerging field within sustainable design, focused on reducing the environmental and social impact of products by moderating how users interact with them (Bhamra et al., 2011). Tromp introduced four different types of influence on user experiences, namely, coercive, decisive, persuasive, and seductive (Tromp et al., 2011). Bhamra proposed 7 design intervention strategies to facilitate sustainable behavior, including Eco-Information (design-oriented education), Eco-Choice (design-oriented empowerment), Eco-feedback (design-oriented links to environmentally or socially responsible action), Eco-spur (design-oriented rewarding incentive and penalty), Eco-steer (design-oriented affordances and constraints), Eco-technical intervention (design-oriented technical intervention) and Clever design (Bhamra et al., 2011).

Design for Sustainable Behavior (DfSB) can be achieved through product-level or system-level innovations. Here, the statement emphasizes sustainable behavior design through product innovation. In this context, DfSB complements other product-related approaches by concentrating on how users interact with products during the use stage, addressing a limitation often overlooked by other approaches. However, DfSB faces challenges and limitations. One significant challenge is the difficulty of designing the extent of behavior change without crossing ethical boundaries and manipulating people's behavior (Bhamra et al., 2011; Pettersen & Boks, 2008). Another challenge is the lack of empirical data that quantifies the potential improvements achieved through DfSB, both in theoretical and practical dimensions (Bhamra et al., 2011). Additionally, there are uncertainties related to environmental trade-offs; implementing DfSB strategies may require additional resources (such as materials or energy), potentially leading to unintended higher environmental impacts (Wever et al., 2010).

In the context of the furniture sector, the application of DfSB is relatively limited. This limitation stems from the fact that DfSB primarily influences the use stage of products, which is especially relevant for energy-consuming products like electric home appliances and vehicles. In contrast, the use phase of furniture typically consumes relatively little energy and has a lower environmental impact compared to other stages (see chapter 5.1.6). There have been limited instances of DfSB application in the furniture sector, with one notable example being its use in street furniture, which extends the scope of furniture to include energy-consuming street facilities (Allameh & Heidari, 2020).

Regenerative design

In 1996, John Tillman Lyle published “Regenerative Design for Sustainable Development”, the first comprehensive articulation and handbook for the concept of regenerative design (Mang & Reed, 2012). Regenerative Design represents a system of technologies and strategies grounded in a profound comprehension of the inner workings of ecosystems. This approach seeks to formulate designs to regenerate rather than deplete the fundamental life support systems and resources within socio-ecological wholes (Mang & Reed, 2012). Researchers argue that green design merely mitigates the pace of environmental degradation. Designers are progressively recognizing the necessity for design practices to go beyond the principle of causing no harm; they must actively initiate regenerative processes to counteract the deterioration caused by previous practices (Dias, 2015).

Regenerative design seeks to integrate nature, architecture, and human interactions. While green and sustainable design aims to mitigate our impacts through operation and maintenance, it is imperative for sustaining life that we actively engage in the restoration and regeneration of the living systems. Ray Cole articulated several key implications of a regenerative approach to the built environment (Mang & Reed, 2012): (1) Regenerative design redefines the role of design by considering it as the act of "designing the 'capability' of the constructed world to support the positive co-evolution of human and natural systems." It shifts the focus away from designing "things" like buildings and infrastructure and instead emphasizes designing for sustainable patterns of living. (2) Regenerative design underscores the importance of buildings in actively supporting both human and natural processes rather than viewing them as mere products. (3) Regenerative design positions buildings as integral components within larger systems, contributing to the creation of higher levels of order, increased variety, and complexity. (4) Regenerative design acknowledges that buildings are interconnected within a larger system, shifting the emphasis from individual building-level energy self-reliance to opportunities for fostering positive connections and creative synergies with neighboring buildings and the surrounding natural environment.

In general, regenerative design encompasses four distinct levels or scopes: (1) Biomimetic which draws inspiration from nature's design principles, embracing approaches such as Cradle to Cradle and Biomimicry. (2) Biophilia incorporates natural elements and features to nurture a deep affinity for nature and obtain its positive impact on human well-being. (3) Restorative aims to re-establish the self-organizing and evolving capacity of natural systems. (4) Regenerative-level design recognizes that humans are an integral part of nature and holds the potential for evolving in harmony with the broader ecosystem, acknowledging the interconnectedness of all life forms (Mang & Reed, 2012).

Currently, there is no existing literature specifically addressing the intersection of "FURNITURE" and "REGENERAT*." However, there are identifiable links between furniture and cradle-to-cradle (CTC) design principles that promote sustainability. Before exploring its potential role within the larger regenerative design framework, it is crucial to primarily focus on understanding and resolving the environmental impact of furniture.

Cradle-to-cradle design

Cradle-to-cradle (CTC) design is rooted in the concept of mimicking the closed-loop nutrient cycles found in nature, where there is no waste. In this approach, materials are categorized into two types: biological nutrients, which can be safely returned to nature after use, and technical nutrients, which circulate within industrial systems in closed-loop cycles, involving production, recovery, and remanufacture (McDonough & Braungart, 2003). To adhere to the fundamental principles of CTC, which include the ideas that waste should be viewed as a resource, that eco-effectiveness should be prioritized, and that diversity should be respected, it becomes essential to consider the design of various elements across all scales of the built environment. This encompasses compounds, materials, products, industrial facilities, and even entire cities, and how they relate to one another within the techno-, socio-, and ecospheres (Ceschin & Gaziulusoy, 2019). Indeed, the Cradle-to-Cradle (CTC) concept presents an inspiring vision with a strong emphasis on regenerative processes, non-human species, and future generations at a rhetorical level.

However, it faces technical challenges and practical limitations (Gaziulusoy, 2015). Currently, it is not technically feasible to make biological or technical nutrients circulate indefinitely without incurring energy losses, quality degradation, and quantity reduction. This underscores that CTC primarily represents a shift from a waste-centric paradigm to a resource-centric one, with a primary focus on end-of-life treatment, often neglecting other critical life cycle stages and the interactions with other artifacts.

In the context of furniture, the significant environmental impact often occurs in the pre-production stage, followed by production, distribution, and end-of-life, which is also proved by the Life Cycle Assessment of 25 furniture pieces (chapter 5.1). Focusing solely on the end-of-life stage is insufficient to achieve sustainability given current technological constraints. A holistic approach that addresses all stages of the furniture life cycle, along with advancements in technology, is essential to work towards sustainability in the furniture industry.

2.2.3 System Design for environmental-economic sustainability

Systemic design

Systemic Design, born from the integration of systemic thinking with the discipline of Design, applies a holistic approach to the design of products, services, and systems (Jones, 2014) while supporting active collaboration among different stakeholders (Giraldo Nohra et al., 2020). In other words, the systemic design (SD) approach seeks to create not just industrial products but complex industrial systems. It aims to implement sustainably productive systems where material and energy flows are carefully planned, ensuring that waste from one process becomes a resource for other processes, thus preventing environmental release of waste (Barbero & Toso, 2010). There are five main principles as the basis of this approach: Output (waste) becomes an input (resource); Relations generate the system; The system is self-generating; Actions are local; The human being is at the center of the project (Bistagnino, 2011). Systemic Design intends to develop methodologies and approaches that help to integrate systems thinking with design towards sustainability at the environmental, social and economic levels (Lu et al., 2022). The solutions involve and interlink elements of the biosphere (e.g. natural resources), sociosphere (e.g. local knowledge and practices) and technosphere (e.g. material and energy flows) (Ceschin & Gaziulusoy, 2019). As explained by Jones (2014), Design as a discipline has evolved over time, increasingly broadening its domain and scope, thus moving from design for producing artefacts to design that deals with complex social transformations. This approach shares common elements with Cradle-to-Cradle (CTC) Design, regenerative design, eco-design (or LCD) and Product-Service System Design.

When addressing the environmental impact of the furniture sector, the Systemic Design approach is highly relevant. Actually, it is crucial to consider not only the material and energy flows but also the entire life cycle and the broader consumption system. This holistic perspective recognizes that achieving sustainability in the furniture sector involves Life Cycle Design and Product-Service System (PSS) design for sustainability which are the focus of this research.

Product–Service System Design for Sustainability (S.PSSD)

Product–Service System Design for Sustainability (S.PSSD) is defined as "an offering model that provides an integrated mix of products and services that are together able to fulfil a particular customer demand (delivering a "unit of satisfaction"), based on innovative interactions among the stakeholders within the value production system (satisfaction system), where the products' ownership and/or the life cycle service costs/responsibilities remain with the provider/s, so that the same provider/s, driven by economic interests, to continually seek/s environmentally and/or socio-ethically beneficial new solutions" (Vezzoli et al., 2021b). S.PSSD expands the traditional design focus beyond the product itself to the "satisfaction unit," broadens the scope of innovation beyond technological aspects to encompass configurations of stakeholder and extends the benefits of sustainability from individual products to the entire system. Consequently, it has the potential to create a win-win scenario by delivering solutions that are both economically competitive and environmentally and socially beneficial.

The implementation of Product-Service System Design for Sustainability (S.PSSD) requires collaboration among various stakeholders. Governments play a pivotal role in promoting and facilitating the adoption of S.PSS. They must define and implement policies and regulatory measures that encourage and spread S.PSS practices within their respective regions. Designers and developers are responsible for creating functional S.PSSs that offer both economic and environmental benefits. However, there is often a lack of knowledge and expertise in S.PSS design and development among designers and professionals. Developing this expertise necessitates a new generation of professionals capable of conducting complex system-level research and innovation. Companies and organizations are also highly significant stakeholders. The adoption of S.PSS often demands a fundamental cultural shift within the organization, involving changes in business models and corporate mindset. Companies must incorporate new skills and competencies to effectively implement S.PSS solutions. Furthermore, S.PSS entails medium to long-term investments, which can sometimes conflict with short-term profits generated at the point of sale. This discrepancy can result in uncertainties about cash flows and financial sustainability. Another critical stakeholder group consists of the end-users. In industrialized contexts, there is a need for a cultural shift to embrace behavioral changes. This includes transitioning from ownership-based consumption to a consumption model based on access and sharing. Additionally, many users lack knowledge about life cycle costs, making it challenging for them to grasp the economic advantages of ownerless-based solutions. This shift in consumer behavior often requires a well-planned transition path.

In the furniture sector, Product-Service Systems (PSS) hold significant potential for reducing the environmental impact of furniture production and consumption system. There are several key advantages to implementing furniture S.PSS: (1) PSS has the potential to close the material cycle by enabling the return of furniture from customers to manufacturers. This facilitates remanufacturing, updating, and reusing of furniture components, reducing the demand for new raw materials and minimizing waste (Besch, 2005). (2) PSS promotes strategic partnerships. Collaborative relationships between furniture manufacturers, suppliers, customers, supporting institutions, and other stakeholders can promote the development of a culture focused on value-added products in the furniture industry (Schuler, 2003). (3) PSS can strengthen the relationship between furniture enterprises and consumers (Aurich et al., 2010). Information collected from consumers can be leveraged to develop new systems that enhance product performance and increase the competitiveness of enterprises (Sundin et al., 2009). (4) PSS relieves consumers of the responsibility for life cycle services like maintenance, and product end of life treatments (Beuren et al., 2013). (5) PSS facilitates servitization and resource productivity. Servitization offers access to a functional dematerialized future that is achievable in the long run, as well as opportunities to increase resource productivity in the short run (Cook et al., 2006).

Despite the significant sustainability benefits that PSS can bring to the furniture sector, current applications often prioritize new business opportunities and economic benefits. Governments are facilitating the adoption of S.PSS. Within the European Union, several regulations promote the application of S.PSS. For instance, the Circular Economy Action Plan recommends "incentivizing product-as-a-service or other models in which producers retain ownership of the product or responsibility for its performance throughout its life cycle" (European Commission, 2020). However, for furniture system designers and developers, the knowledge base and expertise for implementing Furniture Product-Service System Design (S.PSSD) are still in the early stages of development. Realizing the full potential of PSS in the furniture industry will require a collective effort to promote sustainability alongside economic gains and further advance the necessary expertise in S.PSSD. This aspect is another focal point of the study in addition to furniture Life Cycle Design.

2.2.4 System design for environmental-social-economic sustainability

In the latter half of the 2000s, in alignment with the principles advocated by Papanek (1972), an increasing number of design researchers began to shift their focus towards the social dimensions of sustainability. The following paragraphs introduce three key approaches that promote social-ethical sustainability, discuss their main characteristics, their relevance to the furniture sector, and explore the potential role of furniture in these processes.

Design for Social Innovation (DfSI) encompasses a wide range of design activities aimed at addressing societal challenges and fostering positive social change (Chick, 2012; Tracey & Stott, 2017). These activities include the design of products, services, strategies, ideas, new organizational forms, and even social movements. DfSI is not limited to any specific design field but draws from various design approaches, such as product design, participatory design, collaborative design, strategic design, service design, urban design, and game design (Chick, 2012; Selloni & Corubolo, 2017; C.-F. Yang & Sung, 2016). It involves problem-framing, research, and solution-development methodologies commonly used in these fields.

Design for the Base of the Pyramid (BoP) involves the creation and development of products and services specifically tailored for low-income individuals and communities (Ceschin & Gaziulusoy, 2019; Jagtap & Kandachar, 2011).This concept has evolved from initially targeting BoP as consumers to recognizing their potential as producers and business partners. Moreover, the focus of design solutions for BoP has shifted from mere products and services to broader social innovations. During this transition, various design approaches have demonstrated their synergy, including Sustainable Product-Service System Design (S.PSSD) and the distributed economy. “PSS innovations, in particular, can serve as business opportunities that promote social-economic development in emerging and low-income contexts. They offer a way to shift from individual consumption and ownership of massproduced goods to a "satisfaction-based" and resource-efficient advanced service economy”(UNEP, 2002).

Design for sustainability transitions (DfST) goes beyond merely influencing technological innovations; it encompasses social, institutional, and organizational innovations as well (Vergragt & van Grootveld, 1994; Weaver et al., 2017). DfST incorporates elements of S.PSS, which seeks to reshape production-consumption systems through innovative business models, as well as design for social innovation, aiming to facilitate social change independently of technological determinants. More recently, DfST has extended its focus to urban areas, as evidenced in works by Ryan (Ryan, 2013; Ryan et al., 2016). The outcomes of DfST efforts encompass a wide range of design domains, including but not limited to product design, service design, city design, and policy design.

This pluralistic approach guides us towards a more nuanced sustainable design culture, where critical discussions unpack, question, and explore new approaches to addressing sustainability challenges through design (Chapman, 2009).

For furniture, there is potential for the furniture sector to contribute to social innovation by collaborating with other sectors and stakeholders. For instance, to reduce Egypt's reliance on imported wood and create employment opportunities for highly marginalized and impoverished rural communities, Professor Hamed El-Mously from Ain Shams University initiated a project of making wood and furniture from locally abundant and renewable resources, specifically palm midribs, in collaboration with local entrepreneurs and residents. This project holds promise not only for enhancing knowledge and skills in the local rural community but also for improving the income of the local population (El-Mously, 2018).

Specifically, when furniture is incorporated into a Product-Service System, there is an opportunity to bring about socio-ethical benefits such as enhancing local economies, improving access to furniture, and preventing interruptions in furniture usage (Vezzoli et al., 2021b). Furniture S.PSS can provide affordable access to quality furniture for low-income individuals or start-ups through models like pay-per-period. Additionally, involving furniture businesses in underdeveloped areas has the potential to create economic opportunities for local residents by utilizing local resources. However, there is a broader scope of social sustainability goals, including those related to poverty reduction, eliminating hunger, promoting good health and well-being, and ensuring quality education, among others (United Nations, 2023), where furniture plays a more limited role.

2.3 Design for sustainability method, tools and the relevance for the furniture sector

This chapter presents the research on Design for Sustainable (DfS) methods and tools with a systematic literature review of 58 articles and books published between 2012 and 2022, as well as desk research encompassing 29 institutes' websites and publications. The aim was to understand the existence of various DfS tools, their potential application in the furniture sector, and to identify gaps in DfS tools for the furniture system. I conducted an exploration of ten DfS approaches and their potential application in the furniture sector. For each sustainable design method, I delved into the design process, its aims and steps of each design process, and the expected outcomes upon using the method. In the case of tools, I investigated the following aspects: (a) General Information: This covered the aim and contents of the tool, the procedure for utilizing it, tool availability, necessary resources, form, developer, and other relevant details; (b) Tool functions and type; (c) Tool Integration in the Design Process: All tools were analyzed for their integration within two design methods, the

Method for Product Design for Sustainability (MPDS) and the Method for System Design for Sustainability (MSDS). (d) Potential Application in the Furniture Sector: I assessed the potential applicability of these tools in the context of the furniture sector. As a result, this chapter provides a comprehensive comparison of two sustainable design methods, as well as 120 existing DfS tools that are categorized based on their functions and levels of innovation.

2.3.1 Method

Literature Review

The literature review process involved a systematic selection of publications based on the following integrated criteria: (1) Chronological Order: Publications between 2012 and 2022 were considered. (2) Topic of Interest: Publications related to tools for Design for Sustainability were selected. (3) Type of Publications: The review included literature reviews, case studies, and introductions to tool development.

The literature review was conducted using Web of Science, Scopus, Google Scholar, and the Polimi online library. The search employed keywords such as 'Design for sustainability,' 'eco-design,' 'design for the environment,' 'life cycle design,' 'sustainable product-service system design,' 'circular economy,' 'furniture design,' and 'tool.' Duplicate papers across different databases were eliminated, resulting in a total of 109 papers and books. The initial selection was made based on the content of abstracts to assess relevance, ultimately leading to 58 publications chosen as the main focus of the review.

Desk Research

In parallel with the literature review, desk research on DfS tools was carried out with specific criteria: (1) Topic of Interest: Focusing on DfS tools. (2) Type of Institutions: Including academic institutions and consultancy institutions, as well as projects related to DfS.

The desk research was performed using Google Chrome, employing keywords similar to those used in the literature review. A total of 28 institutions and projects related to DfS were identified. The official websites and publications of these entities served as primary references for the analysis.

Tools Analyze and Description

For an in-depth understanding of each tool, the study described the following aspects of each tool: (1) Aim/Goals/Function and Content; (2) Detailed Procedure for Using the Tool; (3) Integration in the Design Process; (4) Expected Outcomes from the Tool; (5) Availability and Necessary Resources; (6) Form; (7) Developer(s); (8) Sources of Tools.

2.3.2 Methods on Design for sustainability

The Method for Product Design for Sustainability (MPDS) (product design method) (Vezzoli, 2018) and the Method for System Design for Sustainability (MSDS) (product-service system design method) (Vezzoli et al., 2021b) are reliable methods that were developed and improved over many years within the context of European research projects and practical applications. These methods align with international standards and are introduced comprehensively in this research.

MPDS was originally developed by the Design and System Innovation for Sustainability (DIS) research unit of the Design Department at Politecnico di Milano, resulting from over 20 years of research, educational activities, and consulting work for companies, public institutions, and trade associations (Vezzoli, 2018). The method aligns with the UNI ISO/TR 14062:2007 standard, which addresses the integration of environmental aspects into product design and development. In contrast, MSDS was developed and enhanced through the participation in three European Union-funded research projects spanning from 2007 to 2019, along with consulting experiences. This method is designed to guide and shape the entire process of system innovation development toward sustainable solutions. Both MPDS and MSDS are reliable methods that can provide guidance for achieving sustainable solutions.

Both MPDS and MSDS are designed to cater to a broad spectrum of users, including designers working in studios, companies, or organizations. These methods are modular and flexible, making them adaptable to the specific needs of individual designers and firms and enabling their application in various project contexts. The modular structure is particularly advantageous in several aspects: (1) Procedural Phases: The methods are organized into phases and related processes. Users can choose to undertake all phases or select specific phases based on the project's unique requirements. (2) Tools Selection: Accompanying the methods are a range of tools. Designers have the flexibility to select and deploy these tools during the design process according to the project's needs. (3) Integration of Other Tools and Activities: The methods are structured to allow the integration of design tools not specifically developed for them. This flexibility enables the modification of existing activities or the addition of new ones to address specific aspects of the design project. (4) Dimensions of Sustainability (specifically for the MSDS): The MSDS considers multiple dimensions of sustainability, encompassing environmental, socio-ethical, and economic aspects. Users can opt to focus on environmental or socio-ethical dimensions, or a combination of both, with economic aspects automatically integrated.

The MPDS method is intended to support design processes for developing sustainable products. The method can be tailored to specific design requirements and integrated into existing design workflows. It comprises four main phases, each with its unique purpose: (1) Strategic Analysis: This phase involves evaluating critical areas and Life Cycle Design (LCD) strategies with the highest potential for reducing environmental impact related to the product under consideration. (2) Concept Design: During this phase, the focus is on guiding the generation of design concepts toward environmentally sustainable solutions compared to existing products. (3) Product Design (and Engineering): In this stage, the emphasis is on steering the detailed design of the project toward environmentally sustainable solutions compared to existing products. (4) Communication: The final phase centers on effectively communicating the product's features and highlighting aspects related to its environmental sustainability. The processes and objectives of each phase in the MPDS method, as they relate to different stages of the design process, are detailed in Figure 3.

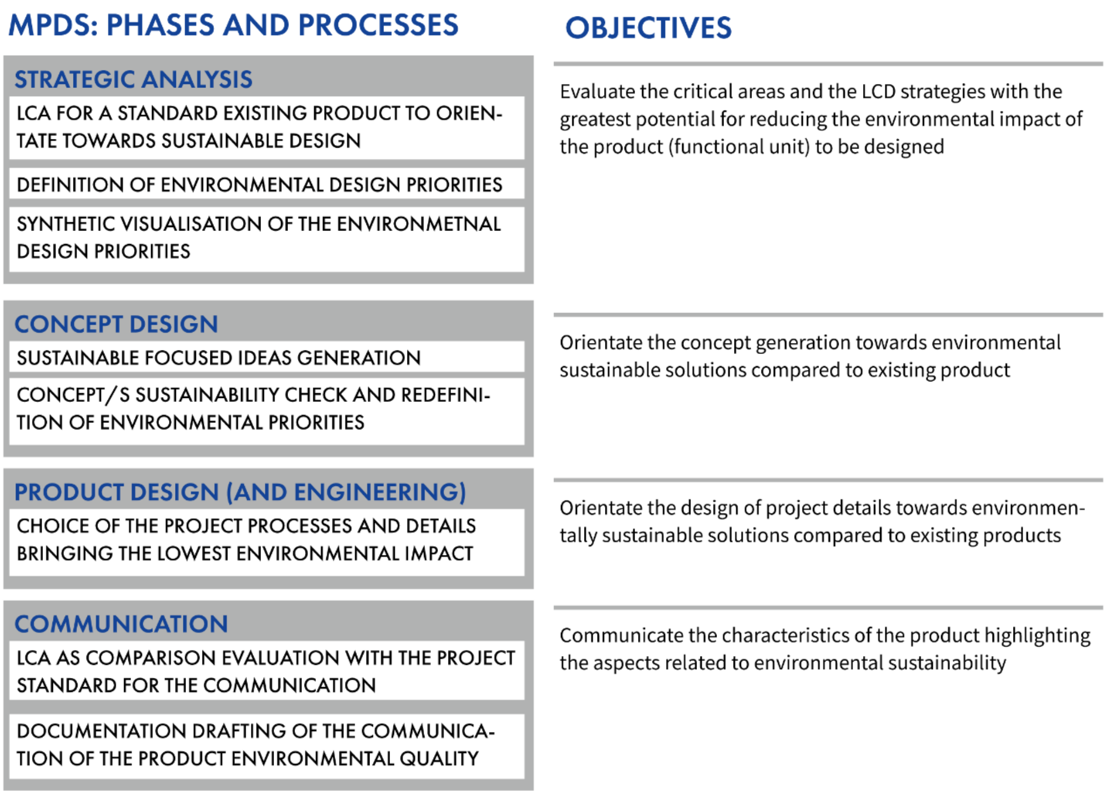


Figure 3 The MPDS method phases, processes and objectives (Vezzoli, 2018)

The MSDS method is designed to facilitate design processes for the development of Sustainable Product-Service Systems (S.PSS). The method can be adapted to specific design requirements and integrated into existing design workflows. It consists of five main phases, each serving a distinct purpose: (1) Strategic Analysis: This phase aims to gather essential information to facilitate the generation of sustainable system innovation ideas. (2) Exploring

Opportunities: In this stage, the focus is on creating a catalog of promising strategic possibilities, essentially forming a sustainability-oriented scenario or a set of system ideas with a strong sustainability potential. (3) System Concept Design: This phase is dedicated to developing one or more system concepts that prioritize sustainability. (4) System Detailed Design: The most promising system concept is refined into a detailed version that is ready for implementation. (5) Communication: The final phase involves preparing reports that effectively communicate the system's general characteristics, particularly those related to sustainability. The processes and objectives of each phase within the MSDS method, in relation to various stages of the design process, are outlined in Figure 4.

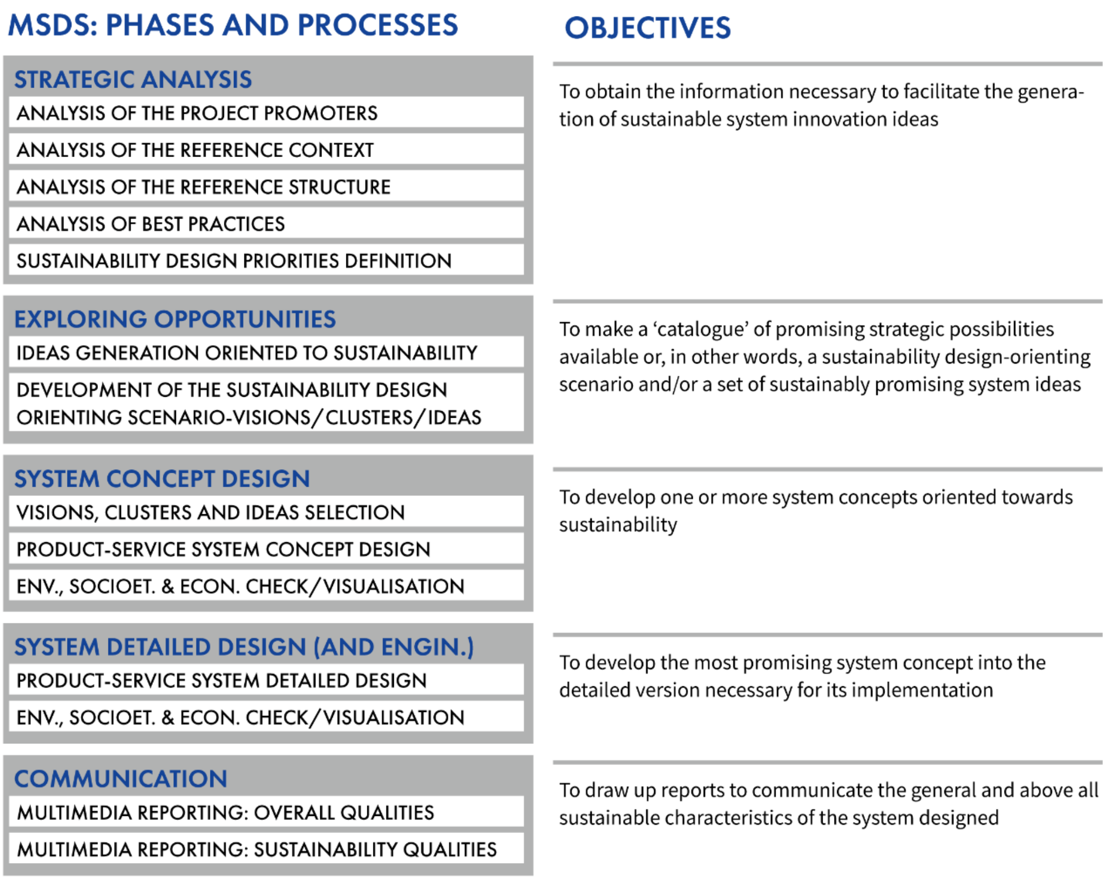


Figure 4 The MSDS method phases, processes and objectives (Vezzoli et al., 2021b)

2.3.3 Tools for Design for Sustainability

With the advancement of Design for Sustainability (DfS), numerous tools within the DfS domain have been introduced (Elena Windolph et al., 2014). Simultaneously, as the field witnesses the rapid increase of DfS tools, users frequently encounter increased uncertainty and a deficiency in the necessary knowledge base and competencies needed to select the appropriate tools for specific situations.

A comprehensive analysis was conducted on 120 tools originating from 29 different institutions and 58 publications. These tools, specifically tailored for promoting sustainable design, can be classified into two primary categories. The first category comprises tools intended for product design for sustainability, while the second category encompasses tools geared towards Product-Service System (PSS) or service design for sustainability, as illustrated in Figure 5.

Within the first category, tools for product design for sustainability can be further subdivided into two main types: (1) tools for environmental assessment, encompassing both quantitative and qualitative evaluation tools, and (2) orientation tools for the generation of environmentally sustainable solutions (Vezzoli, 2018). This paper goes on to categorize orientation tools as follows: (2.1) Dedicated tools for specific environmental performance aspects, such as tools for material selection, minimizing the use of toxic or harmful materials, designing for recyclability, enabling disassembly and remanufacturing, and adhering to sustainable regulations, policies, and standards. (2.2) Tools for comprehensive Life Cycle Design (LCD) of products. (2.3) Tools tailored for specific product types, industries, or sectors, such as those used in aircraft or electric facilities. (2.4) Tools for describing, organizing, and documenting the design process, such as design briefs.

For the second category, tools for PSS/service design for sustainability could be further classified as (1) tools for sustainability evaluation including qualitative check for one solution/concept or comparison among different solutions/concepts, and (2) orientation tools including design tools, description tools and specific tools for certain types of PSS/firm/sector.

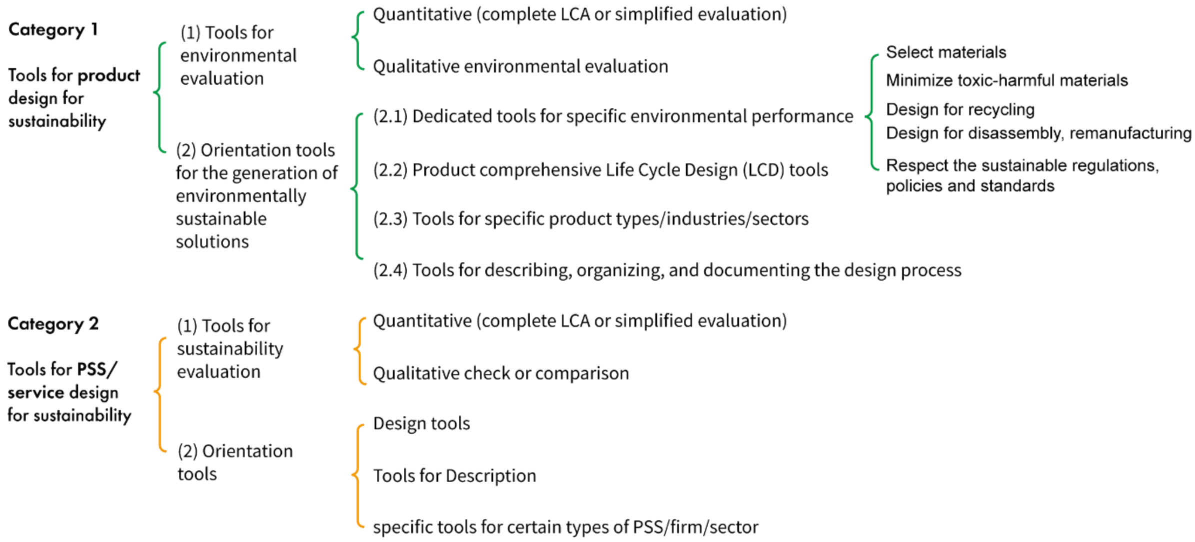


Figure 5 Classification of DfS tools, image adapted from (Charter & Tischner, 2001; Vezzoli, 2018) and with new findings within this study

2.3.4 Tools for Sustainable Furniture System Design

Among all the investigated tools, some are specifically developed for furniture, while some are general but applicable to furniture. Although I have identified certain general tools that can be utilized in furniture design, there are gaps in the furniture design process. On the product level, there is a lack of qualitative environmental evaluation tools tailored for furniture products and furniture-specific Life Cycle Design (LCD) tools, see

Table 4. On the Product-Service System (PSS) level, there is a lack of qualitative environmental evaluation tools and Sustainable PSS design tools tailored for furniture systems, see Table 5.

Table 4 The existing tool applicable to furniture product Life Cycle Design and the gaps

Categories	Sub-categories	Tools
Tools for furniture product environmental evaluation	Complete LCA tools	Annex 7_table 2
	Simplified evaluation tools	Annex 7_table 3 and table 4
	Qualitative Environmental Evaluation Tools	gap
Tools for furniture product orientation	Dedicated tools for specific environmental performance	Annex 7_table 9
	Life Cycle Design (LCD) Tools	gap
	Tools for description	Annex 7_table 12

Table 5 The existing tools for /applicable to furniture S.PSS design and the gaps

Categories	Sub-categories	Tools
Tools for Sustainable furniture PSS Evaluation	Complete LCA tools	Annex 7_table 2
	Qualitative Evaluation Tools for furniture	gap
Tools for Sustainable furniture PSS design	SPSS Design Tools for furniture	gap
	System Description Tools	See Annex 7 table 16

Chapter 3 The research scope and research questions

Building upon the findings from the first two chapters, this research has established the scope of investigation based on three key aspects: Definition of Furniture, Sustainable Dimensions and Design for Sustainability approaches adopted in this PhD work.

Sustainable Dimensions considered by this research

Research that comprehensively evaluates sustainability within the furniture industry, considering the Triple Bottom Line, remains limited in availability (Feil et al., 2022; Hartini et al., 2020). In a specific study that assessed the sustainability of micro- and small-sized furniture companies in Brazil, the findings revealed that enhancing sustainability primarily requires a concentrated effort on improving critical environmental aspects, rather than diverting focus to areas such as social and economic factors. This improvement was suggested to be achievable through the development of a strategic planning framework with predefined objectives aimed at elevating the sustainability level (Feil et al., 2022).

The research draws upon data from Chapter 1, which underscores the significant environmental impact stemming from both the life cycle of furniture and the furniture production and consumption system. Consequently, the need for environmental improvements within the furniture sector is pressing. It is essential to recognize that while environmental improvements are crucial, they should not come at the expense of the economic benefits of stakeholders operating within the furniture system. Therefore, the research scope is designed to encompass both the environmental and economic dimensions, ensuring a holistic approach to sustainability within the furniture industry.

The adopted design for sustainability approaches

Having examined a range of Design for Sustainability approaches and their applicability to the furniture sector, this study has recognized significant potential for promoting sustainable furniture system development. These opportunities manifest at both the product and Product-Service System levels. On the product level, the application of the Life Cycle Design (LCD) approach proves to be highly effective in enhancing the sustainability of individual furniture products. On the broader production and consumption system level, the furniture system can greatly benefit from the adoption of the Sustainable Product-Service System Design (S.PSSD) approach, as illustrated in Figure 6. By addressing sustainability considerations at both these levels, the research aims to contribute to a more environmentally and economically sustainable furniture system.

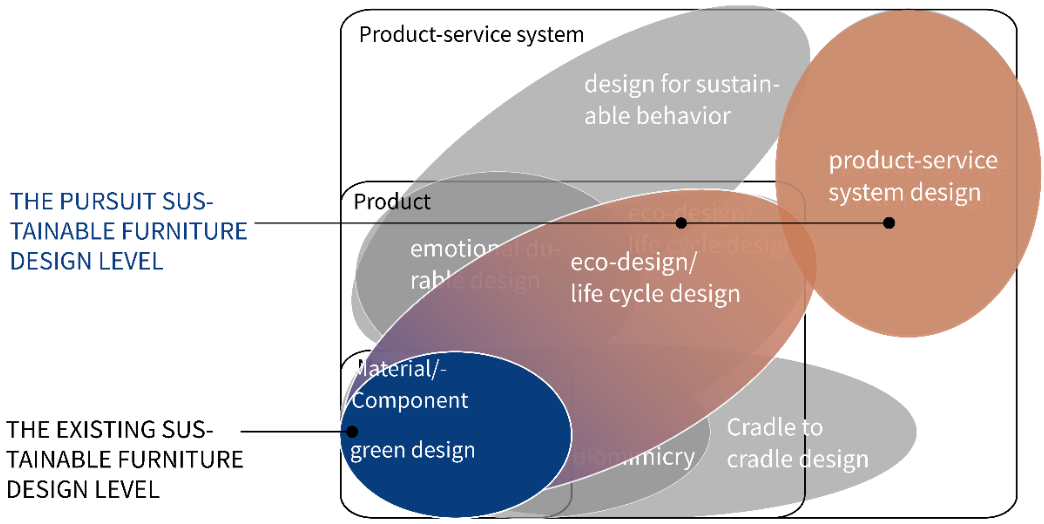


Figure 6 The potential of design for promoting sustainable furniture system development

Moreover, the European Union, as outlined in the Circular Economy action plan, recognizes the pivotal role of design in steering product-level innovation. It emphasizes that as much as 80% of a product's environmental impacts are determined during the design phase. Importantly, the EU also acknowledges that environmental concerns extend beyond the product itself. The action plan recommends incentivizing models such as product-as-a-service or others where producers retain ownership of the product or responsibility for its performance throughout its life cycle (European Commission, 2020). This concept aligns with the "win-win offer model" or "business model" known as Sustainable Product-Service System (SPSS), a subject that has been under study since the late 1990s, as illustrated in Figure 7.

Figure 7 The rationale of design intervention on both product and Product-Service System levels (European Commission, 2020)

In summary, this research endeavors to address the environmental impact within the furniture sector while concurrently taking into account economic sustainability. It achieves this by delving into the application of Design for Sustainability (DfS) approaches in the furniture system. The research's primary goal is to tackle environmental challenges from both the lifecycle of furniture products and the broader furniture production and consumption system. To accomplish this, it employs two key DfS approaches, namely Life Cycle Design (LCD) and Sustainable Product-Service System Design (S.PSSD). Through this dual approach, the research aims to promote environmental sustainability without compromising the economic benefits of stakeholders in the furniture industry.

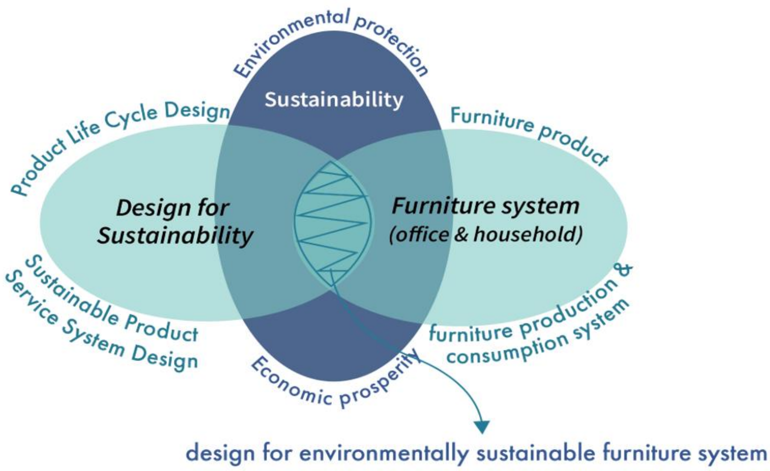


Figure 8 The scope of the research

Research questions

According to the former considerations, the main research questions for this research are:

RQ1: What are the framework and characteristics of environmentally Sustainable Furniture Systems?

RQ1.1 What are the innovation requirements and characteristics of environmentally sustainable furniture products (product level)?

RQ1.2 What are the characteristics of environmentally and economically sustainable win-win furniture Product-Service Systems (PSS level)?

RQ2: What new knowledge is needed to design environmentally Sustainable Furniture Systems?

RQ2.1 What new competencies, skills, methods, and tools are needed for environmentally sustainable furniture Life Cycle Design (product level)?

RQ2.2 What new competencies, skills, methods, and tools are needed for environmentally Sustainable furniture Product-Service System Design (PSS level)?

Chapter 4 Research Methodology

This chapter presents the roadmap to address the research questions for this research. It describes elements for the research design of the paradigm, approach, purpose, strategy, methodology, and the rationale of this roadmap. It clarifies how this design research is designed.

"Research design is the logic that links the data to be collected and the conclusions to be drawn to the initial questions of a study."
(Yin, 1994).

4.1 Research paradigm

Research paradigm is a worldview that guides researchers or investigators in choosing methods in ontologically and epistemologically fundamental ways (Guba & Lincoln, 1994). This research follows the constructivism paradigm, with the idea that there is a reality of sustainable furniture systems which are composed of furniture products and Product-Service systems with identifiable properties. The research constructs the truth (knowledge) of sustainable furniture systems and facilitates the final application of these knowledge in the practical furniture system, in collaboration with experts from the design for sustainability community and furniture practitioners.

Ontologically, this research assumes that the knowledge base and know-how of the Sustainable Furniture System can be constructed through the PhD researcher with experts' lived experiences and interactions with other practitioners within the furniture system. The PHD candidate facilitated all subject-involved research activities (interviews/ workshops/ focus groups with experts/designers) to ensure the knowledge produced is reflective of reality. Another stance is the results from broadly contextualized research methods may prove too global and abstract to be useful in many settings (Cobb, 2001; Cobb et al., 2003; E.

Baumgartner & Bell, 2002), so furniture-specific DfS knowledge base and know-how are necessary to make the design efficient and effective.

Epistemologically, this research on developing knowledge base and know-how for Sustainable Furniture System Design is simultaneously empirical, intersubjective, and process oriented. Along the research process, the data generated by experts or practitioners from research activities like interviews always contain our lived experiences. Paradigmatic strands of research are fluid and keep altering and enlarging. In other words, the boundaries between paradigms are shifting (Denzin & Lincoln, 2018). This research also admits the critical subjectivity and four ways of knowing: experiential, presentational, propositional, and practical, which are the paradigm of participatory.

This paragraph introduces some practical issues of this research related to its paradigm. The research aims are twofold. Firstly, this research aims to develop specific knowledge, including conceptual framework, data, approaches, guidelines, methods, and tools, of Sustainable Furniture System Design (obtained from the joint construction/reconstruction of lived experiences of the researcher with other experts, practitioners; second, such knowledge of Sustainable Furniture System Design is sought to inform praxis (improved practice). To ensure the quality of this research, which encompasses the credibility, transferability, dependability, and confirmability of the results, the study incorporates expertise from both academic and practical experts spanning interdisciplinary fields such as design for sustainability and furniture design. Knowledge from diverse sources, including literature, reports, furniture companies, and design studios are gathered. Additionally, evaluations involve various stakeholders and undergo iterative improvement processes. The PhD candidate plays the role of a passionate participant and facilitator of multi-voice reconstruction and attempts to gain increased knowledge regarding the sustainable furniture system by interpreting different stakeholders’ perceptions and experiences about the topic. This is to say that data produced on this research topic do not have to be from a common unit, and multiple forms of data are generated. This research paradigm has some commensurability with the participatory paradigm.

Methodology is an important element of the paradigm. However, it is also a complex issue to be considered. Chapter 4.3 demonstrates the methodology of this research in detail.

4.2 Research purposes, strategies, and approaches

4.2.1 Research purposes

The dominant purpose of this PhD research is exploration. Overall, the research aims to find out the knowledge base (in the form of theoretical framework, data, approaches, guidelines, etc.) and know-how (in the form of methods, and tools) for Sustainable Furniture System Design, specifically for furniture Life Cycle Design (LCD) and Sustainable furniture Product-Service System Design (PSSD), which have not been comprehensively understood. Although general LCD and S.PSSD knowledge (for example, general guidelines) have been developed, it is not said that they are efficient or even proper for specific product sectors, in this case, furniture. To be effective in a specific context, knowledge base, and know-how should inspire and indicate design decisions and solutions that have the major potential to be sustainable as precisely as possible; they should "provide specific advice and strategies on how to reduce impacts" (Vezzoli & Sciama, 2006).

More than one purpose can be associated for the same study, with one normally dominating a particular study (Neuman, 2014). For this PhD research, exploratory activities dominate the direction and main outcomes, with some descriptive purposes pursued throughout the whole research process.

Table 6 Research questions and objectives

Research Questions	Research objectives
RQ1: What are the framework and characteristics of environmentally Sustainable Furniture Systems?	To provide a comprehensive framework of sustainable furniture systems
RQ1.1 What are the innovation requirements and characteristics of environmentally sustainable furniture products (product level)?	to explore furniture products' life cycle profile (activities and environmental impact) to identify design interventions for environmentally sustainable furniture products
RQ1.2 What are the characteristics of environmentally and economically sustainable win-win furniture Product-Service Systems (PSS level)?	to explore furniture system's environmental impact to explore furniture PSS's profile, and characteristics to develop an archetypal furniture S.PSS map
RQ2: What new knowledge is needed to design environmentally Sustainable Furniture Systems?	to develop guidelines, methods and tools for Sustainable Furniture System Design
RQ2.1 What new competencies, skills, methods, and tools are needed for environmentally sustainable furniture Life Cycle Design (product level)? RQ2.2 What new competencies, skills, methods, and tools are needed for environmentally Sustainable furniture Product-Service System Design (PSS level)?	to develop furniture-specific system design guidelines (including furniture LCD and furniture S.PSSD) to develop furniture system design method and tools

4.2.2 Research design strategies

This PhD research dominantly follows the qualitative research approach (Creswell, 2009) and applies the flexible design strategy (Robson & McCartan, 2016) and inductive approach (Dewey, 1997). Table 7 presents a visual representation of how various approaches and strategies are integrated within this research. It outlines a comprehensive research process that highlights the activities carried out to address the Research Questions. To address RQ 1 specifically, a qualitative strategy has been employed, complemented by the LCA utilizing a quantitative approach, all guided by an inductive methodology. The activities carried out to meet the objectives of RQ 1 are: (1) Literature reviewing to explore furniture system's environmental impacts and design insights from academic perspective; (2) LCA of 25 furniture pieces to explore furniture products' environmental impact and design insights from practical perspectives, which further developed furniture products' life cycle profile (integrated into 162 histograms giving insights to designers, in annex 6); (3) Best cases analysis and semi-structured interviews on furniture products and furniture S.PSS, to identify sustainable characteristics and developed case cards. On the products level, sustainable furniture products design insights were identified; on the PSS level, furniture S.PSS win-win benefits and furniture S.PSS archetypal map was developed.

Knowledge developed in the first phase has been used as the foundation to carry out a second stage of the research aimed at answering RQ 2. A qualitative strategy has been applied, adopting a mixed inductive-deductive approach. The activities carried out to meet the objectives of RQ 2 including a workshop and an iterative process of design, evaluations (in workshops, interviews, questionnaires), and refinement. Within workshops with experts, draft guidelines for sustainable furniture system design (on both product and S.PSS levels) are developed based on the general guidelines (with a hierarchy structure of strategy-sub-strategy-guidelines, and by integrating knowledge from the RQ1 and experts' knowledge. Specifically, with the LCA results, the priorities of design strategies were identified using a qualitative approach. These guidelines are further reviewed by experts from academic and practical fields to generate the final comprehensive furniture-specifci LCD and S.PSSD guidelines with priorities. On a second step, these developed guidelines were integrated into several furniture LCD and S.PSSD tools. After iterative evaluation and refinement, the final version of furniture LCD and S.PSSD tools were developed.

4.2.3 Design research approaches

The aforementioned research strategies (in chapter 4.2.2) have been adopted from the field of social sciences and have been employed to establish a broad framework for this study Table 7. However, it is worthwhile to consider approaches from the design field that can offer a more comprehensive framework for this research.

Firstly, consider Cross's definition (Cross, 2006), this Ph.D. research lies in design phenomenology which is the study of the form and configuration of artifacts, in this research, sustainable furniture product Life Cycle and sustainable furniture PSS. The result are furniture-specific design knowledge, strategies/guidelines on the LCD aspects and S.PSSD aspects. Secondly, this PhD research lies in design praxeology, which is the study of the practices and processes of designing Sustainable Furniture Systems. The result is Sustainable Furniture System Design methods and tools.

Considering Fallman's framework for design research positions (Fallman, 2008), this research can be defined as design studies. This research focuses on contributing to the knowledge that is specific to the furniture system. The research develops theories of furniture Life Cycle Design and furniture Sustainable Product-Service System Design in the form of environmental profiles, conceptual framework, and design strategies/guidelines. The research also develops a methodology for Sustainable Furniture System Design with detailed design steps and tools.

If considering Frayling's classification (Frayling, 1993), the research follows a Research Through Design approach because research activities for answering requestions emphasize creating design knowledge rather than project solutions. Design knowledge includes conceptual framework, data, approaches, guidelines, methods, and tools. Activities taken in this research aim to acquire and shape Sustainable Furniture System Design knowledge that assists in future design activities. The PhD candidate is directly involved in each activity to establish, connect, and shape research objects (i.e. the Sustainable Furniture System).

To develop sustainable furniture system design method and tools, the research follows research through design approach. These methods and tools provide guidance, information, and data that designers can apply to achieve a result in their projects. The artifacts undergone iterative process of design-evaluation-refinement as a legitimate method of inquiry to develop satisfied tools (comprehensibility, usability, usefulness/success) for the needs of furniture designers.

Table 7 Research strategies, approaches, activities, purpose to address research question within this PhD research.

	Research questions	Research objectives/ purposes	Research activities	Research strategy/ approaches
preliminary research	RQ1 What are the framework and characteristics of environmentally Sustainable Furniture Systems?	A to provide a comprehensive conceptual framework for sustainable furniture systems **(exploration)**		Qualitative & inductive & Design phenomenology
	1.1 What are the innovation requirements and characteristics of environmentally sustainable furniture products (product level)?	A1 to explore in detail furniture products' furniture products' life cycle profile (life cycle activities, environmental impact and design insights) from practice A2 to explore the sustainable characteristics, deisgn insights of furniture products	literature review A1 A3 life cycle assessment A1	
	1.2 What are the characteristics of environmentally and economically Sustainable win-win furniture Product-Service Systems (PSS level)?	A3 to explore the sustainable characteristics, deisgn insights, potential win-win benefits of furniture S.PSSD A4 to develop an archetypal furniture S.PSS map	case study A2 A3 A4 semi-structured interviews A2 A3 A4	
Prototyping	RQ2 What new knowledge is needed to design environmentally Sustainable Furniture Systems?	B to develop knowledge and know-how for SFSD **(exploration and description)**		
	2.1 What new competencies, skills, methods and tools are needed for environmentally sustainable furniture Life Cycle Design (product level)?	B1 to develop furniture-specific system design guidelines (including furniture LCD and furniture S.PSSD) with priorities **(exploration)**	expert workshops B1	
Assessing	2.2 What new competencies, skills, methods and tools are needed for environmentally Sustainable furniture Product-Service System Design (PSS level)?	B2 to develop furniture system design method and tools **(description)**	design workshops/focus groups evaluation questionnaire interviews refine B2	Qualitative& deductive & design praxeology

4.3 Research Methodology – Design-Based Research [11]

Due to the complexity of this research and the number of strategies/approaches adopted and activities planned, a design research methodology framework needed to be adopted to guide throughout the conduction of this PhD research.

After reviewing the research methodologies, paradigms, approaches, etc., the Design-Based Research (DBR) methodology is adopted in this research. DBR can be defined as a systematic but flexible methodology aimed to improve practices through iterative analysis, design, development, and implementation of interventions, based on collaboration among researchers and practitioners in real-world settings and leading to contextually-sensitive design principles and theories (F. Wang & Hannafin, 2005). DBR does not replace or conflict with other methodologies, such as quantitative or qualitative methodologies, but provides an alternative approach that emphasizes direct, scalable, and concurrent improvement in research, theory, and practice.

Brown and Collins are widely acknowledged as early contributors to the definition and activation of design-based research. They described DBR as a methodology that requires (Brown, 1992; Collins, 1992):

- addressing complex problems in real contexts in collaboration with practitioners;
- integrating known and hypothetical design principles with technological affordances to render plausible solutions to these complex problems and
- Conduct a rigorous and reflective inquiry to test and refine innovative learning environments as well as to define new design principles.

[11] This chapter, 4.3, partially refers to the publication of the author entitled "Design for Environmentally sustainable furniture systems – the knowledge and know-how of furniture life cycle design and furniture sustainable product-service system design" (Yang, 2023).

Design-based research (DBR) strives toward two main goals simultaneously: advancing theoretical understanding and developing an intervention in the real world. DBR has the following characteristics: focusing on the design and testing of interventions, using mixed methods, involving multiple iterations, stemming from a partnership between researchers and practitioners, yielding design principles, different from action research, and is concerned with an impact on the practice field (Anderson & Shattuck, 2012).

DBR consists of four main stages: Analysis of practical problems, development of solutions informed by existing design principles, iterative cycles of testing and refinement of solutions in practice, and reflection to produce design principles and enhance solution implementation (Herrington et al., 2007; Reeves et al., 2005), see Figure 9. Some researchers follow a three-stage research process with preliminary research, prototyping and assessment, and reflection (Ceschin, 2012; Diehl, 2010), see Figure 10. These two research processes are the same, with the latter merging prototyping and assessment while the former separates these two steps.

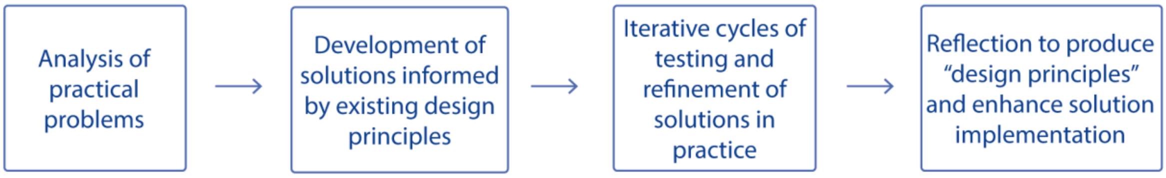


Figure 9 Design-based research methodology process (Herrington et al., 2007; Reeves et al., 2005)

Figure 10 Design-based research methodology process (Ceschin, 2012; Diehl, 2010)

The following paragraphs introduce the characteristics of this research and the the process conducted.

4.3.1 Characteristics of this research

DBR methodology is chosen to be used in this research because this research has the following characteristics that are coherent with DBR: (a) pragmatic, (b) grounded, (c) interactive, iterative, and flexible, (d) integrative; and (e) contextual.

This PhD research is Pragmatic. DBR addresses practical issues to promote a fundamental understanding of the design (Orrill et al., 2004). The main practical issue to be addressed is the environmental impact that occurred during the furniture's life cycle and from the furniture production and consumption system. The research process is iterative exploration, development, and implementation. The main knowledge includes detailed furniture life cycle profile, a conceptual framework of Sustainable Furniture System Design, the furniture-specific Life Cycle Design strategies/guidelines and Sustainable Furniture Product-Service System design strategies/guidelines. These outcomes are useful for conceptual understanding of furniture system and practical for design activities. From a design-based research perspective, theory development is inextricably linked to practice (Brown & Campione, 1996). Research should refine both theory and practice fields (Collins et al., 2004) as well as provide new possibilities. To make the aforementioned knowledge (strategies/guidelines/environmental profile/conceptual framework) more practical, the research also designed relevant tools to support the real design process of furniture LCD and Furniture S.PSSD through a new round of exploration, tool design, evaluation, and refinement. Ultimately, the value of these design strategies and guidelines is validated during the design process by informing and improving practice.

For this research, the development of furniture Life Cycle Design knowledge and tools was integrated into the project "The Circular Economy for the Competitiveness of the Made in Italy Industry – GIOTTO." This project, conducted in collaboration with eleven national organizations and funded by the Italian Ministry of Education and Research (MIUR), aimed to develop and disseminate innovative design guidelines and tools to foster a sustainable and circular economy within the competitive value chains of the Made in Italy industries, including furniture, food, and fashion. Through a multidisciplinary and collaborative research consortium, GIOTTO empowered small and medium enterprises with innovative approaches to minimize the environmental impact of their products across their entire life cycle. The project-furniture section involved experts from various disciplines and institutions, including: 1) COSMOB: Centro Tecnologico specializzato per il settore legno – arredo, 2) Cluster Arredo: Società consortile preposta allo sviluppo del Cluster di iferimento del Friuli Venezia Giulia, con l'obiettivo di fornire servizi alle aziende del comparto e, in qualità di Polo di innovazione. 3) UNIVERITA' DI CAMERINO (UNICAM): L'Unità di Disegno Industriale della Scuola di Architettura e Design UNICAM.

For this project's furniture section, I initially conducted a literature review, case studies, organized a workshop to develop furniture-specific Life Cycle Design (LCD) guidelines and developed the ICSxFurniture toolkit for evaluation by collaborators. However, the PhD research was not linear but iterative. Following the GIOTTO project, the research was further deepened by conducting a more comprehensive literature review, broader research of cases, semi-structured interviews, and a comprehensive Life Cycle Assessment (LCA) to finalize the concept framework and furniture-specific LCD guidelines. A series of evaluation and improvement activities were conducted to finalize the ICSxFurniture toolkit. These knowledge and tools were developed to contribute to theory and practice in sustainable furniture product design or Furniture Life Cycle Design in this research.

The part concerning furniture Sustainable Product-Service System Design theory and practice, another important aspect of this research, was not included in the GIOTTO project.

This PhD research is grounded. Prior to embarking on Design-Based Research (DBR), researchers select a theory about learning and instruction. They examine existing literature and available design cases, identifying gaps to ensure the research's value (Edelson, 2002), as well as pinpoint any existing problems or issues. In subsequent phases, they aim to revise and refine this chosen theory by determining which interventions should (or should not) be introduced and which should be eliminated. The foundational theory for this PhD research is rooted in Design for Sustainability theories, within which the theories of Life Cycle Design (LCD) and Sustainable Product-Service System Design (S.PSSD) serve as focal points for further exploration within the context of furniture systems. Extensive literature reviews and case studies were conducted to assess the applicability and value of these theories within the furniture system, particularly in identifying gaps that existed in the realm of furniture's sustainable development. Given that the general theory may not be entirely applicable to the unique domain of furniture, the research subsequently aimed to tailor and refine these theories to make them more specific and relevant to furniture.

This PhD research is interactive, iterative, and flexible. It is interactive between researchers and practitioners, emphasizing collaboration throughout the research process. The aim is to identify approaches and develop principles to address the environmental challenges from the furniture sector. Different practitioners, including furniture designers, furniture sustainability managers, furniture marketing managers, etc., were involved in the research activities for developing/evaluating theoretical/practical outcomes during semi-structured interviews, workshops, focused groups, etc. The PhD candidate herself had a background in furniture design and management. During the research activities which involved other experts or practitioners, she played a pivotal role in managing the process, nurturing relationships with practitioners, and, most importantly, gaining a deeper understanding of the research context. In addition, this PhD research methodology is flexible and iterative. During the research process, the initial research plan was improved iteratively since the research activities were iterative and data were accumulated. The main outcomes of this research include theory contributions (environmental profiles, conceptual framework, an archetypal furniture S.PSS map, design strategies/guidelines) and practical contributions (method and tools) for furniture LCD and furniture S.PSSD. Both development processes are not linear but rather iterative, with several rounds of development, evaluation, and refinement/ improvement.

The PhD research is Integrative. Design-based research draws from a diverse range of commonly employed approaches, including surveys, expert reviews, evaluations, case studies, interviews, inquiry methods, and comparative analysis (see, e.g., (Richey et al., 2004)). Through the utilization of a combination of these methods, the research benefits from data derived from multiple sources, thereby enhancing the objectivity, validity, and relevance of the ongoing research. This PhD research applied various methods, including quantitative and qualitative ones. For example, to identify the environmental impact of furniture, a qualitative literature review, and quantitative life cycle assessment were conducted with coherent results achieved. To develop furniture-specific strategies/guidelines, the general strategies/guidelines were examined, the best practices were analyzed, the literature review was conducted, experts' ideas were collected, etc., to reach a finalized version. To evaluate the developed furniture system design tools, workshops/interviews/focus groups with designers and researchers were conducted to collect opinions from different sides. By using different methods, involving different roles of experts, and collecting data from different sources, the researcher tried to make the research valid and applicable.

The PhD research is contextual and relevant to the furniture sector. The outcomes derived from broadly contextualized research methods are overly general and abstract, limiting their utility in diverse settings (Cobb, 2001; Cobb et al., 2003; E. Baumgartner & Bell, 2002). In the context of Design for Sustainability, many general sustainable design guidelines, methods, or tools have been developed. However, they are less useful or inefficient for the furniture context. This research aims to develop a furniture-specific theoretical and practical knowledge base and know-how to improve the sustainable furniture system design efficiency.

4.3.2 Research stage I: Analysis of practical problems (preliminary research)

The first phase of design-based research is rooted in essential steps of problem identification, literature survey, and problem definition (Bannan-Ritland, 2003), which are common to most research approaches. The main objectives of this stage are developing a picture of the existing situation, i.e., identification of research problems, goals, and questions in a specific research area. In the next research step, the area of investigation is also referred to as the Initial Reference Model - the reference against which the intended improvements are benchmarked (Blessing & Chakrabarti, 2009). In other words, this stage aims at gaining a deeper understanding of the phenomenon under investigation to provide the basis for the next stage of developing solutions for existing situations.

For this PhD research, the first stage is to comprehensively understand the theoretical framework of design for sustainable furniture systems, including the existing environmental problems caused by the furniture system (both along its life cycle and from the production and consumption system), the state of art about Sustainable Furniture System Design, and the progress of Design for Sustainability knowledge. Then, the research problems, gaps, and objectives are identified. In the second step, the research further investigated the furniture product's environmental problems using quantitative method, the sustainable characteristics and design interventions of the furniture system (RQ 1).

Several research activities and methods are taken, including a literature review, a set of Life Cycle Assessments (LCA) of furniture from different categories, case study research and semi-structured interviews on sustainable furniture systems. The result is a comprehensive conceptual framework.

Literature review

A literature review is effective in building a logical framework for research (Marshall & Rossman, 2010). This research started with a literature review on sustainable furniture systems, focusing on the environmental sustainability dimension. In particular, the following main issues were explored:

The furniture system's sustainable development context. The aim is to provide a convincing argument that the environmental problems of the furniture system are significant and worth researching (chapter 1).

The state of art of design for sustainability knowledge and sustainable furniture design. The development of design for sustainability and the development of sustainable furniture are explored (chapter 2). By cross-comparison of these two topics, the research opportunities are identified.

Life Cycle Assessment

Life Cycle Assessment has been recognized as a significant technique to understand and address the environmental aspects throughout a product's life cycle (ISO 14044: 2006 Environmental Management - Life Cycle Assessment - Requirements and Guidelines, 2006).

Sampling. To understand the environmental impact of different furniture pieces from different categories along the life cycle, I conducted 25 LCA of typical furniture from 8 typologies (see chapter 5.1). The aims were 3 folded: to define comprehensive furniture life cycle profiles, and present results that can be valuable for designers; to address data gap by providing a comprehensive overview of environmental trends; and to establish a knowledge base in developing furniture guidelines and define design strategies' priorities.

Method. The activity followed the ISO 14040 proposed LCA methodology, with a process of: 1) goal and scope definition, 2) inventory analysis, 3) impact assessment and 4) result interpretation.

Results. detailed furniture life cycle activities were identified, with a system boundary of a general furniture product developed. Each furniture's life cycle inventory was analyzed as the fundamental data of LCA. Furniture products' environmental profiles were developed which offered valuable insights for designers seeking to make more sustainable choices in their designs.

Case study

A case study approach is appropriate for studying new topic areas (Corbin & Strauss, 2015) and especially for understanding complex phenomena (Merriam, 1998). This research collected sustainable furniture product design cases (chapter 5.2) and furniture S.PSSD cases (chapter 6.3) to understand sustainable furniture systems' characteristics, environmental benefits, design interventions.

Sampling. Since the aim is to describe the sustainable characteristics of the furniture system comprehensively, the maximum variation strategy was adopted for selecting cases. This means cases with heterogeneity and maximized diversity are considered to cover all possible differences in sustainable furniture system characteristics.

Method. The triangulation principle was applied when collecting data for a case: multiple methods for collecting data and multiple sources are considered to ensure the convergence of a case. Within this research, the method used to collect data included literature review, desk research, semi-structured interviews, and field investigations. The sources of information are secondary data, including scientific papers such as case studies made by other researchers, reports made by international organizations such as the European Commission, companies' reports, websites, etc.

Results. A final number of 41 sustainable furniture product cases and 44 furniture S.PSSD cases were collected and analyzed. For sustainable furniture products, each case is detailed described with basic information and sustainable design information, including design methods, products' sustainable characteristics, and design strategies with images. 15 sustainable characteristics and 37 design interventions were identified. On the furniture S.PSSD level, each case is detailed described with basic information and sustainable design information including products, services, stakeholders interactions, payment methods, sustainable benefits, and design strategies. Three types of furniture S.PSS were identified; 6 furniture-using contexts were identified; Services related to furniture throughout its life cycle were identified; Furniture S.PSS win-win benefits were confirmed; A comprehensive map with 20 different furniture S.PSS models developed. Each model was accompanied by a descriptive text and a system map to visualize their structure and operation.

Semi-structured interview

Qualitative interviewing is a flexible and powerful method to capture the voices and meaning of experiences (Rabionet, 2011). Interview data is situated and interesting, with a co-constructed nature. Design-based research places much value on the input of practitioners and researchers working in or investigating the problem area (Herrington et al., 2007). The aim was to understand further the characteristics of existing sustainable furniture systems (both furniture LCD and furniture S.PSS) in close collaboration with practitioners in the field of Sustainable Furniture System Design.

Sampling. The interviewees involved in this semi-structured interview are furniture company experts working on the environmental sustainability dimension. They have expertise in sustainable furniture product design and/or sustainable furniture business models or product-service systems design with some of the following experiences: (1) they are conducting or conducted Life cycle assessment for some of their furniture; (2) they are designing furniture products with environmentally sustainable characteristics; (3) they are offering sustainable furniture business models or Product-Service Systems. A total of 10 companies were involved in the semi-structured interview. Firstly, the case details were checked and confirmed with some of these experts; second, the application of design approaches, methods, and tools in their company were investigated.

Method. After confirming the participants, the questions were prepared ahead of time. Interviews were recorded with the permission of the participants. After a process of furniture product design approaches, method and tools discussion, furniture S.PSS relevant questions were discussed. All interviews were further analyzed.

Results. The cases information was detailed. On the furniture product level, different design strategies/design insights were proposed by furniture companies; on the furniture S.PSS level, the furniture S.PSS win-win benefits were verified, and a sustainable furniture system design conceptual framework was developed. Although with some new insights, the results showed a lack of approaches, methods, and tools on sustainable furniture system design for furniture companies.

4.3.3 Research stage II: Development of solutions informed by existing principles (prototyping)

The second phase of the design-based research is to develop solutions to the problems based on the conceptual framework proposed in research stage 1. Design-based research suggests a pragmatic philosophical underpinning, one in which the value of a theory lies in its ability to produce changes in the world (Barab & Squire, 2004).

(1) Development of furniture-specific system design guidelines (for both furniture LCD and S.PSSD)

In this stage, the new role of design in developing environmentally sustainable furniture systems, both on the product and S.PSS level, was defined. Sustainable furniture system design guidelines (both for furniture products and furniture S.PSS) were developed using a consolidated method (Figure 11). Specifically, the development of the furniture-specific guidelines was based initially on the general design guidelines and integrating the insights from the first stage of the research to develop the draft version of furniture-specific guidelines. The draft design guidelines were further reviewed by internal and external experts to form the final version of guidelines.

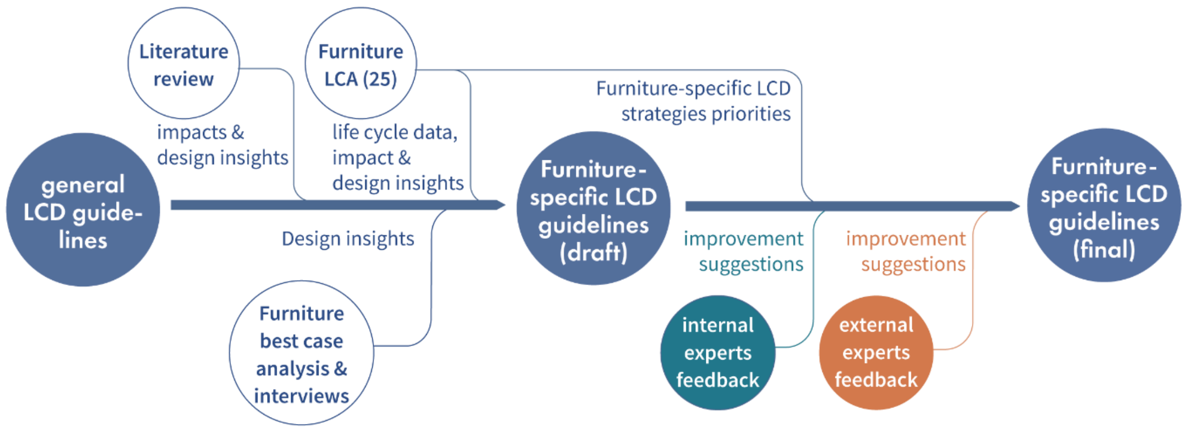


Figure 11 Prior knowledge and steps to develop furniture-specific product LCD and S.PSSD strategies/sub-strategies/guidelines, adapted from (L. I. Chaves, 2008; Vezzoli & Sciama, 2006)

Note: White text with orange background represents external competence (e.g. knowledge and know-how from GIOTTO project partners (COSMOB, Cluster Arredo, and UNICAM). White text with cyan background represents internal competence (inside the LeNS Lab where the PhD candidate involved). Blue text with blue frame represents research activities made by the PhD candidate and the original data, information comes from other researchers (literature), furniture companies (reports, interviews, websites), or practitioners (interviews).

Workshop with experts

Workshops are context-specific research methods where the researcher not only “describes, understand and explain” (Robson, 1993), but also the generation of objects through collaboration within a certain context.

Sampling. Purpose sampling was used to invite participants to the workshop session based on the following criteria since the aim is to generate furniture-specific LCD and S.PSSD guidelines. (1) Heterogeneity. Participants from different and relevant backgrounds (furniture design and design for sustainability) should be involved, so participants come from fields like furniture design and engineering (1 participant), design for sustainability (4 participants), interior and furniture design (1 participant), and (2) Expertise. Participants should have expertise in their fields. A total of 6 experts joined this section.

Method. In the second research stage, workshops were used to develop the draft version of the furniture-specific design guidelines with experts by integrating knowledge developed in the first stage (life cycle profile, design insights, conceptual framework etc.). Before the workshop, a note was sent to participants for them to develop their own version of furniture-specific design guidelines which will be discussed during the workshop. At the beginning of the workshop, the author introduced the knowledge generated from the first research stage and facilitated the specification process. A structured process was implemented for each general guideline, allowing participants to perform a variety of specification actions such as integrating a general guideline related to particular furniture products or typology, adding a new guideline that deals with a certain environmental impact related to particular furniture products or typology; adding notes related to particular furniture product or typology; and erasing a guideline if irrelevant.

Results. The draft version of furniture-specific guidelines was developed and then reviewed by experts to develop the final version of design guidelines, including both the furniture-specific LCD guidelines (chapter 7.1) and furniture-specific S.PSSD guidelines (chapter 7.2). Then with a design process, these guidelines and the knowledge developed in the first research stage were integrated into several tools, including the ICSxFurniture toolkit, SDOxFurniture toolkit, concept sheet for furniture S.PSS and System Map for S.PSS (Chapter 7).

(2) Development of furniture-specific system design method and tools

A review of existing design for sustainability methods and tools was undertaken to identify the gap of sustainable furniture system design tools and identify promising ones that could serve as references when developing furniture-specific ones. Subsequently, a selection and design/adaptation process were followed for adoption within the furniture context. This process included brainstorming sessions with experts in Design for Sustainability. The furniture-specific system design guidelines developed in the former stage and the case studies identified in the first research stage were integrated into these tools. Then, an iterative process of prototyping, evaluation, improvement, and redesign/refinement was conducted for the proposed design method and tools within design-research activities. These activities, such as workshops, focus groups, and interviews with designers, academics, and professionals, were conducted in research stage 3.

4.3.4 Research stage III: Iterative cycles of testing and refinement of tools in practice (assessing)

This research stage (chapter 8) is dedicated to iterative processes of the empirical application, evaluation, updating, and redesign/improvement of the furniture-specific design method and tools. This stage aims to validate the developed knowledge base and know-how for their comprehensibility, usability, and usefulness (success). The main methods used during this stage are a workshop, interviews, a focus group and questionnaires.

Sampling. The strategy adopted was purposive sampling, in which participants were chosen and invited because they are the final users or have the experience as final users. Purposive samples are used when particular people, events, or settings are chosen because they are known to provide important information that could not be gained from other sampling designs (Maxwell, 2008). All developed tools/toolkits underwent an iterative process of testing and refinement involving 70 furniture designers and experts in furniture design and/or design for sustainability. The ICSxFurniture tool was developed and first tested within the GIOTTO project. Then, a workshop involving furniture designers within a course on "design for sustainable furniture" offered by a specializing master by the POLI Design (Politecnico Di Milano) was conducted in February 2022. Subsequently, after updating and refining, these tools were evaluated by 40 participants, including furniture designers from design studio, experts, researchers, and professors from LeNS Network, to get further insights to improve them. This was an iterative process with 4 rounds of evaluation, including an interview with furniture designers, a post-doc, and a teacher with a background in furniture design; interviews with experts on design for sustainability/furniture design from LeNS Network; a focus group within the DESIS China_Hunan University; and an online questionnaire sent to LeNS members.

The continuous application and evaluation of the approach and tools brought to reflect and define the knowledge base designers need.

Workshop: to test the ICSxFurniture toolkir

A method used for the evaluation of the design tools in a real context was the workshop, principally in the form of idea-generation sessions. Different aspects of the design tools were tested: comprehensibility, usefulness, and usability.

The workshop started with the author introducing the aim/function/use steps of these tools, after introducing the knowledge developed in the first stage, the PhD candidate gave a design brief of a workstation etc.

During the practical session, the author provided clarification on how to use the tools when necessary. After presenting their work, they are asked to fill in a questionnaire to evaluate these tools.

Semi-structured interview: to evaluate all tools

During this phase, the semi-structured interviews were utilized to collect feedback on the comprehensibility, usability, and usefulness of all the developed tools. The process unfolds as follows: The the PhD candidate introduced each tool, explaining its purpose, components, usage steps, and its integration into the design process. Participants or interviewees then engage with these tools, assessing their comprehensibility, usability, and usefulness. They share their perspectives on their user experience, provide comments, and offer suggestions for potential enhancements.

Focus group: to test all tools

A focus group is an organized discussion among a selected group of individuals to elicit information about their views (Gray, 2014). This method helps to clarify similarities and differences between the opinions and values held by participants (Freeman, 2006). After the PhD candidate (facilitator) presented background knowledge and each tool, participants were asked to use these tools and evaluate these tools before giving their comments.

Questionnaire: to test all tools

During this stage, the research endeavors to gather extensive advice from experts and practitioners specializing in sustainable furniture system design. The use of a questionnaire offers several advantages for potential participants, such as its cost-effectiveness and flexibility in terms of time and location. In this phase, a questionnaire survey has been identified as the most efficient method for collecting both qualitative and quantitative feedback from a larger pool of experts in relevant fields.

The questionnaire surveys were conducted in two distinct settings:

- Workshops with Poli design specializing master: These surveys featured a combination of open-ended and scaled questions designed to evaluate various aspects of the design toolkit. Questionnaires were distributed to workshop participants immediately after practical activities to capture their most recent experiences.
- LeNS Network partners and selected furniture companies: Questionnaires were sent out to gather additional opinions and data regarding the latest version of the tools.

Results. These questionnaires were strategically employed to ensure a comprehensive collection of feedback from various sources. The continuous application and evaluation of the approach and tools enabled the researcher to reflect on the design intervention, highlight strengths and weaknesses, and continuously refine the approach and tools. Several iterative processes of implementation, evaluation, and refinement took place. Adjustment and refinement of the approach and tools through implementing them in design practices were combined with the insights coming from the assessment made by academic experts and practitioners. This continuously shapes the design approach and tools. The development of a design approach and tools was not the only output of the research stage. In fact, the continuous application and evaluation of the approach and tools brought to reflect the knowledge base needed by designers to operate at such a strategic level. In other words, the output of this second stage was the improvement of the design practice but also the building up of the necessary design knowledge to support this practice.

4.3.5 Research stage IV: reflection to produce design principles and enhance solution implementation

The aim of this research stage (chapter 9) was to carry out a retrospective analysis of the entire study. This analysis focused on the research results achieved as well as on the research methodology adopted. This stage brought to:

- specify the main contribution brought to theory and practice;

- underline the research limitations;
- reflect on the generalizability of results;
- formulate recommendations for follow-up research and practice.

Based on the knowledge base and know-how developed within this research, an open-access course (video, slides, texts) and open-access book are under development to disseminate this knowledge base and know-how. Furthermore, this phase aims to disseminate the above-mentioned knowledge base and know-how with an open-access ethos.

The whole research process with research questions, objectives, activities taken, and relevant chapters is shown in the following **Error! Reference source not found.**.

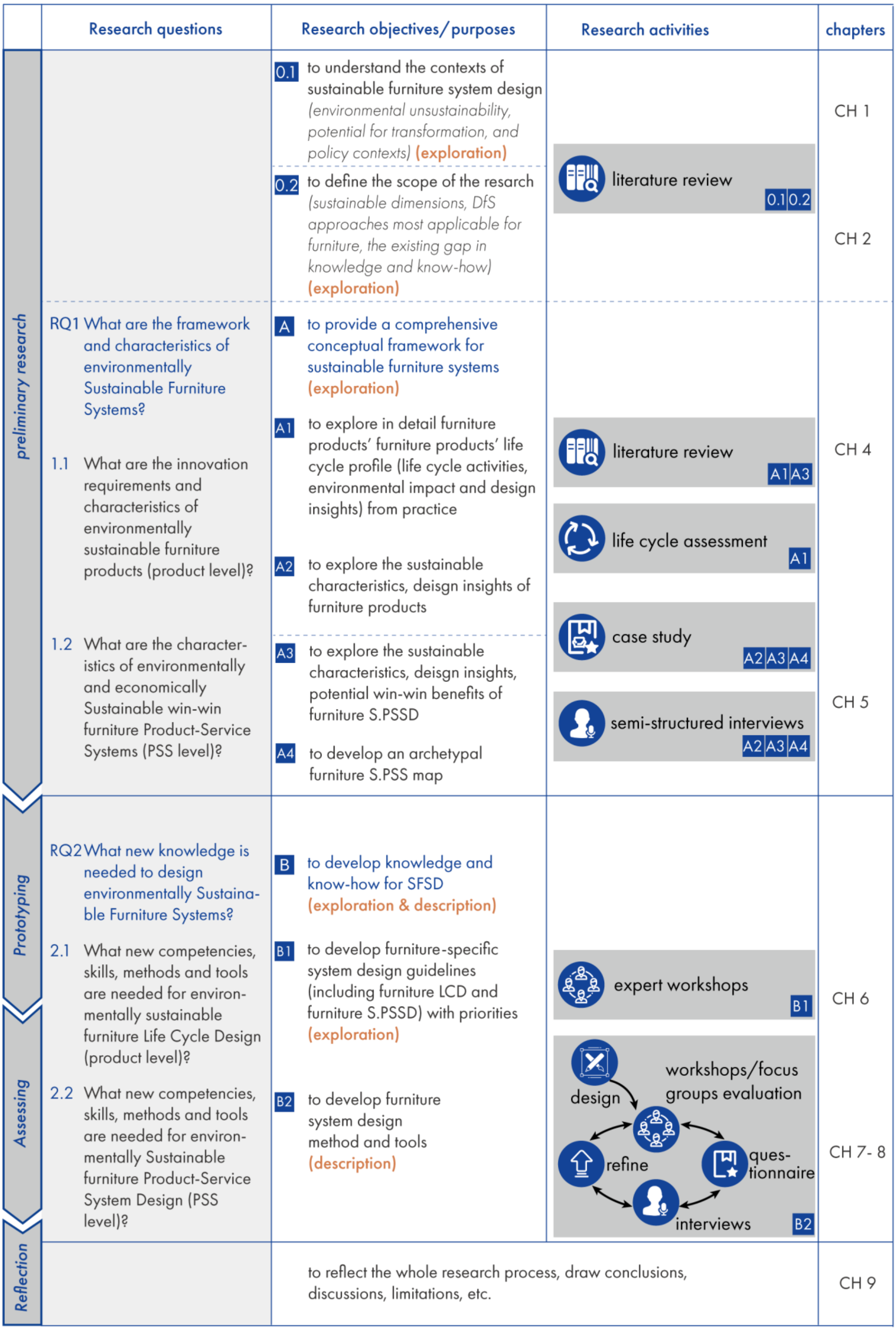


Figure 12 Research questions, objectives, activities and sections within this PhD research

Part II The Characteristics of Environmentally Sustainable Furniture Systems

This part outlines the activities conducted during the Preliminary research phase, with the primary objective of answering RQ1: What are the framework and characteristics of environmentally Sustainable Furniture Systems? RQ1.1 What are the innovation requirements and characteristics of environmentally sustainable furniture products (product level)? RQ1.2 What are the characteristics of environmentally and economically sustainable win-win furniture Product-Service Systems (PSS level)?

The activities and findings outlined in this section can be summarized as follows:

Further illustration of Furniture System's Environmental Impact (Chapter 5.1): The general environmental impact of the furniture system, encompassing both furniture products and Product-Service Systems, was previously introduced and acknowledged in Chapter 1. To facilitate effective design interventions, it is essential to possess detailed life cycle data. In this chapter, Life Cycle Assessment (LCA) was employed on 25 pieces of furniture across 8 types. This analysis aimed to identify a general environmental impact trend and demonstrate how LCA data can inform and guide design interventions. The LCA results obtained were subsequently utilized to define priorities for furniture-specific Life Cycle Design strategies, as detailed in Chapter 7.1.2.

Exploration of the innovation requirements and characteristics of environmentally sustainable furniture products (chapter 5). Recognizing the value of practical experience, an investigation of best-case studies involving 41 sustainable furniture products was analyzed to explore design interventions for sustainable furniture products design. To enrich the insights gathered, a semi-structured interview was conducted with practitioners from furniture companies. In addition, the lack of knowledge and know-how for sustainable furniture product design in furniture companies was confirmed.

Exploration of the characteristics of environmentally and economically win-win furniture Product-Service Systems (S.PSS) and the development of an archetypal furniture S.PSS map (chapter 6). The analysis involved studying 44 best-case studies of sustainable furniture PSSs. The results of this analysis provided insights into the characteristics, definition, classification, and the win-win environmental and economic benefits of furniture S.PSS. To validate and expand upon these insights, a semi-structured interview was conducted. Utilizing the insights from both the case studies and the interview, an archetypal furniture S.PSS map was subsequently developed. In addition, the lack of knowledge and know-how for sustainable furniture Product-Service System Design in furniture companies was confirmed.

As a conclusion of the preliminary research, a novel conceptual framework for the design of environmentally sustainable furniture systems was established. This framework not only elucidated the characteristics of sustainable furniture Product-Service Systems (PSS) but also introduced the mechanisms behind the win-win economic and environmental benefits of furniture S.PSS which facilitats furniture Life Cycle Design (LCD). Crucially, the conceptual framework integrated all essential elements within the furniture system, offering a comprehensive and holistic approach to sustainable furniture system design.

Chapter 5 A science-based understanding of furniture products' environmental impact and sustainable innovation opportunities

5.1 Furniture Life Cycle Assessment: furniture's quantitative environmental performance along the life cycle

Life Cycle Assessment (LCA) is a structured, comprehensive, and internationally standardized method that quantifies the related environmental impacts associated with a product (good or service) throughout the full life cycle (European Commission & Joint Research Centre, 2010). In other words, LCA is the compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its Life Cycle (LC), from raw materials acquisition or generation to final disposal (ISO 14040: 2006, Environmental Management - Life Cycle Assessment - Principles and Framework, 2006; ISO 14044: 2006 Environmental Management - Life Cycle Assessment - Requirements and Guidelines, 2006).

Within this chapter, the research conducted a full LCA for 25 pieces of furniture in 8 categories from 15 companies following the ISO 14044 and ISO 14040 proposed methodology, with four phases: 1) goal and scope definition, 2) inventory analysis, 3) impact assessment and 4) result interpretation (ISO 14040: 2006, Environmental Management - Life Cycle Assessment - Principles and Framework, 2006; ISO 14044: 2006 Environmental Management - Life Cycle Assessment - Requirements and Guidelines, 2006). The EF method[12] (with toxicity, Environmental Footprint) and the database ecoinvent 3.7 version with the cut-off system model within the Simapro 9.1 version were used to conduct the LCA. With the EF method, 14 environmental categories were calculated, and single-score results were considered.

For the database, compared with the 'Allocation at the point of substitution (APOS)' system model, which can reach a level of complexity that makes an assessment of the reasons for impacts challenging, cut-off uses a simple but fundamental decision to separate primary and secondary use stages (Wernet et al., 2016) and it is highly used for Environmental Product Declarations (Saade et al., 2019), so the study chose the cut-off system model.

5.1.1 Goal and Scope Definition

Considering that the sustainable furniture production and consumption system is one of the challenges that should be addressed and improved for a better quality of life for residents and lower pollution levels for the environment, this study aims to propose an overview of the furniture profile (office furniture and household furniture) based on quantitative furniture LCA. To be specific:

First, to identify the category with the highest impact within 8 categories; to compare the different pieces of furniture's impact within each category; to identify stages with the

[12] The assessments are expressed in the form of impacts aggregated into a single value (in "%"), by the EF method. The Environmental Footprint (EF) method is the impact assessment method adopted in the EF transition phase of the European commission. The method includes the normalization and weighting factor. It considers the flowing environmental categories: climate change, ozone depletion, ionizing radiation – human health, photochemical ozone formation – human health, particulate matter, human toxicity (non-cancer), human toxicity (cancer), acidification (terrestrial and freshwater), eutrophication (marine), eutrophication (terrestrial), ecotoxicity (freshwater), land use, water use, resource use (fossils), resource use (minerals and metals).

highest impacts for each piece of furniture; to identify materials/processes with the highest impact within each life cycle stage.

Secondly, to identify opportunities for the environmental performance improvement of furniture at various stages in their life cycles.

Finally, to support decision-making for the purpose of strategic planning, priority setting, furniture product or process design, or redesign through the identification of key environmental performance indicators of furniture life cycle design.

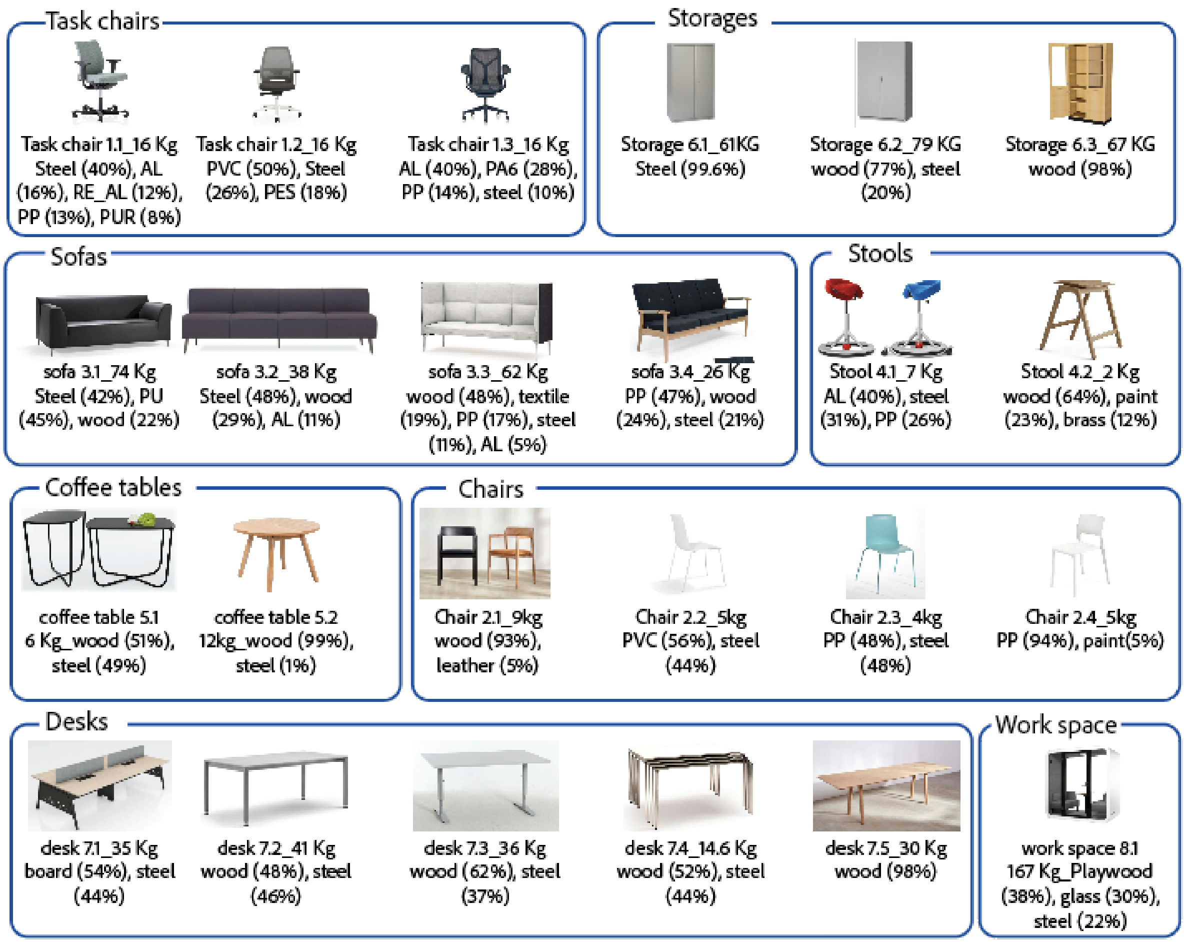


Figure 13 25 pieces of furniture assessed in this study

Note: for chair 2.1, another version with the same appearance assessed; Source of data: Environmental Product Declarations

5.1.2 Assessed furniture cases

The research conducted LCAs for 25 pieces of office and household furniture from 8 categories: task chair (3 cases), chair (5 cases), stool (2 cases), sofa (4 cases), table (5 cases), coffee table (2 cases), Storage (3 cases) and working space (1 case), see Figure 13.

5.1.3 System boundary

The system boundary includes all those activities (processes) directly or indirectly related to furniture before, during, and after its use. In fact, the system boundary corresponds with furniture's life cycle phases which refers to the journey of a piece of furniture from the extraction of raw materials to the end-of-life. More precisely, the furniture life cycle system to be considered includes the following stages: pre-production, production, distribution, use and end-of-life, and all related processes.

(1) The Pre-production stage

Furniture employs various raw materials such as wood-based panels, metal (e.g., aluminum, steel, etc.), plastics, fabrics, leather, glass, and so on (Renda et al., 2014). The pre-production stage incorporates all impacts associated with the acquisition of resources for these raw materials, the delivery to the production area, and the transformation needed for raw materials or energy production.

Let us see a bit more about the pre-production processes of some main materials used in furniture production:

Particle board is often used in furniture production, like desks/tables, storage, bed frames, etc. The production of particle board includes planting, transportation of resources, wood shavings production (which includes wood chipping, shaving and storage), drying and sorting section (which includes drying, sorting, milling and storage), gluing section (which includes modulating, glue/shaving weighting and mix), paving and hot pressing section (which includes paving, weighting, sawing, sanding and inspecting) (Clean Production Standard-Wood-based Panel Industry (Particle Board), 2010; González-García et al., 2019; Silva et al., 2013), see Figure 14. The main raw materials for particle board are wood-based materials (e.g., plantation wood, small diameter wood, branch timber, logging residues, wood processing residues, discarded wood (old furniture, packaging), and a very small part of bamboo, crop straw), adhesive (e.g., Urea-formaldehyde, melamine formaldehyde), and additive (water repellent like paraffin, curing agent like ammonium sulfate) (Clean Production Standard-Wood-based Panel Industry (Particle Board), 2010).

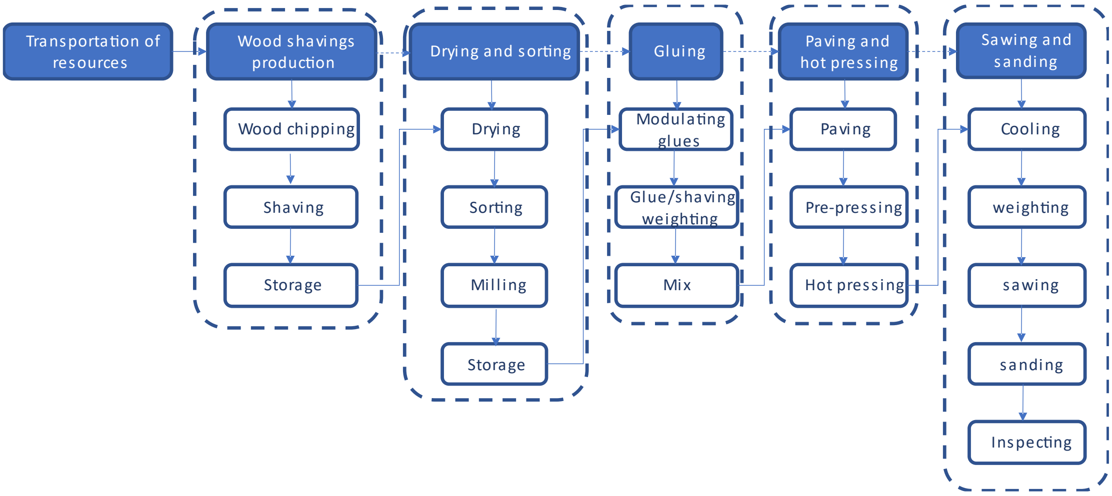


Figure 14 The particle board production processes

Aluminum and steel are widely used in office furniture production. The process for aluminum production includes bauxite mining, alumina production, aluminum electrolysis, ingot casting, etc. (International Aluminium Institute, 2003; Nunez & Jones, 2016; S. Wang et al., 2018; World Aluminium, 2017), See Figure 15.

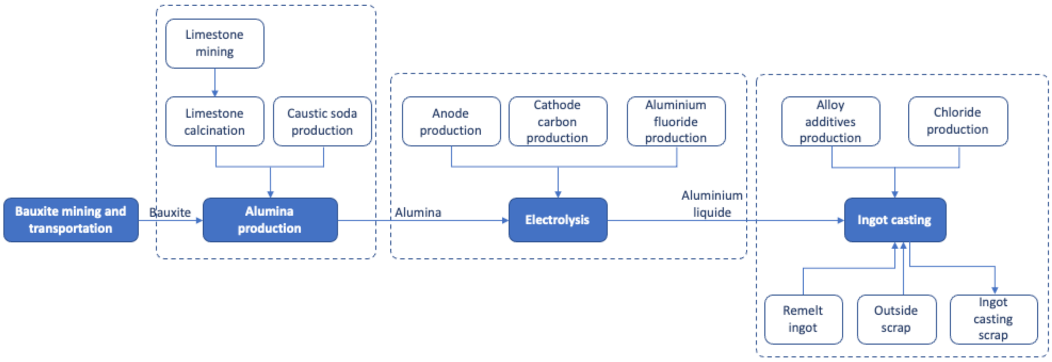


Figure 15 The aluminum production processes, adapted from (International Aluminium Institute, 2003)

The process for primary steel production includes coke making, sintering, iron making (blast furnace), steel making (basic oxygen furnace - BoF), casting, hot rolling (Burchart-Korol, 2013; Olmez et al., 2016; Tongpool et al., 2010), see Figure 16.

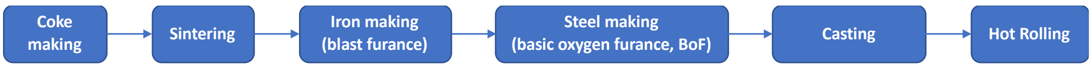


Figure 16 The steel production processes, adapted from (Burchart-Korol, 2013; Olmez et al., 2016; Tongpool et al., 2010)

Textile is widely used in upholstery furniture production. The process for textile production is shown in Figure 17, adapted from (Babu et al., 2007).

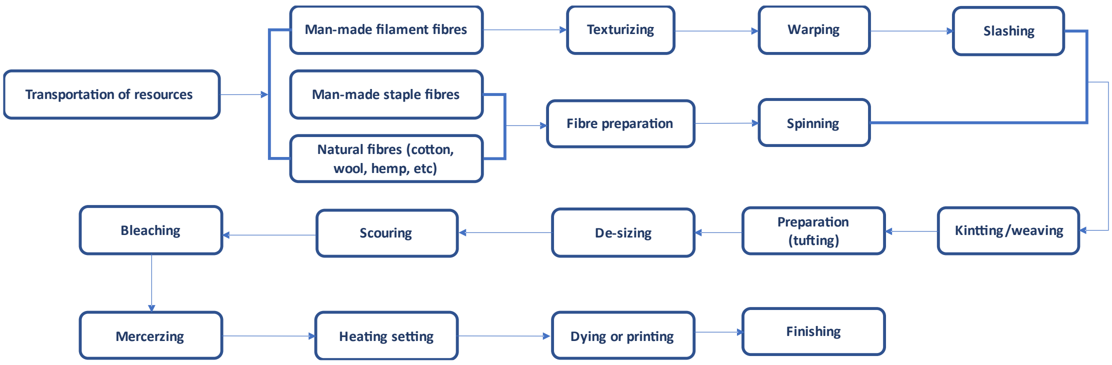


Figure 17 The textile production processes, adapted from (Babu et al., 2007)

Plastics are widely used in furniture production. It is made from by-products from natural gas, crude oil, and brine. The production of polyurethane also needs Polyols, which initially need animal fat and sugar as input. The main production process for plastics includes Brine and fossil fuels extraction, electrolysis/cracking, chemical process, polymerization, etc.

Leather is widely used in upholstery furniture production. The production process is shown in Figure 18, adapted from (Joseph & Nithya, 2009; Navarro, 2020; Notarnicola et al., 2011). There are also other materials used for furniture production, like paper, stone, marble, glass, glue, adhesive, paints, and varnishes.

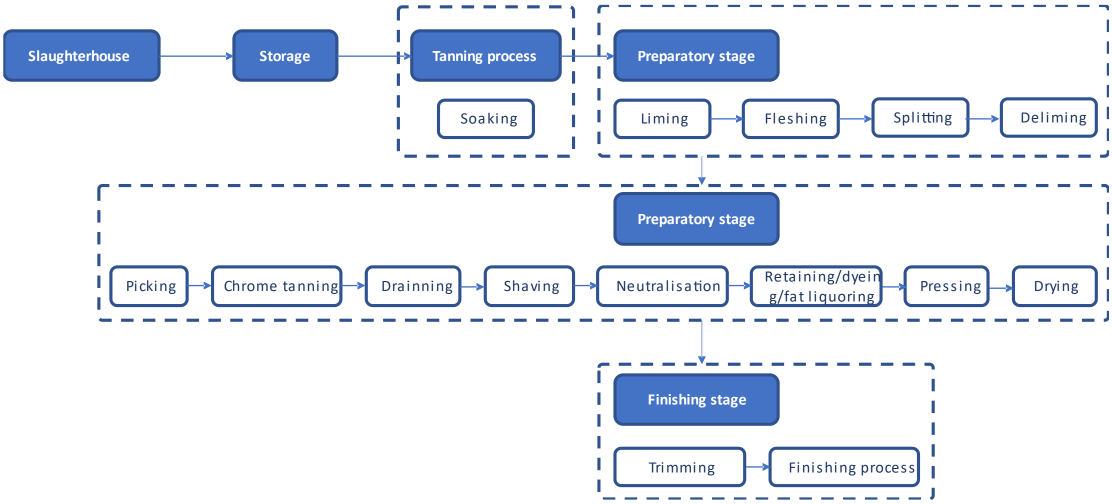


Figure 18 The leather production processes, adapted from (Joseph & Nithya, 2009; Navarro, 2020; Notarnicola et al., 2011)

When analyzing the pre-production phase of the furniture product, the same approach described above for some of the main materials used should be adopted for any other used.

(2) The production stage

The production stage contains all activities of processing raw materials for the production of product components and packaging, the assembly of furniture, and finally, finishing processes, e.g., polishing and painting of solid wood-made furniture. Other activities and processes applied during this stage include furniture design, research, development and quality inspection, equipment plan overhaul, and management of these activities. Figure 19 to Figure 21 show the production processes of 3 kinds of furniture: particle board-made furniture, metal furniture, and plastic furniture.

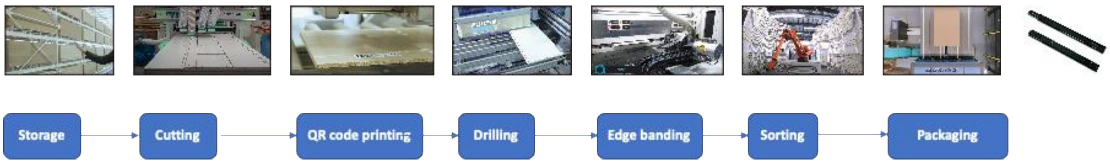


Figure 19 The particleboard-made furniture production process, field investigation in Suofeiya Home, China.

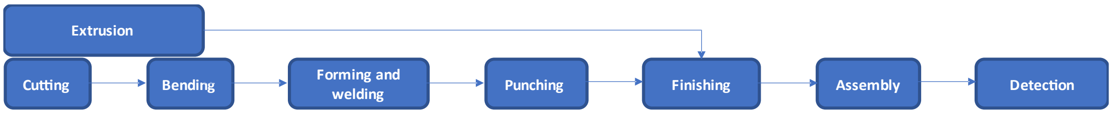


Figure 20 The metal-made furniture production process, adapted from Desk research on PBZ manufacturing - a metal manufacturer. https://www.pbzmfg.com/

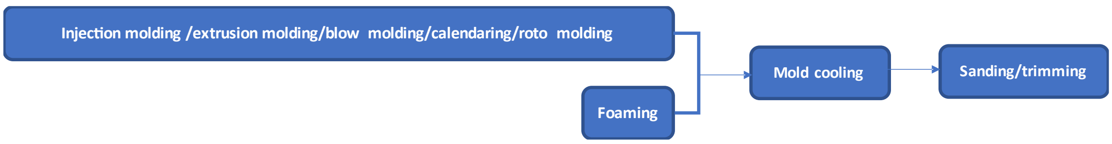


Figure 21 The plastic-made furniture production processes, Adapted from (Harding et al., 2007; Khoo et al., 2010)

(3) Distribution stage

The distribution stage is related to furniture transportation from the production site to a warehouse or the point of end users by means of truck, train, ship, even plane, etc. These activities entail not only energy consumption and emissions for transportation but even those related to packaging produce (indeed all the life cycle phases of the packaging).

(4) Use phase

The use phase considers the impacts associated with furniture maintenance, e.g., cleaning activities. The cleaning of furniture consumes water, detergent, etc. Other activities that occur during use include repairing or replacing damaged parts and upgrading components (e.g., changing the cover of upholstered furniture).

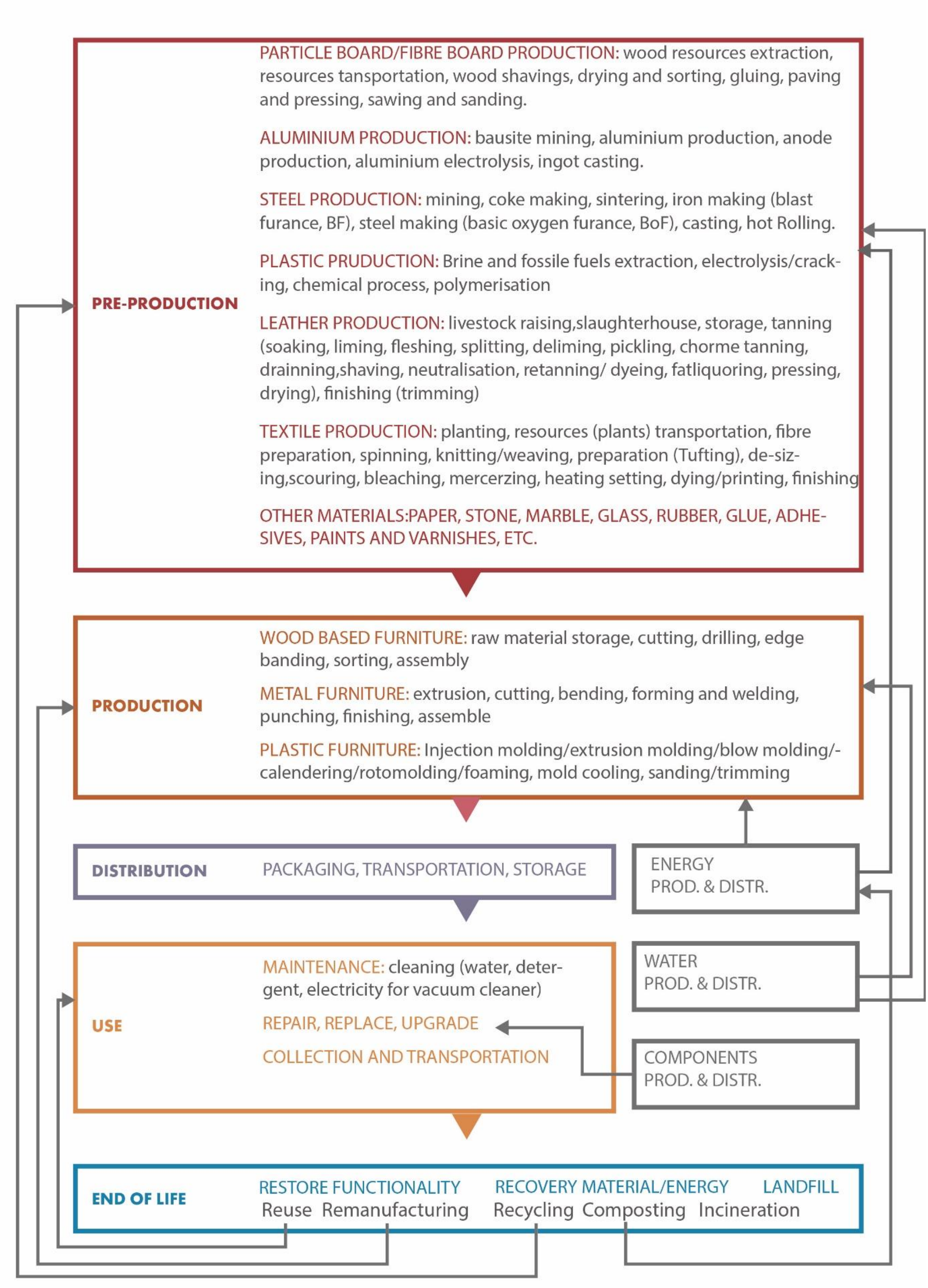


Figure 22 The system boundary of a general furniture product

(5) End-of-life phase

End-of-life phase rates impacts of end-of-life furniture management activities, like the collection and delivery of furniture, reuse, remanufacturing, recycling, compositing, energy recovery/incineration, or landfilling.

These activities compose system boundaries for furniture, see Figure 22. Furniture's environmental impacts associated with these phases are analyzed in further detail in the following paragraphs.

5.1.4 The furniture system's functional unit

Another important concept is the 'functional unit'. When designing or evaluating a piece of furniture, it is not the physical furniture that is under study, but its function, i.e., its services and the supplied results. The functional unit is the "the quantified performance of the product that is being assessed, to use as a reference unit within an environmental impact assessment of all its life cycle stages" (ISO 14025:2006(En), Environmental Labels and Declarations — Type III Environmental Declarations — Principles and Procedures, 2006).

To make this concept clear, the environmental impact comparison between a cardboard seat and a multi-material seat (see Figure 23) could be a helpful example. If we compare the life cycle environmental impacts of these two seats without consideration of the functional unit, it will seem that a muti-materials seat has a greater impact in every phase since it consumes more materials and energy along all of the life cycle stages. However, within Life Cycle Assessment, it is necessary to compare products with the same functional unit[13]. When considering their function (in this case the function unit could be "a seat provides seating supporting for one person per 12 years"), and if a cardboard seat can last 10 days and the

[13] The functional unit can be defined as: a quantified performance of the product that is being designed/assessed, to use as a reference unit within an environmental impact assessment of all its life cycle stages.

multi-material seat last 12 years on average, it appears that we should compare the environmental impact from one multi-material seat with 438 (365 days/ 10 days *12 years) cardboard seat. This environmental impact of the cardboard seat will be around 5.06 times of the environmental impact from the multi-material seat with the same functional unit. How many designers would evaluate/design correctly for environmental sustainability? However, the design community in general is not aware of this knowledge and know-how to design furniture with low environmental impact.

Figure 23 A muti-material seat and a cardboard seat

In this research, the Functional Unit for furniture could be defined as 'using of one piece of furniture (for one average person) based on a general frequency over a period of 15 years in an office and/or household environment'. If detailed to each furniture group:

- Task chair: Using one task chair for one average employee based on a general frequency over one year in an office environment.
- Chair: Using one chair with a general frequency over one year in an office or household environment.
- Sofa: Using one 3-seat sofa with a general frequency over one year in an office or housing environment.
- Stool: Using one stool with a general frequency over one year in an office or housing environment.

- Table: Using one table for one average employee based on a general frequency over one year in an office environment.
- Coffee table: Using one coffee table with a general frequency over one year in an office or housing environment.
- Storage: Using one cabinet with 0.8 m3 storage space for files over one year in the office or housing environment.
- Working space: Using one working space with a general frequency over one year in an office environment.

5.1.5 Inventory Analysis

The inventory data come mainly from Environmental Product Declarations (EPD), which are voluntary documents for a company or an organization to present transparent information about the life cycle environmental impact of their goods or services (Product Category Classification: UN CPC 3812/3813/3814, (Version 2.01)). For this study, all EPDs come from 4 sources: the Norwegian EPD foundation[14], the international EPD system[15], Herman Miller,[16] and Wiesner Hager[17].

A few data assumptions are based on the Product Category Rule (PCR). PCRs provide rules, requirements, and guidelines for developing an EPD for a specific product category (The International EPD system, n.d.). They are a key part of ISO 14025, enabling transparency and comparability between EPDs. Few data are assumed based on LeNS lab's[18] former experiences. Specifically:

---

[14] https://www.epd-norge.no/?lang=en_GB

[15] https://www.environdec.com/library?search_type=simple&Category=9492

[16] https://www.hermanmiller.com/en_eur/

[17] https://www.wiesner-hager.com/en/

[18] LeNSlab is a research lab coordinated by Carlo Vezzoli and active within the Design Department of Politecnico di Milano University for more than 20 years.

Pre-production

For all 25 cases, data used for the pre-production stage are actual materials used for furniture from EPDs by manufacturers.

Production

The data for the production stage is assumed based on materials used in the pre-production stage and refers to PEFCR office chair (Product Environmental Footprint Category Rules - Office Chair (Draft), 2018) and PEFCR office table (Product Environmental Footprint Category Rules - Office Table (Draft), 2018). The contribution of capital goods to the overall impact is relatively small. Hence, the infrastructure of the foreground processes was considered negligible (Medeiros et al., 2019).

Transportation

The data for the transportation stage is based on the following priority: first, the research uses actual transportation distances and types (from EPDs). If there is not, the data are calculated as the average distance of a piece of furniture transported by certain means of transport modes (from EPDs). If there is not, the data are calculated as a 1000 km distance by lorry, which is defined as an average scenario defined in PCRs (Product Category Classification: UN CPC 3812/3813/3814, (Version 2.01); Product Category Classification: UN CPC 3811, (Version 3.0).)

Use

The maintenance scenario includes energy and water cleaning, specifically vacuum cleaning for upholstered parts once a month, like seating, and wet cloth cleaning for wood/plastic/metal components.

For vacuum cleaning of upholstered furniture, the research assumes that a common vacuum cleaner (900W) is used. For the upholstery of one chair, 20 seconds of vacuum cleaning is used. For one three-seater sofa, 80 seconds of cleaning has been taken into consideration. As a result, 0.06 kWh for upholstered chairs and 0.24 kWh for textile-covered sofas per year has been consumed (assumed by LeNs lab).

Another type of furniture (without upholstery parts) is cleaned with a wet cloth, which consumes 1.5L of water per year for chair/table (Product Environmental Footprint Category Rules - Office Chair (Draft), 2018; Product Environmental Footprint Category Rules - Office Table (Draft), 2018), 3L per year for sofa and storage (assumed by LeNs lab). No detergent is consumed only if the EPD mentions it.

End of life

End-of-life scenarios were typically modeled considering the average condition of the waste disposal (Cordella & Hidalgo, 2016). In this study, an average end-of-life scenario has been chosen to implement the assessment of the end-of-life stage: 55% of furniture disposed of in landfill as municipal solid waste, and 45% go to incineration (Castellani et al., 2019).

Table 8 The inventory data for task chair 1.1

Pre-Production (Flokk AS, 2020)		Production (Product Environmental Footprint Category Rules - Office Chair (Draft), 2018; Product Environmental Footprint Category Rules - Office Table (Draft), 2018)	
Materials	weight (kg)	Processes	
Steel	6.39	Impact extrusion of steel	
Aluminium	2.48	Impact extrusion of aluminum	
Recycled Aluminium	1.88	Injection molding (PP, PA, PAGF 30, POM)	
Polypropylene (PP)	2.13	Polymer foaming (PUR, Synthetic rubber)	
Polyurethane (PUR)	1.25	Extrusion (PE)	
Nylon (PA)	0.59	Distribution (Flokk AS, 2020)	
Rubber. Synthetic	0.45	distance	1000KM
Polyamide with glass fibre (PAGF30)	0.28	Packaging	weight (KG)
Polyester (PE)	0.27	Cardboard (cutting)	3.32
Polyoxymethylene (POM)	0.21	Polyethylene (extrusion)	0.07
total product	15.93	Total packaging	3.39
Use		End-of-life (Castellani et al., 2019)	

Electricity (assumed)	0.9 KWH	Processes	(%)
tap water (Product Environmental Footprint Category Rules - Office Chair (Draft), 2018)	22.5 L	landfill	55%
		incineration	45%

Note: the other 24 pieces of furniture's inventory data have been recorded in annex 5.

5.1.6 Results

Below are the results of assessment[19] that identify the environmental impacts of comparing the environmental impact of furniture from different categories, of furniture products within one category of different life cycle phases for each piece of furniture, and of different processes/materials for each life cycle stage. The following paragraphs provide more detailed information and give some design insights.

To facilitate the understanding of the relative impacts within one comparison group, the impact values are expressed in relative percentages, i.e., by setting (normalizing) a certain furniture/phase/process to 100% and rescaling the other impact to lower/higher percentages.

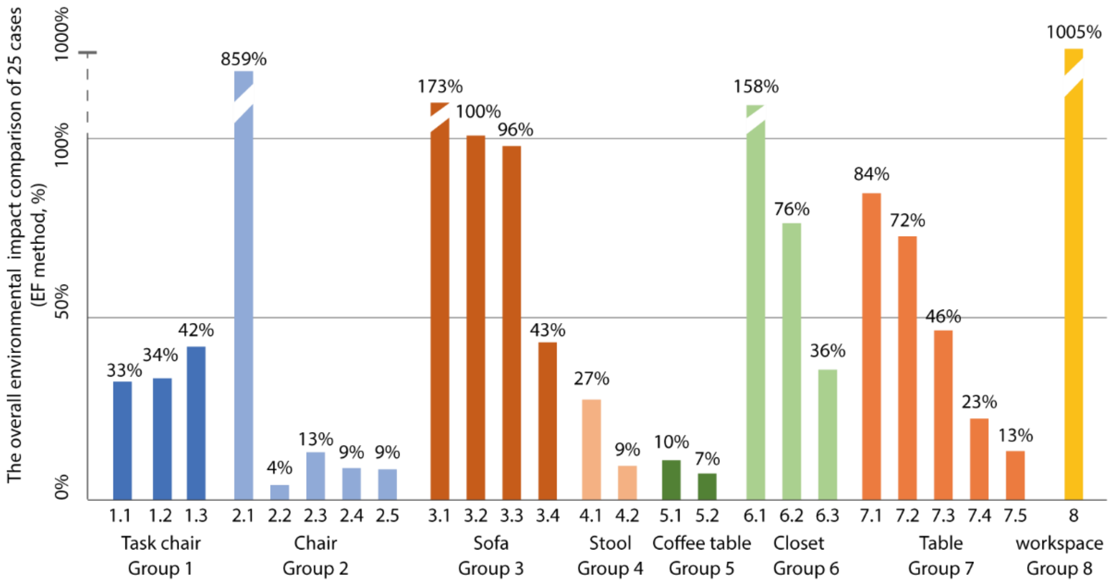
(1) Comparison of all cases

Firstly, the environmental impacts of all furniture products across 8 categories were compared to identify the overall trend. Table 9 shows that, in general, sofas (group 3), storages (group 6), desks (group 7), and workspaces (group 8) have higher environmental impacts compared to task chairs (group 1), chairs (group 2), stools (group 4), and coffee tables (group 5). One plausible reason for this difference is that the former groups consume much more materials than the latter groups. After analyzing Table 10, we observe that the

[19] The assessments are expressed in the form of impacts aggregated into a single value (in %), by the EF method. The Environmental Footprint (EF) method is the impact assessment method adopted in the EF transition phase of the European commission. The method includes the normalization and weighting factor. The EF method includes the flowing environmental categories: climate change, ozone depletion, ionizing radiation – human health, photochemical ozone formation – human health, particulate matter, human toxicity (non-cancer), human toxicity (cancer), acidification (terrestrial and freshwater), eutrophication (marine), eutrophication (terrestrial), ecotoxicity (freshwater), land use, water use, resource use (fossils), resource use (minerals and metals).

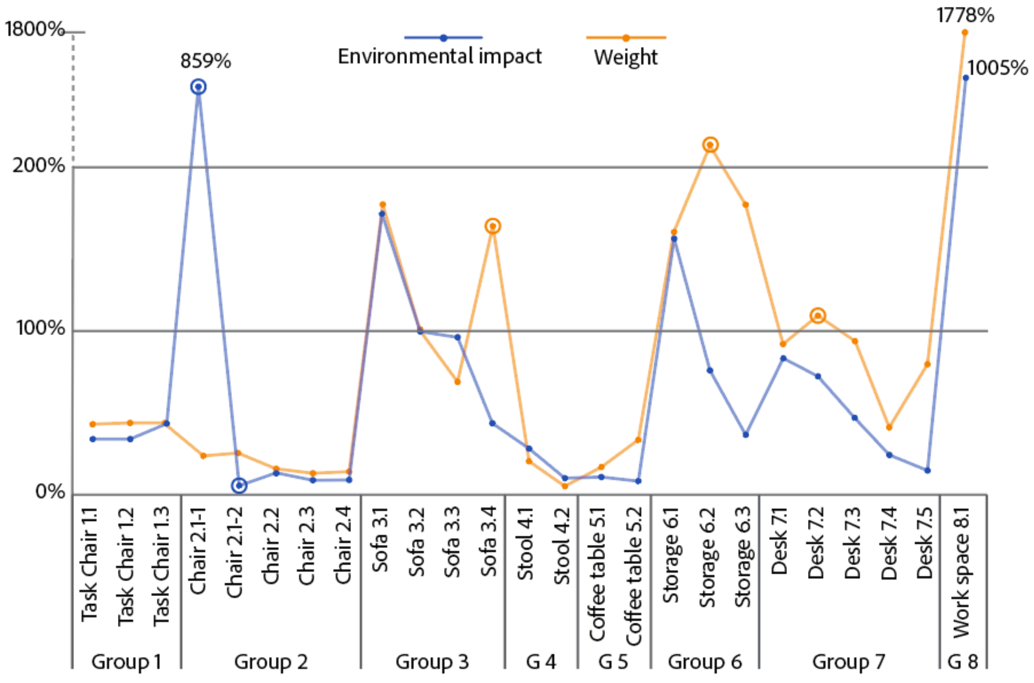
environmental impact of furniture generally presents a positive correlation to its weight (with the same function time), except for some particular cases (chair 2.1-1, sofa 3.4, and storage 6.2).

Table 9 The overall environmental impacts comparison of 25 cases



Note: Each value in the table is a single score value. The environmental impact of sofa 3.2 has been standardized as 100%. The other furniture's impact is rescaled to lower/higher percentages.

Table 10 The cross-comparison of the environmental impact and weight of 25 cases



Note: Each environmental impact value in the table is a single score value. The environmental impact and weight of sofa 3.2 has been standardized as 100%. The other furniture's impact and weight are rescaled to lower/higher percentages.

Table 11 The environmental impact of 25 cases along the life cycle (unit: mpt)

	1.1	1.2	1.3	2.1-1	2.1-2	2.2	2.3	2.4	3.1	3.2	3.3	3.4
PP	6.52	5.51	6.89	221.12	1.03	2.02	1.62	0.93	33.64	19.55	7.24	20.08
P	1.37	1.73	2.16	0.01	0.01	0.55	0.45	0.53	4.88	2.45	2.04	2.96
DT	0.29	0.80	1.00	0.01	0.02	0.56	0.07	0.57	4.10	3.26	1.07	0.83
U	0.05	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.02	0.25	0.18	0.18
DP	0.27	0.67	0.84	0.02	0.01	0.19	0.09	0.17	2.02	0.24	0.51	0.69
SUM	8.50	8.71	10.89	221.17	1.07	3.33	2.24	2.20	44.66	25.74	11.04	24.74

4.1	4.2	5.1	5.2	6.1	6.2	6.3	7.1	7.2	7.3	7.4	7.5	8
5.68	2.02	1.92	1.30	33.62	14.48	5.76	17.25	14.48	9.18	4.37	3.27	184.93
0.67	0.05	0.28	0.02	5.72	3.29	1.62	3.40	3.02	1.78	0.84	0.04	29.57
0.45	0.23	0.24	0.48	0.96	1.59	1.73	0.80	0.94	0.79	0.53	0.05	39.71
0.07	0.01	0.01	0.01	0.05	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.18
0.09	0.02	0.01	0.00	0.22	0.13	0.03	0.09	0.10	0.06	0.05	0.01	4.29
6.96	2.33	2.46	1.82	40.58	19.50	9.15	21.56	18.55	11.83	5.81	3.38	258.68

Note: Each value in the table is a single score value, two decimal places. PP-Pre-production, P-Production, DIS-Distribution, U-Use, EoL-End-of-life. 1.1 to 8 are the number for each assessed piece of furniture, see Figure 13.

Table 12 Environmental impact of 25 pieces of furniture in 5 life cycle stages (unit: %)

	1.1	1.2	1.3	2.1-1	2.1-2	2.2	2.3	2.4	3.1	3.2	3.3	3.4
PP	76.70	63.23	63.23	99.98	96.19	60.69	72.18	42.25	75.33	75.92	81.16	65.60
P	16.14	19.82	19.82	0.01	1.20	16.54	20.15	23.99	10.93	9.52	11.97	18.49
DT	3.41	9.16	9.16	0.01	1.45	16.95	3.07	25.74	9.18	12.66	3.36	9.65
U	0.63	0.10	0.10	0.004	0.33	0.26	0.40	0.40	0.04	0.97	0.74	1.66
EoL	3.13	7.69	7.69	0.01	0.83	5.56	4.20	7.61	4.52	0.93	2.77	4.60
SUM	100	100	100	100	100	100	100	100	100	100	100	100

4.1	4.2	5.1	5.2	6.1	6.2	6.3	7.1	7.2	7.3	7.4	7.5	8
81.66	89.17	78.09	71.49	82.86	74.27	62.92	80.01	78.06	77.56	75.30	96.70	71.49
9.63	5.39	11.21	1.37	14.10	16.85	17.67	15.76	16.26	15.08	14.44	1.04	11.43
6.46	2.63	9.92	26.57	2.36	8.13	18.87	3.73	5.06	6.66	9.13	1.41	15.35
0.95	2.41	0.36	0.49	0.12	0.09	0.19	0.08	0.10	0.15	0.31	0.52	0.07
1.29	0.40	0.42	0.08	0.55	0.65	0.34	0.42	0.52	0.55	0.83	0.33	1.66
100	100	100	100	100	100	100	100	100	100	100	100	100

Note: The value is a single score value, standardized based on the sum value for each piece of furniture (the environmental impact of each piece of furniture has been standardized as 100%, each life cycle stage's impact is rescaled to lower percentages). PP-Pre-production, P-Production, DIS-Distribution, U-Use, EoL-End-of-life. 1.1 to 8 are the numbers for each assessed piece of furniture. See Figure 13.

The environmental impact of 25 pieces of furniture in 5 life cycle stages is presented in Table 11 and Table 12 (single score). The pre-production stage exhibits the highest impact value for all 25 cases, ranging from 42.25% to 99.98%, with an average impact of 76%. The production stage contributes to the total impact with values ranging from 0.01% to 24%, with an average impact of 13% which is the second highest. The distribution stage shows variations from 0.01% to 27%, with an average impact of 9%, while the end-of-life stage's impact ranges from 0.01% to 8%, with an average impact of 2%. Finally, the use stage demonstrates the lowest impact, ranging from 0.004% to 2%, with an average impact of 0.46%.

Design insights

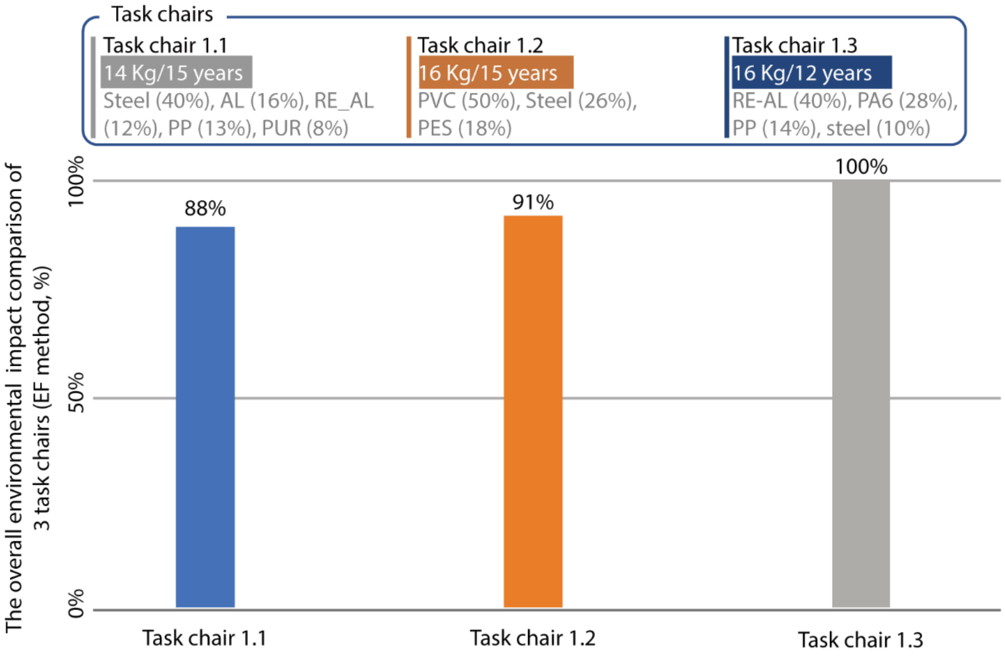
The data from Table 10 indicate that the overall environmental impact is significantly influenced by the weight per functional unit. Furniture with higher weight per functional unit tends to have a higher overall impact. Therefore, given the decisive role of design, designers should be encouraged to design furniture with as minimal weight (per functional unit) as possible to minimize its environmental impact. For achieving it, considering the definition of FU is ‘the use of one furniture piece for one average person based on a general frequency over a period of 15 years in an office/household environment’, different strategies could be applied, including reducing the materials use for furniture; extending the life span of furniture; and intensifying the use of furniture by different (or the same) users, etc.

Moreover, when assessing the environmental impact of a certain furniture piece across all stages of its life cycle, the pre-production consistently accounts for the largest share across all furniture items, as indicated by the data presented in Table 11 and Table 12. Therefore, the adoption of strategies to reduce the environmental impacts of pre-production should be given priority at the design stage.

(2) Comparison of all life cycle stages for a single type of furniture_an example

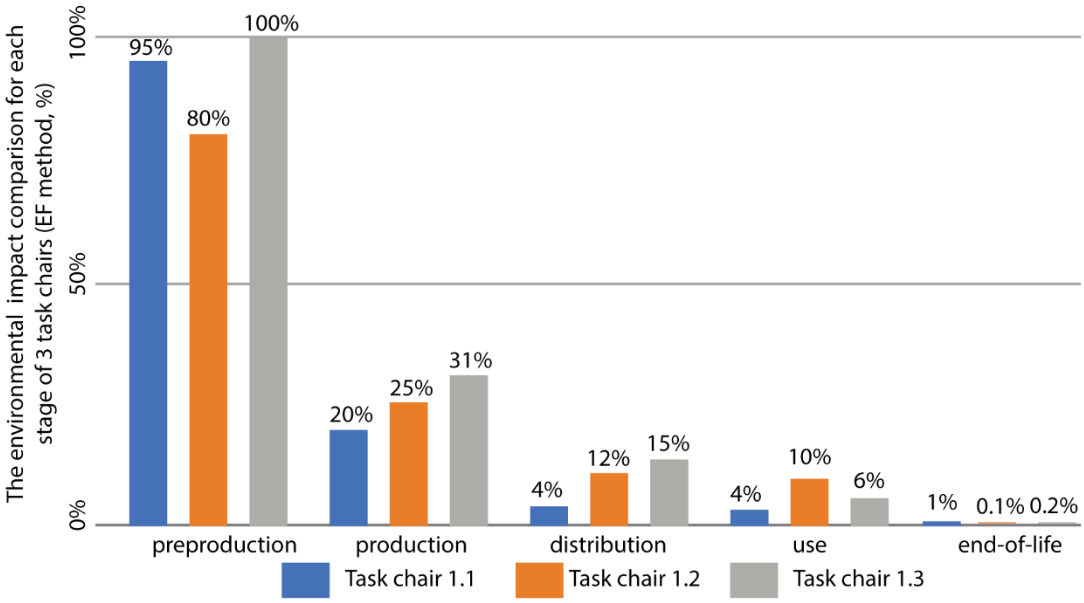
The examination of all furniture cases gives an overall picture of the environmental impact of furniture as a whole. In this chapter, the comparison of furniture pieces from the same category helps to identify what characteristics lead to higher/lower impact. The environmental impacts of furniture pieces from 7 categories (expect the workspace one) were compared. This part shows an example of three task chairs with some insights. The comparisons of the other 7 categories have been detailed recorded in annex 6.

Table 13 The overall environmental impact comparison of 3 task chairs (single score, EF method)



Note: The environmental impact of task chair 1.3 has been standardized as 100%. The other task chairs' impact is rescaled to lower percentages.

Table 14 The environmental impact comparison for each life cycle stage of 3 task chairs (single score, EF method).



Note: the environmental impact of task chair 1.1_pre-production stage has been standardized as 100%. The other life stages' impacts are rescaled to lower percentages.

Design insights

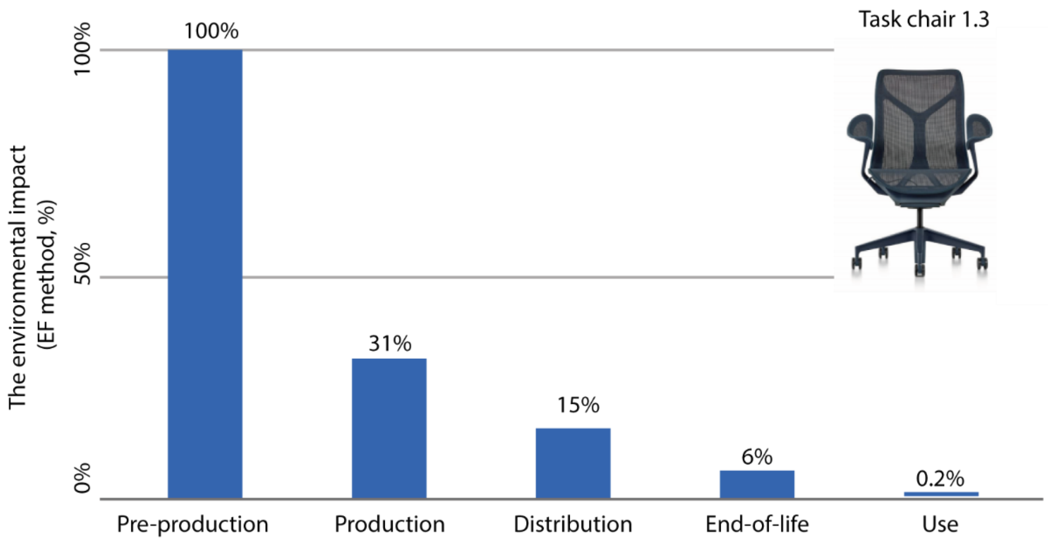
Surprisingly, by comparing the inventory data of task chair 1.1 (14.05 kg per FU with 27% recycled materials) and 1.3 (20.26 kg per FU, with 52% recycled materials), although task chair 1.3 has higher percentage of recycled materials, it still has higher impact. One possible reason for this is assumed that material consumption (per FU) has a greater impact on environmental performance than material recyclability. It becomes evident that designers should prioritize “reducing the materials consumption” per FU, rather than “using recycled materials”, as it significantly diminishes the environmental impact.

When further examining the environmental impacts of each of the 3 task chairs in terms of the different life cycle stages (Table 14), some specific findings are revealed. In distribution stage, Task Chair (TC) 1.2 exhibits a higher impact compared with the TC 1.3, which even though TC 1.3 has a higher weight to be transported. Arguably, it may suggest that employing sea shipment methods (TC 1.3) assists better in reducing environmental impact compared to using lorries. Similarly, TC 1.1 presents a higher impact than the others during the use stage. This may be because that the electricity consumption associated with cleaning the upholstery part plays an important role in furniture’s environmental performance during the use stage. In summary, we recommend that the potential for mitigating environmental impacts through the use of different modes of transportation, and users’ maintenance activities (i.e. cleaning methods) should be taken into account even at the design phase.

(3) Comparison of all life cycle stages for a single piece of furniture

After conducting a comparative analysis of the environmental impact of furniture pieces within the same category, I proceeded to conduct a detailed analysis of the environmental impact of each individual piece. This involved comparing the environmental impact at each stage of the life cycle (including pre-production, production, distribution, use, and end-of-life stages), as well as assessing the materials and processes involved in each stage for each furniture piece. The goal was to identify the most critical stages, materials, and processes that could be targeted for intervention to mitigate the environmental impact of each furniture piece. This analysis delves into a higher level of detail, encompassing all 25 furniture pieces. The corresponding data can be found in Annex 6. To illustrate the significance of these detailed findings and their relevance to design decision-making, we will use Case Task Chait 1.3 as an illustrative example.

Table 15 The environmental impact comparison for Task Chair 1.3's each life cycle stage (single score, EF method)



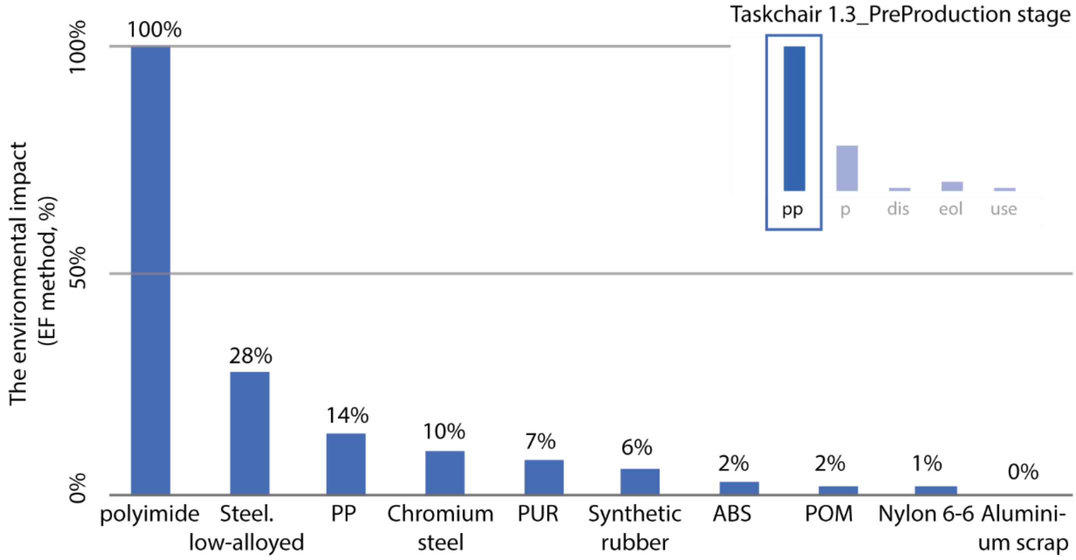
Note: The environmental impact of the pre-production stage has been standardized as 100%. The other life stage's impact is rescaled to lower percentages.

Table 15 presents the environmental impact of Task Chair 1.3 across its five life cycle phases, considering the functional unit. The analysis reveals that the pre-production stage has the highest impact, amounting to three times the impact of the production stage. Comparatively, the distribution stage contributes only 2% of the pre-production stage's impact, the end-of-life stage accounts for 6%, and the use stage registers 0%. Detailed explanations of the impacts of each stage of TC 1.3 (as an example) are provided separately in the subsequent paragraphs. These explanations aim to provide designers with evidence-based guidance, empowering them to make environmentally beneficial decisions with informed judgment.

(4) Comparison of all materials and/or processes per life cycle stage

Pre-production stage

Table 16 The environmental impact comparison for Task chair 1.3's pre-production stage (single score, EF method)



Note: The environmental impact of Polyimide has been standardized as 100%. The other materials' impact is rescaled to lower percentages.) pp represents Polypropylene.

The pre-production stage significantly influences the environmental impact of task chair 1.3, with Table 16 providing a comprehensive breakdown of each material's contribution. Among the materials used, polyamide (4.49 kg), low-alloyed steel (1.63 kg), and PP (2.20 kg) have the most substantial impact on the environment during this stage. In contrast, recycled aluminum presents an impact of zero even though it is the most heavily used material (6.58 kg) in TC 1.3. This is because the environmental impact during the pre-production stage is predominantly associated with the complex processes of primary materials extraction, transportation, and production. Recycled aluminum primarily avoids extraction and production, thus presenting considerably lower environmental impact.

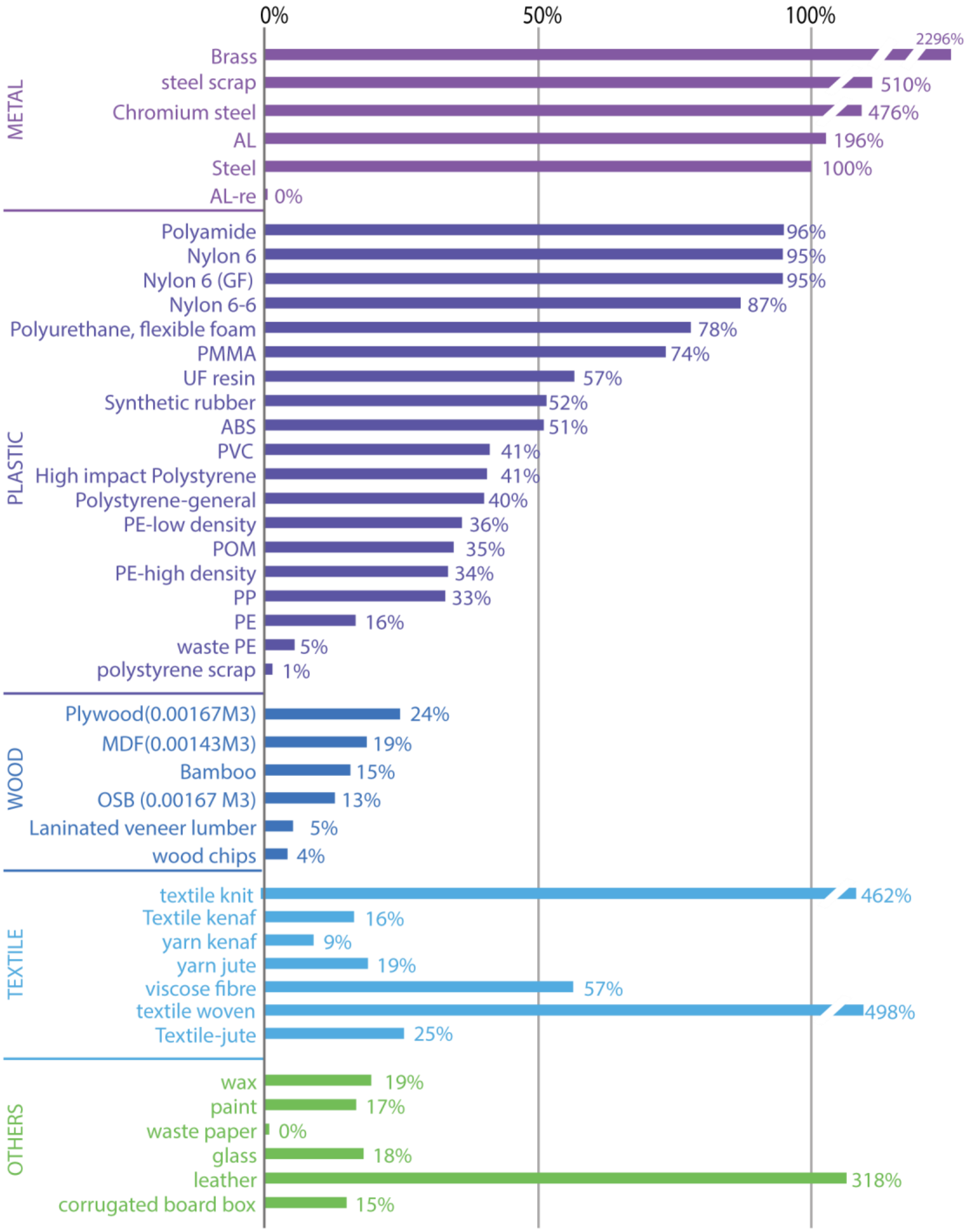
Design insights

Therefore, as a phased summary synthesizing the previous discussion, when considering the goal of designing environmentally sustainable furniture with reduced environmental impacts in the pre-production stage of its life cycle, a significant emphasis lies in minimizing material consumption. Designers have various strategies to achieve this goal. For instance, they can avoid designing over-dimensioned furniture and instead opt for appropriate dimensions; the reduction of resource consumption can be achieved through the utilization of reinforced structures to replace and eliminate non-functional components, representing effective approaches in this regard (see more design guidelines in chapter 7.1.3).

Besides, another highly beneficial avenue is to design and incorporate recycled materials, which inherently carry a significantly lower environmental impact. Thus, designers are strongly advised to prioritize using recycled or renewable materials (e.g. materials derived from discarded products) when selecting materials to substantially reduce the environmental burdens of furniture pre-production. Moreover, incorporating certified wood as a renewable resource is an environmentally sound practice that should be considered (see more design guidelines in chapter 7.1.3).

In addition, since the pre-production stage encompasses impacts primarily associated with resource acquisition, delivery, and energy consumption for raw material transformation, it is arguable that the selection of materials (in the Pre-production stage) with lower environmental impacts per functional unit during design proves effective in alleviating environmental burdens compared to prioritizing other stages in the life cycle such as production, distribution, use or end-of-life. Table 17 shows an environmental impact comparison of frequently used raw materials for furniture production in the pre-production stage. For example, the consumption of 1 kg recycled aluminum showed no impact, compared with 1 kg of primary aluminum which showed an impact of 196%. Therefore, it can be concluded that recycled aluminum with the same function unit shows lower environmental impact than primary aluminum, thus is more recommended in the Pre-production stage.

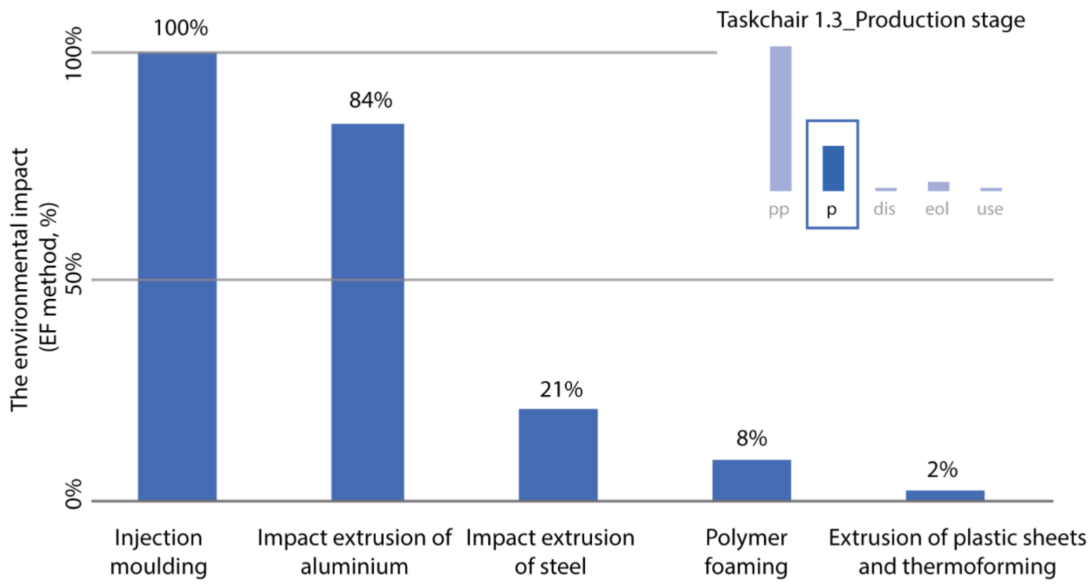
Table 17 The environmental impact of main materials in furniture production per 1 Kg (single score, EF 3.1 method).



Note: This table compares the environmental impact of 1 Kg of different materials. The environmental impact from 1 KG steel is standardized as 100%.

Production stage

Table 18 The environmental impact comparison for Task Chair 1.3's Production stage (single score, EF method)

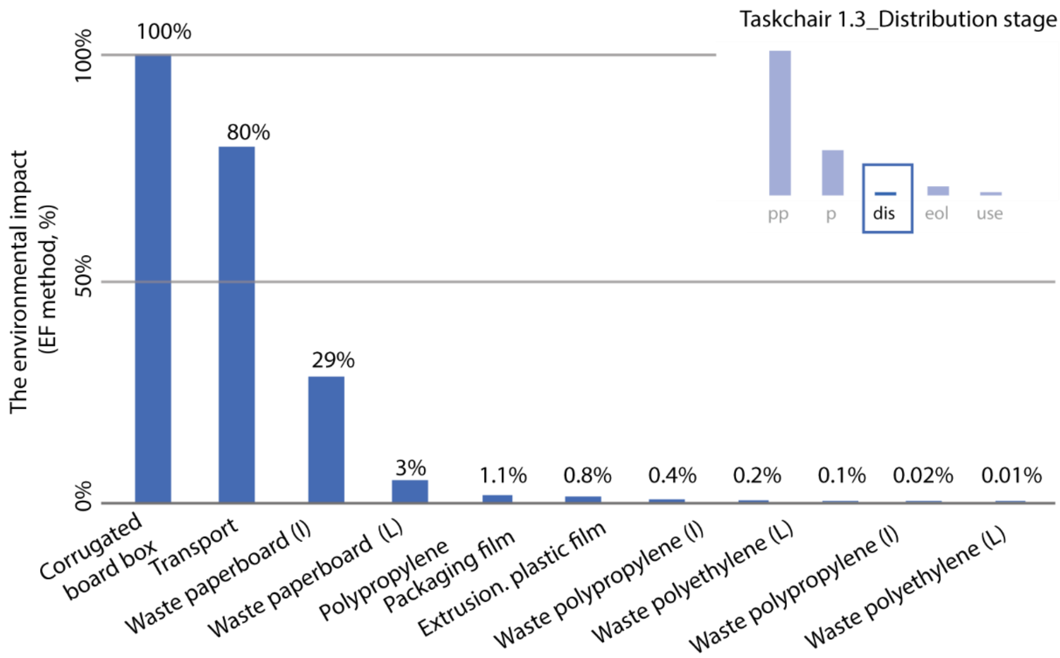


Note: The environmental impact of Injection molding' has been standardized as 100%. The other process's impact is rescaled to lower percentages.

For task chair 1.3, In the production stage, the 'injection molding' process emerges as the most impactful, closely trailed by impact extraction of aluminum, polymer foaming, and extrusion. The magnitude of impact during this stage is intricately linked to the energy consumed during these processes. Accordingly, the possible design measures could include selecting processing technologies with the lowest energy consumption possible (e.g. extrusion of plastic sheets and thermoforming in this case), (see more design guidelines in chapter 7.1.3).

Distribution stage

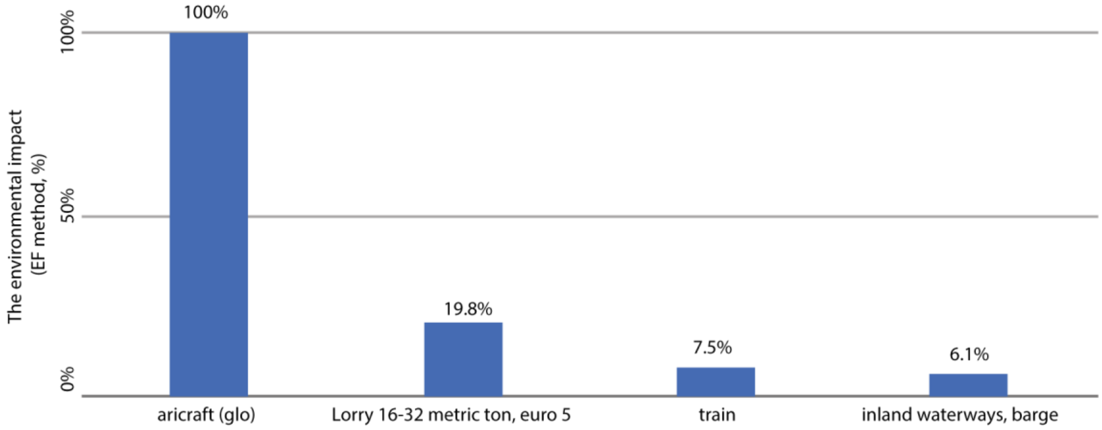
Table 19 The environmental impact comparison for Task Chair 1.3's distribution stage (single score, EF method).



Note: The environmental impact of 'corrugated board box' has been standardized as 100%. The other processes' impacts are rescaled to lower percentages.

At the distribution stage, the greatest environmental impact is primarily attributed to the preparation and treatment of packaging materials (particularly the corrugated board box), as well as transportation activities, accounting for 100% and 80% respectively, in the case TC 1.3. It is therefore important to minimize the impact of packaging materials during design, with the possible measures including avoiding packaging, applying materials only when absolutely necessary (e.g. packaging solely for safeguarding essential components), see more details in chapter 7.1.3.

Table 20 The environmental impact of four different means of transportation (weight: 1000 kg, distance: 1000 km)

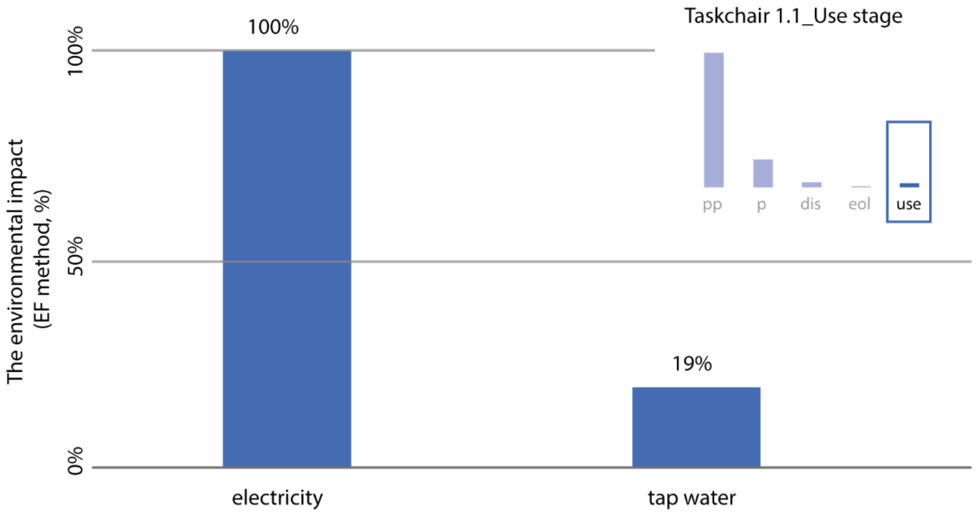


Design insights

For transportation, minimizing or eliminating transportation is also a recommended strategy for reducing environmental burdens, which can be achieved in a variety of methods, such as optimizing logistics, incorporating on-site assembly for furniture, and designing compact, stackable, and lightweight furniture, among other measures, etc., see more design guidelines in chapter 7.1.3.

Use stage

Table 21 The environmental impact comparison for Task Chair 1.1's use stage (single score, EF method).

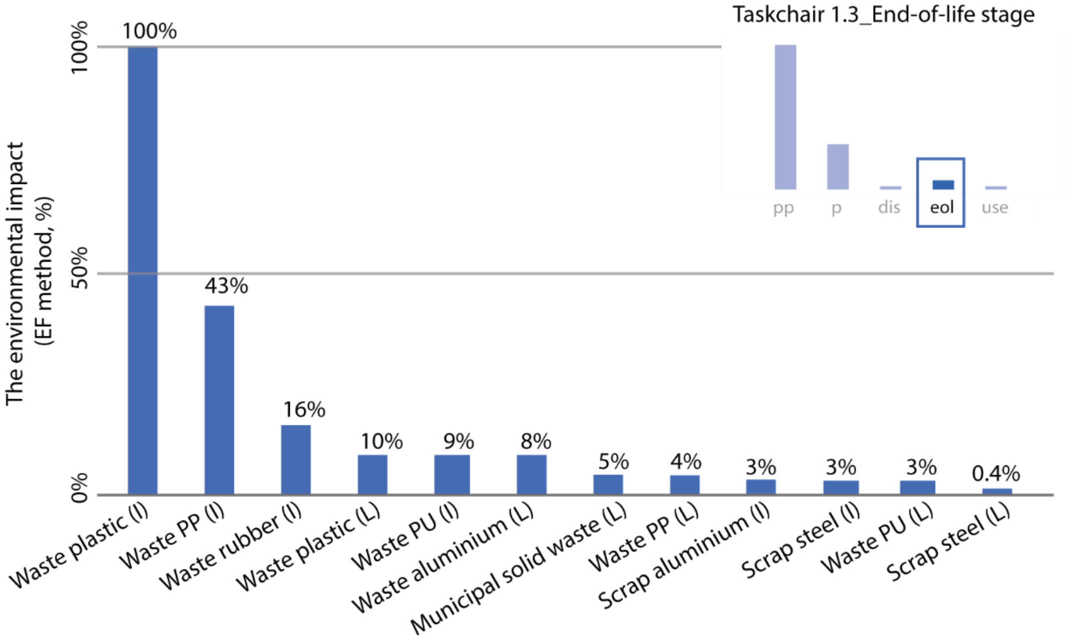


Note: The environmental impact of 'electricity' has been standardized as 100%. The other process's impact is rescaled to lower percentages.

The environmental impact of furniture during the use stage results mainly from user maintenance behavior, which is related to design (e.g. material selection and structure design). For example, TC 1.1 is designed with upholstered components, which is cleaned by the user with a vacuum cleaner that consumes electricity. Therefore, for the same functional unit, it is recommended to avoid the use of upholstered and textile-made components, in order to avoid electricity consumption during maintenance such as cleaning which is identified as a major factor in the environmental impact of furniture in use stage for task chair 1.3.

End-of-life stage

Table 22 The environmental impact comparison for Task Chair 1.3's end-of-life stage (single score, EF method)



Note: The environmental impact of 'waste plastic (I)' has been standardized as 100%. The other process's impact is rescaled to lower percentages. (I) represents incineration; (L) represents landfill.

The end-of-life stage is modeled based on an average scenario, where 55% of furniture is disposed of in landfills as municipal solid waste, while the remaining 45% undergoes incineration (Castellani et al., 2019). The model used for this stage is the allocation, cut-off by the classification system, which considers the environmental burden during incineration but not any credits generated from the process (such as heat or electricity). As a result of this modeling approach, all incineration processes exhibit a higher environmental impact than the landfill process for the end-of-life of the same material. To address this limitation and gain more comprehensive insights into the environmental implications of varying treatment methods in the end-of-life stage, the study recommends modeling each end-of-life method separately. Nonetheless, certain components, such as those made of metal, may have a significantly longer lifespan compared to components made of materials like plastic. Hence, it is worth for designers to consider the differing durability of various components and striving to maximize their longevity comprehensively in the design process. For example, incorporating features that facilitate easy disassembly and separation for further use can promote notable environmental advantages.

As a conclusion, this chapter gives some examples from the task chair category. Detailed furniture life cycle data such as the comparison among different furniture from each same category; different life cycle stages for each furniture and different processes/materials for each life cycle stage were detailed recorded in the annex files. Designers are encouraged to explore in detail these valuable data to guide the design process. The detailed Life cycle environmental impact for 25 pieces of furniture is recorded in annex 6.

5.1.7 Conclusions

To comprehensively understand the overview of environmental impact of furniture, this research presents a complex Life Cycle Assessment (LCA) of 25 pieces of office and household furniture from 8 different categories. It also unveils a comprehensive trend regarding the environmental impact across the various life cycle stages of furniture through analyzing the LCA data:

- Findings from this LCA data consistently reveal that the pre-production stage exerts the highest environmental impact.
- In 15 out of the 25 cases examined, the production phase ranks as the second most impactful stage, though it demonstrates much better environmental performance than the pre-production stage.
- Meanwhile, in 9 out of 25 cases, the distribution stage is identified as the second most impacting stage.
- The end-of-life phase exhibits notably low impact when compared to both the pre-production and production phases.

Across all cases, the use phase consistently showcases favorable environmental performance. The impact incurred during this stage is significantly lower than all other phases and with an average impact of 0.2% when compared to the whole life cycle impact.

With the same functional unit, furniture comprising a higher proportion of metal exhibits a greater environmental impact than furniture made primarily of plastic, while wood-made furniture demonstrates superior environmental performance compared to metal and plastic variants. For instance, within the chair category, chairs crafted from plastic and metal (2.2, 2.3, and 2.4) have approximately 2-3 times the environmental impact of their wood-made counterparts. Similarly, in the storage category, steel-based furniture (6.1) carries roughly double the environmental impact of furniture made from a combination of wood and steel (6.2), and approximately 5 times the impact of wood-made storage (6.3).

Upon analyzing the inventory data from the 25 cases, it becomes evident that steel and aluminum are the most frequently employed metals in furniture manufacturing. Notably, the use of recycled aluminum demonstrates significantly better environmental performance compared to primary aluminum.

Among other materials used in furniture production, wool stands out with an incredibly high environmental impact. For instance, the use of 0.09 kg of wool generates an environmental impact 545 times greater than that of 0.4 kg of timber (Chair 2.1-1 case).

Therefore, avoiding wool in upholstered furniture is strongly recommended to mitigate its environmental impact.

Generally, the environmental impacts of different processes exhibit a similar trend with the weight of materials treated during the production stage. For example, if steel is the most used material, the corresponding impact of steel extrusion will have the highest impact.

In terms of furniture packaging during transportation, corrugated board and PE (polyethylene) are frequently used packaging materials. Based on the assessed data from the 25 cases, the environmental impact caused by packaging materials surpasses that of transportation. However, this depends on specific distances covered and tools utilized, necessitating individual case analysis to gain a more accurate understanding. Considering various means of transportation, air transportation has the highest environmental impact, followed by transportation by truck, train, and water.

During the use stage of the furniture life cycle, the most commonly used resources are water for cleaning, electricity for cleaning upholstered furniture, and soap for cleaning cloth. Among these, electricity has a higher environmental impact compared to water. Additionally, when soap is used, it generates a higher environmental impact than water. However, it is worth noting that no inventory data indicates any instances of repair, refurbishment, or upgrading of furniture, which are crucial practices for extending the lifetime of furniture products and reducing overall environmental impact and are recommended for further research investigations and application in design practices.

Regarding end-of-life, with an average end-of-life scenario, incineration of materials has a higher impact than material landfill. Looking at different end-of-life treatment processes, the treatment of plastics shows a higher environmental impact than other materials.

5.2 Case study: Characteristics of environmentally Sustainable Furniture Products

This chapter collected and analyzed 41 sustainable furniture product cases. The objective of this step was to develop an understanding of their sustainable characteristics, environmental advantages, design interventions/approaches for mitigating environmental impact. The method and results are reported in the following paragraphs.

5.2.1 Method: case study

Sampling strategy. Once the research aim was established, the initial step involved the selection of cases for analysis. To ensure the robustness of the results, the case study analysis was structured following the principles of maximum variation sampling (Miles & Huberman, 1994) and data triangulation (Yin, 1994). The case study involved collecting data with maximum variation, including cases with different design interventions, design approaches, and sustainable benefits, capturing diverse perspectives from various cases (heterogeneous), and identifying common patterns across these variations (homogeneous). On the other hand, this study employed data triangulation strategy to ensure reliability and enhance the overall validity. Sources of information included scientific papers, reports from international organizations, news articles from websites, company reports and websites, field investigation on the Salone di mobile, as well as semi-structured interviews with furniture companies.

Case selection criteria. The criteria for selecting environmentally sustainable furniture product cases were as follows: (1) Inclusion of furniture pieces from different categories, including office and household furniture (e.g., chairs, tables, sofas, storage, etc.); (2) Exclusion of products in the concept stage; only products that have been officially launched were considered; (3) Inclusion of furniture pieces with environmental sustainability characteristics.

Case analysis. For the case analysis, a specific format (see Annex 1) was designed to collect the required information. This format was structured into the following sections: (1) General Information: This section covered details about the producer or designer, the furniture or series name, location, contact information, and the source of information. (2) Furniture Product Characteristics: Information in this section encompassed the furniture category, design characteristics, applied design strategies, life cycle stages of intervention, and the approach used for intervention. (3) Sustainable Benefits. (4) Limits and Constraints Encountered. Each case was assigned a unique case number marked with "#" for identification. The primary design approaches were denoted with "A*", while detailed design approaches were marked with "B*". For instance, in the #1 case - Ripple Table, the general information revealed that it is designed by Layer Design in the UK. This specific product implemented the design strategy of 'Reducing material consumption,' resulting in a reduction of environmental impact across various stages, including the Pre-production stage, the Production stage, the Distribution stage, and the End-of-Life stage. It achieved this by decreasing the weight of raw materials to be prepared (pre-production), processed (production), transported (distribution), and treated (end-of-life). The specific design approach employed for the Ripple Table was "reinforced structure (A1)" through the use of "corrugated plywood (B1)". Following the analysis of each individual case, a cross-case study analysis was conducted to draw broader insights and conclusions.

5.2.2 Results

The study uncovered a range of (potential) sustainable benefits across 41 cases, each showcasing distinct environmental advantages and applied different design strategies[20]. Notably, 31% of the cases indicated the possibility of furniture use extension or intensification, while 20% demonstrated benefits related to reducing energy consumption. Furthermore, 17% of the cases highlighted the possibility of prolonging the lifespan of materials, and 15% exhibited advantages concerning resource conservation and biocompatibility. Additionally, 14% of the cases emphasized the benefits of reducing material consumption, and 3% showed potential for toxicity reduction.

Furniture use extension or intensification

Furniture use extension or intensification can have a substantial impact on the environment across multiple stages of the furniture life cycle, encompassing pre-production, production, distribution, and end-of-life stages. This strategy is detailed into five primary design approaches (marked with "A*") as identified from the case studies. These design approaches are further detailed with 14 specific sub-approaches (marked with "B*"), as outlined in Table 23.

Table 23 Design approaches for 'Furniture Use Extension', implemented by furniture companies and designers within the 41 furniture product cases analyzed

The design approaches for 'Furniture Use Extension or intensification'		
design approaches	**detailed design sub-approaches**	**Number of cases**

[20] Design strategies serve as broad visions that steer design directions. Within the Life Cycle Design (LCD) framework, there are 6 general design strategies, namely: Product lifespan optimization, Extending the lifespan of materials, Minimizing materials consumption, Optimizing resources renewability and biocompatibility, Minimizing energy consumption and Minimizing resource toxicity and harmfulness (Vezzoli, 2018). The initial case study analysis aligned with these general LCD strategies. Subsequently, following the development of furniture-specific LCD strategies, complete with sub-strategies and guidelines (as outlined in Chapter 7), each case was then associated with these more specific design strategies. In this results section, I present cases aligned with the furniture-specific LCD strategies. It's important to note that the research did not follow a linear process.

A6 modular system	B10 Modularity with different functions	#5, #13
	B35 Modularity with different sizes	#16
	B36 changeable shapes (e.g., bed, sofa)	#15
A7 disassemble and assembly connections	B11 embedded nuts	#6
	B14 zipper connections	#8, #12, #19
	B15 Reduction in the number of components/connections	#8, #9, #10
	B18 Tupperware-like connections	#17
	B19 wedge dowel connections	#20
	B31 buckle connections	#30
	B34 special brackets and cut-outs	#41
A8 multi-functions	B12 changeable dimensions (e.g., beds)	#7
	B36 changeable shapes (e.g., beds, closets)	#11
A9 standardization	B13 universal components	#8
A15 uses strong materials	B9 Incorporation of metal as raw materials	#37

Note: #N refers to the number of a case, see Annex 3_ Case study innovation intervention_furniture products_coding

Reduce energy consumption of the furniture system

Reducing energy consumption of the furniture system through design innovations primarily influences one category of consumption (energy) and affects mainly the distribution stage (the transportation process) and use (energy for cleaning and transportation if any). This strategy is detailed into four primary design approaches (marked with "A*") as identified from the case studies. These design approaches are further detailed with 7 specific sub-approaches (marked with "B*"), as outlined in Table 24.

Table 24 Design approaches for 'Reduce the energy consumption of the furniture system', implemented by furniture companies and designers within the 41 furniture product cases analyzed

The design approaches for "Reducing the energy consumption of the furniture system"		
design approaches	**detailed design approaches**	**Number of cases**
A2 reduced packaging volume	B3 stackable design	#3, #21
	B22 flat packaging	#23, #30, #42
	B25 vacuum packaging	#25
	B32 inflation assembly/disassembly	#31
A3 distributed economy	B4 use of local raw materials	#3, #4
	B17 on-site assembly	#16, #39

A12 enhancing environmental benefits rather than reducing impacts	B24 integration of energy generation mechanisms	#24
A14 lightweight		#31

Note: #N refers to the number of a case, see Annex 3_ Case study innovation intervention_furniture products_coding

Furniture materials life extension

Furniture material life extension can have a substantial impact on the environment during the end-of-life and pre-production stages. This strategy is detailed into four primary design approaches (marked with "A*") as identified from the case studies. These design approaches are further detailed with 12 specific sub-approaches (marked with "B*"), as outlined in Table 25.

Table 25 Design approaches for 'Furniture materials life extension', implemented by furniture companies and designers within the 41 furniture product cases analyzed

The design approaches for "Furniture materials life extension"		
design approaches	**detailed design approaches**	**case number**
A5 use of low-impact materials_renewable/non-exhaustible/biocompatible materials	B8 use of recyclable materials	#4
A7 disassemble and assembly connections	B14 zipper connections	#19
	B18 tupperware-like connections	#17
	B19 wedge dowel connections	#20
	B31 buckle connections	#18, #30
	B11 embedded nuts	#6
	B15 reduction in the number of components/connections	#8, #9, #10
	B34 special brackets and cut-outs	#41
A10 mono-materials	B7 3D printing technology	#4
	B20 plastic molding processes	#18, #30
	B37 aluminium extrusion	#21
A11 easier recycling	B21 materials marking	#22

Note: #N refers to the number of a case, see Annex 3_ Case study innovation intervention_furniture products_coding

Resource conservation and biocompatibility for furniture

Resources conservation/biocompatibility for furniture predominantly influences the environmental categories of resources use_fossils and resources use_minerals and metals.

This strategy is detailed into one primary design approaches (marked with "A*") as identified from the case studies. These design approaches are further detailed with 5 specific sub-approaches (marked with "B*"), as outlined in Table 26.

Table 26 Design approaches for 'Resources conservation/biocompatibility for furniture', implemented by furniture companies and designers within the 41 furniture product cases analyzed

The design approaches for "Resources conservation/biocompatibility for furniture"		
design approaches	**detailed design approaches**	**case number**
A5 use of low-impact materials_renewable/non-exhaustible/biocompatible materials	B6 utilization of waste plastic from other sectors	#4
	B8 use of recyclable materials	#4
	B16 utilization of waste components from other furniture within the same sector	#35, #42
	B23 use of sustainably sourced materials	#23, #38
	B33 utilization of renewable materials (e.g., bamboo, palm leaves, rattan)	#36, #39

Note: #N refers to the number of a case, see Annex 3_ Case study innovation intervention_furniture products_coding

Reduce material consumption of furniture

Reducing material consumption of furniture plays a significant role in shaping the environmental impact across several stages of the furniture life cycle, namely pre-production, production, distribution, and end of life. This strategy is detailed into three primary design approaches (marked with "A*") as identified from the case studies. These design approaches are further detailed with 7 specific sub-approaches (marked with "B*"), as outlined in Table 27.

Table 27 Design approaches for 'Reduce material consumption of furniture system', implemented by furniture companies and designers within the 41 furniture product cases analyzed

The design approaches for 'Reduce material consumption of furniture system'		
design approaches	**detailed design approaches**	**case number**
A1 reinforced structure	B1 corrugated plywood	#1
	B2 ribbed structure	#2, #29
	B27 cross inset structure	#27
A4 one-piece molding	B5 incorporation of bent wood craft	#3

	B7 3d printing technology	#4
	B30 compression molding	#30
A13 avoids packaging waste	B28 packaging as component(s)	#28

Note: #N refers to the number of a case, see Annex 3_ Case study innovation intervention_furniture products_coding

Reduce toxicity of the furniture system

Reducing toxicity of the furniture system only affects several specific categories within the furniture life cycle, including the toxicity_cancer and toxicity_non cancer. This strategy is detailed into one primary design approaches (marked with "A*") as identified from the case studies. These design approaches are further detailed with 2 specific sub-approaches (marked with "B*"), as outlined in Table 28.

Table 28 Design approaches for 'Reduce toxicity of the furniture system', implemented by furniture companies and designers within the 41 furniture product cases analyzed

The design approaches for 'Reducing toxicity of the furniture system'		
design approaches	**detailed design approaches**	**case number**
A5 use of low-impact materials_renewable/non-exhaustible/biocompatible materials	B23 use of sustainably sourced materials	#32
	B29 water-based glues	#38

Note: #N refers to the number of a case, see Annex 3_ Case study innovation intervention_furniture products_coding

In conclusion, through the case study, 15 design approaches and 36 design sub-approaches were identified, the coding details are recorded in annex 3. These design insights were integrated into the development of furniture-specific Life Cycle Design guidelines in chapter 7.1.

A total of 41 case cards were developed with a designed format and made available with open access ethos, see annex 2. An example is provided in Figure 25. These case cards serve as valuable resources for brainstorming and have been linked with the design guidelines and been seamlessly integrated into a toolkit_the ICSxFurniture toolkit, as detailed in the second research stage (Chapter 7.2.1).

All the cases featured in these cards showcased environmentally sustainable benefits and applied innovative design approaches. However, it's worth noting that only 7 of these cases incorporated the Life Cycle approach, considering the sustainable possibilities across the entire furniture life cycle. For instance, the task chair from 'Orange Box' Figure 25 (#17) accounts for both furniture life extension and material life extension. Most cases focused on dedicated design approaches that target specific indicators, such as the case presented in Figure 26 (#37), which primarily emphasizes using recycled materials.

Figure 24 A case card of a sustainable furniture product with Life Cycle Design consideration

Figure 25 A case card of a sustainable furniture product with single design indicator

5.3 Semi-structured interview and desk research: the nowadays application of sustainable product design guidelines, methods, and tools in furniture companies and by furniture designers

In this research, a combination of semi-structured interviews (with practitioners and experts) and desk research was employed to gather the most current knowledge on the design of sustainable furniture products as employed by furniture companies. The specific objectives of these activities were: (1) To gain insight into the environmentally sustainable furniture design approaches, strategies, and tools employed by furniture companies. (2) To validate the findings from the case studies through semi-structured interviews.

To comprehend the approaches and design strategies employed by furniture companies in the realm of furniture life cycle design (LCD), various aspects were investigated. This study delved into the utilization of different furniture LCD strategies, encompassing but not limited to the following: 1) furniture use extension/intensification; 2) furniture materials life extension (recycling, energy recovering, composting); 3) design for furniture disassembly; 4) reduce material consumption of furniture; 5) resources conservation/ biocompatibility for furniture (renewable materials/energy, biodegradable materials, non-exhausting resources, etc.); 6)reduce toxicity of the furniture system; 7) reduce energy consumption of the furniture system[21]. Another facet of the research involved an exploration of the extent to which these strategies are implemented, either in the furniture products or by designers.

To gain insight into the methods and tools employed by furniture companies in the development of sustainable furniture products, this study examined the tools utilized at various stages of the design process. The investigation focused on the identification of design strategy priorities, generation of sustainable ideas, qualitative evaluation of existing products and new concepts, as well as the application of Life Cycle Assessment (LCA). The study further explored the specific purposes for which LCA tools are employed in the context of sustainable furniture product design.

5.3.1 Method

The qualitative interview stands out as a powerful and flexible method for capturing individuals' voices and their unique ways of constructing meaning from their experiences (Rabionet, 2011). Particularly, the semi-structured interview has gained widespread acclaim

[21] The 7 furniture-specific LCD strategies employed in the interviews were formulated during the second research stage, specifically detailed in Chapter 7.1. It's crucial to emphasize that this research did not follow a linear process. Following the definition of these furniture-specific LCD strategies, interviews were subsequently conducted. The insights generated from these interviews were then iteratively applied to developing furniture-specific LCD guidelines, marking a dynamic and interactive progression in the research methodology.

as a robust data collection technique owing to its demonstrated versatility and adaptability (Kallio et al., 2016).

In the context of sustainable furniture design, the findings derived from the semi-structured interview were utilized to explain a phenomenon. To maintain coherence in the narrative and effectively organize the discussion, an interview manuscript was crafted. Notably, terms such as "Design for Sustainability" were employed instead of "Circular Design," and design techniques were drawn from the "Handbook for Sustainable Furniture System Design." It is noteworthy that both the interviewer and participants shared common interests in engaging in a meaningful dialogue and exchanging ideas regarding sustainable furniture (system) design throughout the interview process.

Process

The research commenced with desk research, involving the analysis of 22 furniture companies with a focus on the mentioned aspects. Subsequently, 10 of these companies were selected for more in-depth examination through semi-structured interviews. Prior to the interviews, all potential participants were contacted to provide background information, objectives, processes, tools, expected durations, and scheduling details. An interview manuscript was sent in advance to facilitate comprehension. The interviews were conducted using both online platforms, specifically Microsoft Teams, given the prevailing COVID circumstances, and offline sessions during the Salone del Mobile event. This approach allowed for the engagement of a diverse range of potential interviewees from different countries.

Prepare questions. Based on the objectives, questions were determined before the semi-structured interview, so as to offer an organized structure for the discussion during the interview. 4 main topics were defined: Application of design for sustainable furniture strategies (guidelines) in the company; Application of methods and tools for environmentally sustainable furniture products design; Verification and discussion on the LCA results (only for companies who own furniture products that were considered in the LCA in chapter 5.1).

Plan the documentation process. While questions were formulated in advance, respondents were prompted to broaden the scope and delve deeper into the topics, providing insights based on real-life scenarios encountered during their work processes. Interviews were recorded only with the permission of the interviewees, and notes were diligently taken by the interviewer to capture key points of the discussions.

Reflect on the interview. Each session extended for approximately one hour. Throughout the interviews, questions from the manuscript were not only addressed but also served as a ground to explore additional, relevant topics. For instance, when respondents were asked about the application of specific design strategies for sustainability in their companies, the responses went beyond a simple yes or no. Instead, detailed information was shared, encompassing the methods used to achieve these strategies and the specific design approaches adopted. This interview strategy proved effective in gathering comprehensive and valuable information on the predefined questions, enhancing the overall utility of the data collected. Despite occasional deviations from the main topic, the structure provided by the manuscript facilitated a seamless return to the original subject. Each interview was documented through either note-taking or recording. All audio recordings were fully transcribed and subjected to thorough analysis as part of this study.

Sampling

The main objective of the sampling process is to choose respondents and data sources that are anticipated to yield robust, rich, and deep levels of understanding (Thompson, 1999), This involves selecting individuals who exhibit characteristics or live in circumstances relevant to the phenomenon under investigation (Pope & Mays, 2020). In contrast to quantitative research, which often relies on large sample sizes, this interview selects interviewees purposefully on the basis that they are the information-rich case, which can be a small sample (Gray, 2014).

This study examined a total of 22 furniture companies, all of which were investigated through desk research and 10 of them were interviewed. These companies were deemed promising due to their active engagement in designing sustainable furniture products or furniture Sustainable Product-Service Systems (S.PSS). The criteria for their classification as promising are as follows: (1) involvement in conducting Life Cycle Assessments (LCA) or producing Environmental Product Declarations (EPDs) for their products (13 companies); (2) application of furniture S.PSS (16 companies); and (3) promotion of sustainability at Salone di Mobile (2 companies).

The study employed the triangulation approach, incorporating multiple methods and data sources (Patton, 1999). The methods utilized in this study encompassed desk research and semi-structured interviews. Data were sourced from various outlets, including companies' websites, reports, academic papers, as well as verbal statements provided by designers or managers from design or sustainable development/research departments.

Table 29 Sampling of investigated companies/design studios

number	**company**	**location**	**sampling**	**method**
1	Flokk	Norway	EPD, S.PSS	Semi-structured interview, Desk research
2	Nordic Comfort	Norway	EPD, S.PSS	Semi-structured interview, Desk research
3	For a form AS	Norway	EPD, S.PSS	Semi-structured interview, Desk research
4	IKEA	Sweden	LCA, S.PSS	Semi-structured interview and desk research, Desk research
5	Shangpin home	China	S.PSS	Semi-structured interview, Desk research
6	Gispen	The nether land	S.PSS	Semi-structured interview, Desk research
7	Presikhaaf Schoolmeubelen	The nether land	S.PSS	Semi-structured interview, Desk research
8	Ahrend	The nether land	S.PSS	Semi-structured interview, Desk research

9	Opnieuw!	The nether land	S.PSS	Desk research
10	Vitra	Switzerland	S.PSS	Desk research
11	Lyght Living Furniture Leasing	Germany	S.PSS	Desk research
12	Furlenco	India	S.PSS	Desk research
13	Aarsland Møbelfabrikk AS	Norway	EPD, S.PSS	Desk research
14	Arper	Italy	EPD, Salone, S.PSS	Semi-structured interview and desk research
15	Helland Møbler AS	Estonia	EPD	Desk research
16	Svenheim Møbelindustri AS	Lithuania	EPD	Desk research
17	Wiesner-Hager	Austria	EPD	Desk research
18	Koleksiyon	Turkey	EPD	Desk research
19	Benchmark	UK	EPD, S.PSS	Desk research
20	Bisley	UK	EPD, S.PSS	Desk research
21	Herman miller	USA	EPD, S.PSS	Desk research
22	Capdell	Spain	Salone, S.PSS	Semi-structured interview and desk research

5.3.2 Result

The first step after the investigation was reading, and re-reading the transcripts (Maguire & Delahunt, 2017). The goal was to gain familiarity with the data before proceeding to the next analytical step. For each investigation, a report was formulated, exemplified as follows. Subsequently, an overarching result of the investigation was derived.

A sustainable design report for each company_an example of Gispen

- Aim: to discuss Gispen’s Environmentally sustainable furniture design approaches, strategies and tools
- Location: Microsoft teams
- Duration: 45 minutes

Interviewee: Dionne Ewen (sustainability manager)

Figure 26 The interview with Gispen

Topics

(1) Design for environmentally sustainable furniture products approaches, strategies.

Gispen offers new and remanufactured office furniture, adopting a suite of environmentally sustainable furniture design strategies:

For ‘Furniture Use Extension/Intensification’, Gispen works on enhancing adaptability. Their furniture designs are easily adaptable on-site and at any time to meet new requirements. They prioritize the creation of modular furniture that allows easy (dis)assembly, providing flexibility, upgradability, and adaptability. In essence, they emphasize the use of as many intermediate products as possible. All Gispen products are designed with the intention of reusing furniture products, modules, or components. The company strives to produce durable and high-quality furniture.

In terms of 'Design for Furniture Disassembly,' all furniture pieces by Gispen are designed for ease of disassembly. The assembly process involves screws, magnets, or Snap-On connections, and no special tools are needed for (dis)assembly. Gispen ensures that interchangeable modules, parts, and components are always taken into consideration during the design phase.

Concerning 'Reduce Material Consumption of Furniture,' Gispen designs furniture pieces with minimized volume, weight, and packaging. They adopt a sustainable approach by collecting and recovering all residual powder generated during the powder coating processes for further use. Small particles generated from the design process are returned to the manufacturer for subsequent production. Additionally, 3D technology is considered when necessary to prevent material waste. The ultimate goal is to minimize waste, aiming for no waste throughout the entire life cycle.

Concerning 'Furniture Materials Life Extension,' Gispen utilizes materials that are easily recyclable or suitable for reuse. In the context of 'Resources Conservation/ Biocompatibility for Furniture,' Gispen opts for sustainability by using recycled materials, renewable energy/materials, and sustainable fabrics. Their fabric choices include renewable jute and recycled plastics, and they are committed to avoiding the use of energy from non-renewable resources or virgin materials. For 'Reduce Toxicity of The Furniture System,' Gispen prioritizes the use of non-toxic substances or coatings in their furniture manufacturing processes. Regarding 'Reduce Energy Consumption of the Furniture System,' Gispen employs local resources and implements carefully planned, clever logistics. These strategies are consistently applied to the majority of their products, accounting for 80% of their product range, and are embraced by all designers to inspire innovative design ideas.

(2) Design for environmentally sustainable furniture products methods and tools

Gispen employs a 'Design sprint' method encompassing a design process from mapping to sketching, deciding, prototyping, and testing. Sustainability is consistently a pivotal consideration throughout this process.

In the 'map' stage, designers initiate the process with a comprehensive design framework containing 47 statements categorized into 7 themes—materials, production, (dis)assembly, logistics, maintenance, upgrade, reuse, and return. This framework aids in the selection of materials, production methods, transportation methods, and maintenance possibilities.

During the 'sketch' stage, the design framework serves as a tool to evaluate the concept. Priorities are established, giving precedence to reuse or functional adjustments during use, followed by rebuilding a product, and ultimately recycling materials.

In the 'test' stage, Gispen conducts Life Cycle Assessments (LCA) for certain products to assess sustainable performance, utilizing tools such as the Circular Life Cycle Analysis tool (C-LCA) and eco chain.

All data from the interviews and desk research conducted on the investigated companies have been recorded in reports. Subsequently, a comprehensive analysis was undertaken after recording detailed information.

5.3.3 The nowadays application of product Life Cycle Design knowledge and know-how in furniture companies

(1) The application of LCD strategies

Across all seven furniture Life Cycle Design (LCD) strategies, the most widely recognized and acknowledged strategies primarily revolved around material improvements. Notably, the strategy of "Materials Life Extension" stand out with the highest acknowledgment and application percentage, reaching 91%. This achievement is attributed to practices such as materials recycling or energy recovery through combustion.

Following closely was the strategy of "Resources Conservation/ Biocompatibility," which pertained to the utilization of renewable and non-exhaustible resources. For instance, some companies reported using FSC certified wood, GOTS certified fabrics, PEFC certified wood, etc. A significant portion, 82% of the companies, apply approaches relevant to this strategy.

The strategy of "Use Extension or Intensification" ranked as the third most recognized strategy, with 73% of the investigated companies applying it. Following closely were the strategies of "Reduce Materials Consumption" and "Reduce Toxicity," both adopted by 64% of the companies. The strategy of "Reduce Energy Consumption" was implemented by 59% of the investigated companies. Notably, the least adopted strategy was "Design for Disassembly," with only 36% adoption among the investigated companies.

Given that all the investigated companies are actively engaged in design for sustainability, it is noteworthy that each company adopts at least one strategy from the identified set.

Among all the investigated companies, only 7 explicitly mentioned (either orally or on their websites) that they have a structured approach to guide their design activities. Notable examples include Flokk, which developed a 5-3 philosophy with design principles. Fora Form AS adhered to certification requirements such as FSC and chemical standards. IKEA has formulated its democratic design approach and circular design guide principles. Gispen utilized a circular design framework and a checklist comprising 47 statements. Ahrent followed the general Ecodesign guidelines set by the EU, while Arper aligned with the Good Environmental Choice Australia principles. This observation suggested a demand for detailed and actionable instructions in the realm of sustainable design practices.

(2) The use of methods and tools

- Method for Life Cycle Design (LCD): 3 companies employed method that focus explicitly on sustainability, 4 incorporates sustainability to some extent, and 2 did not specifically address sustainability;
- Tools for LCD strategies prioritization: 4 companies utilized tools to prioritize LCD strategies, while 6 did not use such tools, and 1 company had a predefined priority;
- Tools for ideas generation: 5 companies employed tools for generating sustainable design ideas, while 3 did not utilize such tools;

- Use of Life Cycle Assessment (LCA) tools at the design beginning: 4 companies integrated LCA tools at the outset of the design process, whereas 6 companies did not;
- Use of LCA Tools throughout the process: 3 companies incorporated LCA tools at various stages of the design process, while 7 companies did not use them in this context.

In terms of design methods and tools, 7 companies incorporated sustainability into their general design process, while 1 company focused the entire design process exclusively on sustainability. The remaining companies did not integrate sustainability into their design processes.

Among the strategies applied, only 1 company utilized tools to define design priorities. Notably, 1 company prioritized 'use extension' without employing any specific tools, while 2 companies prioritized on material considerations, leveraging tools such as the "Material Safety Data Sheet." Other companies did not define design priorities.

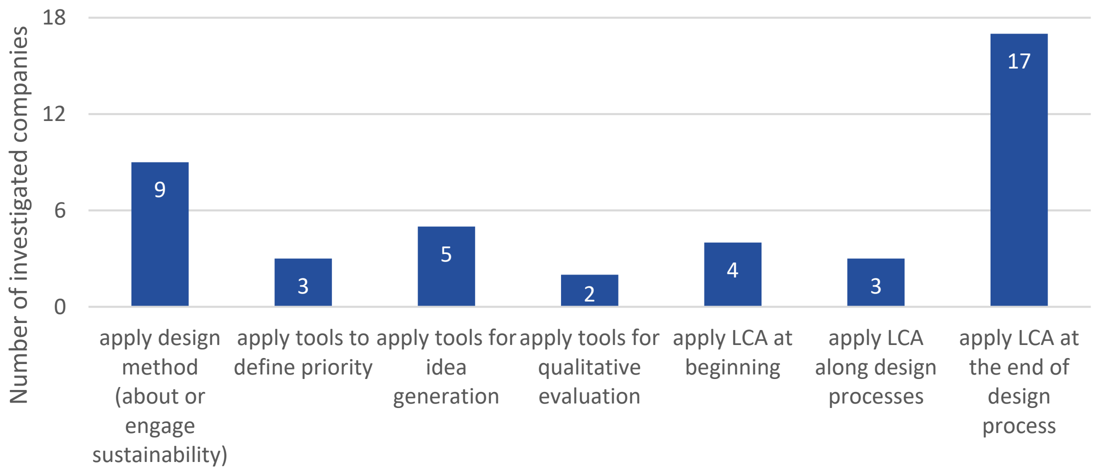
About tools for ideas generation, only 5 companies applied some tools in this design stage. For Flokk, apart from the 5-3 design philosophy, they have a list of materials to be used; IKEA uses the circular design guide for ideas generation; Gispen has a framework and a list of statements for idea generation; Ahrend has a list of sustainable and circular design principles to be followed.

Regarding tools for ideas generation, only 5 companies applied tools in this stage. For instance, Flokk utilized a 5-3 design philosophy with a list of priority materials, IKEA employed the circular design guide, Gispen used a framework and a list of statements for idea generation, and Ahrend relied on a list of sustainable and circular design principles.

For tools related to qualitative evaluation, Flokk employed the 5-3 design philosophy for concept evaluation, and Gispen applied a design framework in the form of spider web diagram.

Concerning the application of Life Cycle Assessment (LCA), 17 companies utilized LCA methods, including tools like LCA.no, EPD generation tools, Circular Life Cycle Analysis tool (C-LCA), eco chain, GHG protocol, etc. However, only 4 companies applied LCA at the beginning of the design process, and 3 integrated it along the design process.

Table 30 The application of LCD tool among interviewed companies



In the examination of furniture companies committed to sustainable development, a significant proportion were observed to adopt various design strategies. However, a notable finding was that only 7 companies have a well-defined design approach to guide their processes, while others predominantly relied on the intelligence of their designers. Furthermore, only one company employed a sustainable design method, whereas 7 companies used a general design method.

Despite 17 companies applying Life Cycle Assessment (LCA) for their products, the full potential of LCA remained underutilized across the industry. The research emphasized the critical role of designers in influencing the environmental impacts of their designs if the detailed life cycle impacts were notified. Notably, the ability to effectively mitigate both Initial Embodied Impacts and whole-life impacts diminishes as the design progresses (Estokova & Porhincak, 2015; London, 2017; Treasury, 2013). In other words, applying LCA at the beginning and throughout the design process proves more effective than applying it solely at the end.

In conclusion, the investigation underscored a deficiency in appropriate and comprehensive approaches, methods, and tools to guide furniture design processes toward sustainable solutions. Designers predominantly relied on their own knowledge, emphasizing the need for a furniture product Life Cycle Design (LCD) method and supporting tools. These tools should aid in sustainable idea generation, strategy priority definition, and qualitative evaluation, backed by a consolidated knowledge base.

5.4 An overall understanding of environmentally sustainable furniture products

5.4.1 Life cycle

The entire life cycle of a piece of furniture encompasses a series of activities and processes that consume resources such as materials and energy. These activities undergo transformations and generate various emissions. Typically, to facilitate the mapping of the life cycle of furniture, these activities and processes are categorized into five phases: pre-production, production, distribution, use, and end-of-life.

The study's conclusion indicates that if the entire impact of furniture is set at 100%, the average impact distribution across different stages is as follows: pre-production stage contributes 76%, production stage 13%, distribution stage 9%, use stage 0.46%, and end-of-life stage 2%. Activities in the pre-production stage primarily involve resource (materials and energy) extraction and production. The production stage includes manufacturing, assembly, and finishing processes. Distribution stage activities mainly revolve around packaging, transportation, and storage. In the use stage, activities predominantly include cleaning, repairing, maintenance, and potential upgrades. Finally, in the end-of-life stage, activities encompass landfill, incineration for energy recovery, reuse of components, and recycling of materials. A visual representation of these detailed life cycle activities has been synthesized in Figure 22, providing a comprehensive overview of the environmental impact distribution across the various stages of a furniture's life cycle.

5.4.2 Functional unit

When conducting an environmental impact assessment (e.g., Life Cycle Assessment), or conducting a Life Cycle Design (LCD), another key issue is the definition of Functional Unit (FU). Basically, the functional unit for furniture is a key approach for both the environmental impact assessment and the furniture Life Cycle Design (LCD). In other terms, it is not the physical furniture that will be studied, but its function, i.e., its services and the supplied results (Shi et al., 2016). All impacts of processes that are involved in satisfying the given function by the examined furniture are under assessment.

5.4.3 Design strategies

This research conducted a thorough analysis of the application of design strategies in best cases. The study adopted the general LCD strategies tailored for the furniture sector, as outlined in Table 31. Each strategy has the potential to impact specific stage(s) within the life cycle of furniture. Furniture use extension/intensification can significantly reduce the environmental impact throughout various stages of the furniture life cycle, including pre-production, production, distribution, and end of life. Furniture material's life extension mainly affects the impacts happened at the end-of-life and pre-production stages. Reduced material consumption of furniture plays a significant role in shaping the environmental impact across several stages of the furniture life cycle, namely pre-production, production, distribution, and end of life. Reducing energy consumption of the furniture system through design innovations primarily influences one category of consumption (energy) and affects mainly the distribution stage (the transportation process) and use (energy for cleaning and transportation if any). Resources conservation/biocompatibility for furniture predominantly influences the environmental categories of resources use_fossils and resources use_minerals and metals. Reducing the toxicity of the furniture system only affects several specific categories within the furniture life cycle, including the toxicity_cancer and toxicity_non cancer.

Table 31 The general LCD strategies (Vezzoli, 2018), and the furniture-specific LCD strategies

General LCD strategies	**Furniture-specific LCD strategies**
Product lifespan optimization	Furniture use extension/intensification
Extending the lifespan of materials	Furniture materials life extension
Minimizing materials consumption	Reduce material consumption of furniture
Optimizing resources renewability and biocompatibility	Resources conservation/biocompatibility for furniture
Minimizing energy consumption	Reduce energy consumption of the furniture system
Minimizing resource toxicity and harmfulness	Reduce toxicity of the furniture system

5.4.4 Design Approaches (guidelines)

The case study on environmentally sustainable furniture products revealed some design characteristics that were coded on two levels of detail. Firstly, the study revealed 15 design approaches and 36 detailed design sub-approaches. These 15 design approaches include A1 reinforced structure, A2 reduced packaging volume, A3 distributed economy, A4 one-piece molding, A5 use of low-impact materials (renewable/non-exhaustible/biocompatible materials), A6 modular system, A7 disassembly and assembly connections, A8 multi-functions, A9 standardization, A10 mono-materials, A11 easier recycling, A12 enhancing environmental benefits rather than reducing impacts, A13 avoiding packaging waste, A14 lightweight, A15 use of strong materials.

37 detailed design sub-approaches are: B1 - Corrugated plywood, B2 - Ribbed structure, B3 - Stackable design, B4 - Use of local raw materials, B5 - Incorporation of bent wood craft, B6 - Utilization of waste plastic from other sectors, B7 - Application of 3D printing technology, B8 - Use of recyclable materials, B9 - Incorporation of metal as raw materials, B10 - Modularity with different functions, B11 - Embedded nuts, B12 - Changeable dimensions (e.g., beds), B13 - Universal components, B14 - Zipper connections, B15 - Reduction in the number of components/connections, B16 - Utilization of waste components from other furniture within the same sector, B17 - On-site assembly, B18 - Tupperware-like connections, B19 - Wedge dowel connections, B20 - Plastic molding processes, B21 - Materials marking, B22 - Flat packaging, B23 - Use of sustainably sourced materials, B24 - Integration of energy generation mechanisms, B25 - Vacuum packaging, B26 - Incorporation of recycled materials from the furniture sector or other sectors, B27 - Cross-inset structure, B28 - Packaging as component(s), B29 - Water-based glues, B30 - Compression molding, B31 - Buckle connections, B32 - Inflation assembly/disassembly, B33 - Utilization of renewable materials (e.g., bamboo, palm leaves, rattan), B34 - Special brackets and cut-outs, B35 - Modularity with different sizes, B36 - Changeable shapes (e.g., bed, sofa), B37 aluminum extrusion.

In conclusion, the characteristics of environmentally sustainable furniture systems are summarized in Figure 27. The left part illustrates the furniture products' life cycle stages from Pre-production, Production, Use, Distribution, to End-of-life, highlighting the main activities in each stage and their average environmental impact. On the right part, the environmentally sustainable furniture products' Life Cycle Design (LCD) strategies and approaches, also known as guidelines, implemented by furniture companies and designers from case studies and semi-structured interviews are illustrated. It is noteworthy that some design approaches/sub-approaches are relevant or universal to several different strategies. These universal approaches/sub-approaches are marked in grey. Additionally, the life cycle data (on the left) and the design approaches (on the right) are interconnected because these design strategies have specific influence on different life cycle stages.

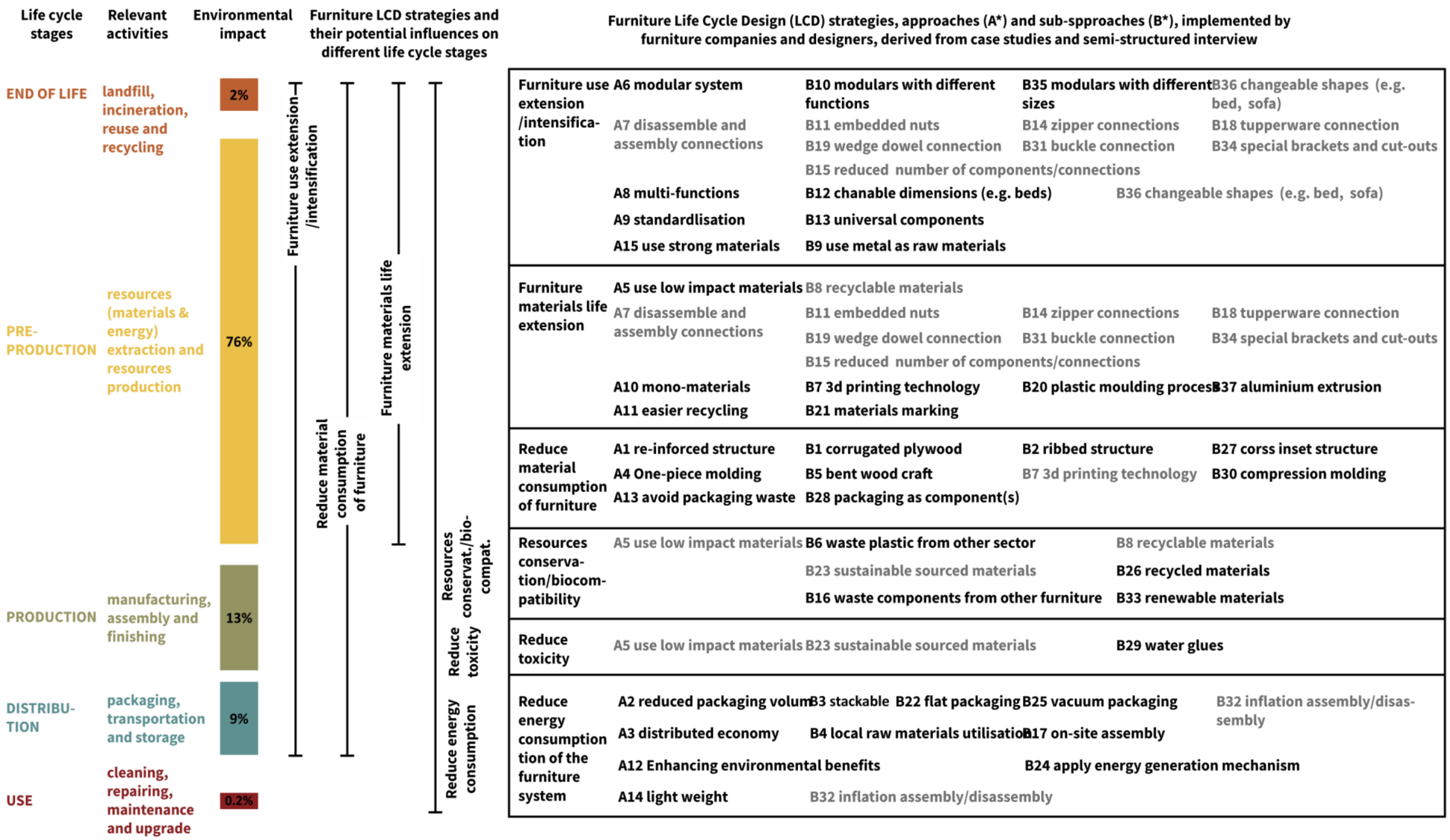


Figure 27 An overall understanding of the characteristics of environmentally sustainable furniture products

Chapter 6 Sustainable furniture Product-Service System and innovation opportunities

6.1 Sustainable Product-Service System: an introduction

The adverse environmental impacts of the production and consumption system have accelerated research into the causes and potential solutions to address these issues. There is an increasing recognition of undertaking radical measures towards sustainability. A pivotal approach for product innovation, particularly environmentally sustainable product design (also referred to as Life Cycle Design, LCD), is crucial to improving products' environmental performance concerning the life cycle processes Ceschin and Gaziulusoy, 2019). However, adhering to the traditional business logic of product sales, manufacturers often lack economic incentives to optimize sustainability throughout a product's life cycle. For instance, extending the product lifespan may not align with their economic interests (Manzini et al., 2003). Considering these factors, there is a urgent need to shift from a focus solely on product innovation to a more comprehensive and systematic approach.

A central contemporary question revolves around identifying opportunities within the intricate and interrelated environmental, social, and economic crises. Are there any offerings or business models capable of generating (new) value while decoupling it from material and energy consumption? In other words, can we significantly reduce the environmental impact of traditional production/consumption systems?

Researchers emphasize the significance of system innovations, wherein discussions extend beyond individual products to encompass production processes, artifacts, consumption patterns, and access to goods and services (Adams et al., 2015; Brezet, 1997; Manzini, 2002).

In this context, the Sustainable Product-Service System (S.PSS) emerges as a promising approach which has been under studying since the late 1990s (European Commission, 2020; Goedkoop et al., 1999; Manzini, 2002; Manzini & Vezzoli, 2003; Mont, 2002; Stahel, 1997; Tukker, 2004; UNEP, 2002; Vezzoli et al., 2014). Recent studies have confirmed that S.PSS is a highly promising business model, extending access to goods and services even to low- and middle-income users, thereby enhancing social equity and cohesion (Vezzoli, 2018; Vezzoli et al., 2021b). Importantly, it represents a win-win offer model that integrates the three dimensions of sustainability: economic, environmental, and socio-ethical. The definition of an S.PSS is as follows: "an offer model providing an integrated mix of products and services that, together, fulfill a particular customer/user demand (delivering a 'unit of satisfaction'). It is based on innovative interactions between stakeholders in the value production system (satisfaction system), where the ownership of the product/s and/or the life cycle services costs/responsibilities remain with the provider/s. This ensures that the same provider/s continuously seek/s environmentally and/or socio-ethically beneficial new solutions with economic benefits"(Vezzoli et al., 2021). S.PSSs are value propositions that introduce significant innovation on different levels:

- PSS redirects the business focus from merely selling products to providing a "unit of satisfaction," encompassing a combination of products and services that collectively achieve ultimate user satisfaction.
- PSS alters the perceived value by the customer/end-user, moving from individual ownership to access to goods and services.
- PSS pivots the primary focus of innovation from a technological standpoint to innovation at the stakeholder interaction level.

This approach aligns with the European Union's Circular Economy action plan, which advocates for incentivizing models like "product-as-a-service," where producers retain ownership of the product or responsibility for its performance throughout its lifecycle (European Commission, 2020). Crucially, in the core understanding of our discussion, S.PSSs represent offer models with a win-win sustainability potential. In other words, they are business models capable of generating (new) value, detaching it from resource consumption, reducing negative environmental impact, extending access to goods and services to low- and middle-income individuals, and simultaneously fostering social equity and cohesion.

This PhD work primarily centers on the environmental and economic dimensions. Thus, the question arises: When is a Sustainable Product-Service System (S.PSS) eco-efficient? More precisely, when does an S.PSS successfully decouple economic interests from both an increase in resource consumption and a decrease in environmental impacts? In simpler terms, why and under what circumstances is an S.PSS producer/provider economically motivated to design for environmental sustainability?

An S.PSS is considered eco-efficient when the product ownership and/or the economic responsibility for its life cycle performance remains with the producers/providers who sell a unit of satisfaction rather than just the product. In this scenario, S.PSS shifts or allocates the direct economic and competitive interest from reduced environmental impacts of the products and/or services onto the stakeholder. Consequently, within an S.PSS model, a product Life Cycle Design (LCD) or eco-design approach becomes economically beneficial. In other words, an S.PSS producer/provider is economically interested in designing for (Vezzoli et al., 2018):

- product lifespan extension and use intensification;
- material life extension (recycling, energy recovery, composting);
- material consumption minimizations;
- energy consumption minimizations;
- resources’ (materials and energy) renewability/biocompatibility;
- resources’ (materials and energy) toxicity/harmfulness minimization.

6.2 Sustainable Furniture Product-Service System environmental and economic potential win-win benefits[22]

Based on the literature, this section formulates hypotheses suggesting that Sustainable Product-Service Systems (S.PSS) for the furniture system could yield win-win benefits for environmental sustainability and economic prosperity in the aforementioned six aspects, each with its own distinctive characteristics.

6.2.1 S.PSS for furniture facilitates furniture use extension

What happens when the furniture S.PSS provider is offering the furniture products retaining the ownership and being paid per unit of satisfaction, or offers all-inclusive furniture with maintenance, repair, upgrade, reconfiguration, substitution, and end-of-life treatment? The longer the furniture or its components last (yielding environmental benefits), the more the furniture producer/provider avoids disposal costs, as well as the costs of pre-production, production, and distribution of new furniture substituting the disposed one (resulting in economic benefits), as illustrated in Figure 28. Consequently, the furniture producer/provider is incentivized by economic considerations to design for the lifespan extension of furniture.

6.2.2 S.PSS for furniture facilitates furniture use intensification

What happens when the furniture S.PSS provider is selling a shred use of furniture to various users?Tthe more intensively the furniture is used (leading to environmental benefits),

[22] This chapter, 6.2, refers to the paper published by the author entitled “A Case Study Analysis of the Furniture System From Sustainable Product-Service System Design Perspective” (Vezzoli & Yang, 2021).

the higher the profit (resulting in economic benefits). Consequently, the furniture producer/provider is motivated by economic interests to enhance the intensity of furniture use. See Figure 29.

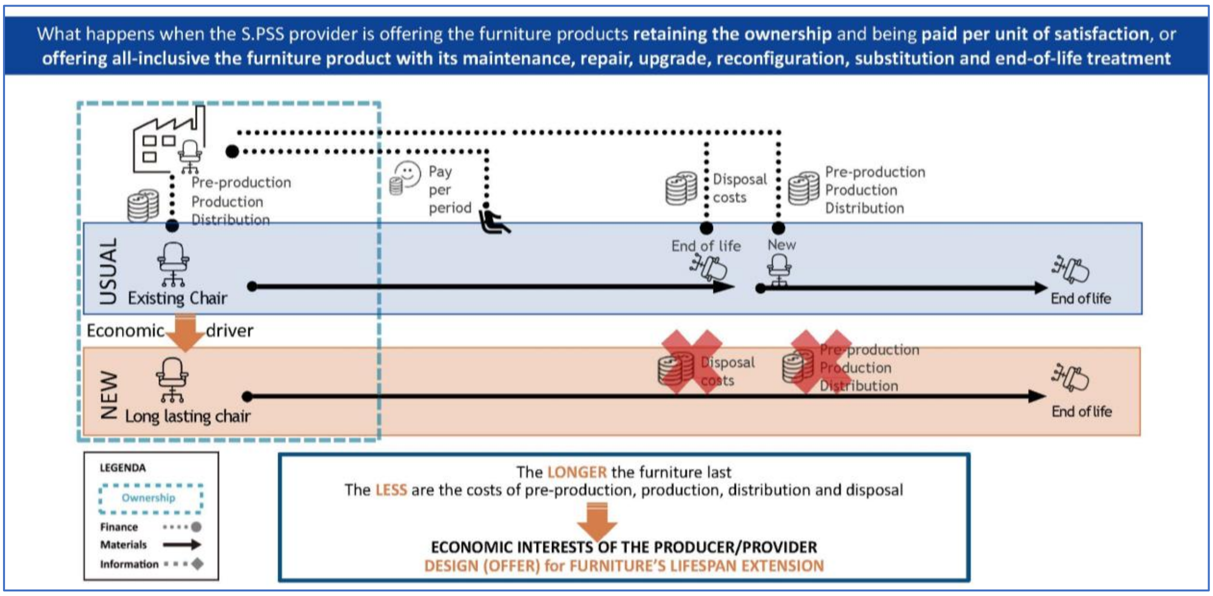


Figure 28 The win-win benefits of S.PSS for furniture (furniture life extension)

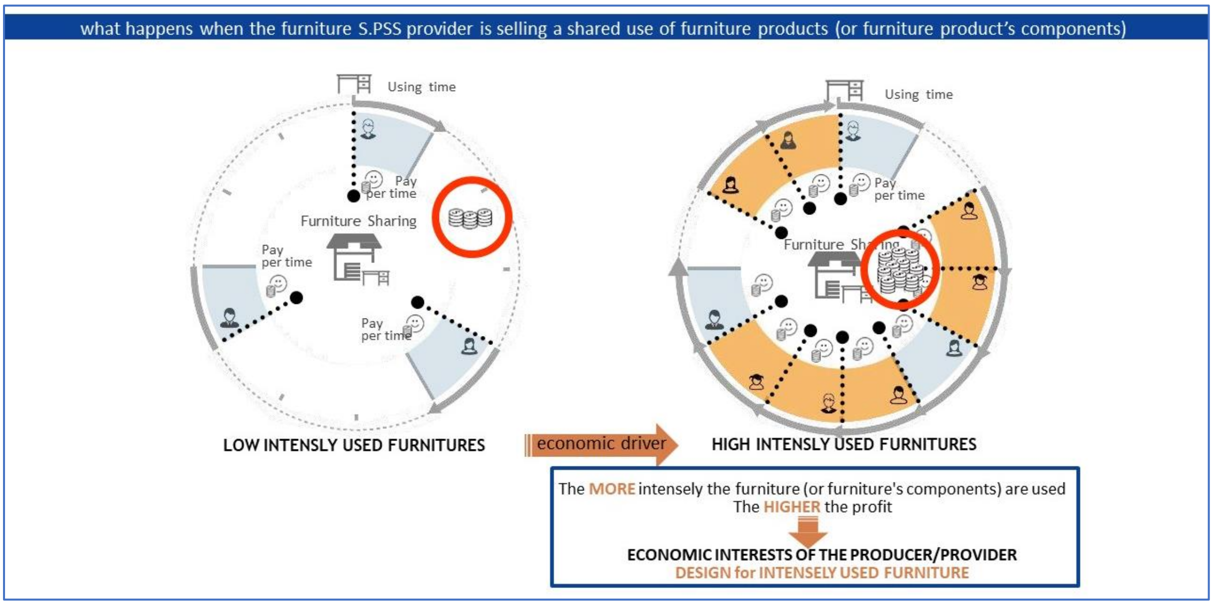


Figure 29 The win-win benefits of S.PSS for furniture (furniture use intensification)

6.2.3 S.PSS for furniture facilitates material life extension (recycling, energy recovery)

What happens when the furniture S.PSS provider is selling all-inclusive furniture with its end-of-life treatment? The more the materials are either recycled or incinerated with energy recovery (leading to environmental benefits), the more costs are avoided related to landfilling, the purchase of new primary materials, or energy (resulting in economic benefits), as depicted in Figure 30. Hence, the furniture producer/provider is driven by economic interests to design for material life extension (utilizing recycling, energy recovery, etc.).

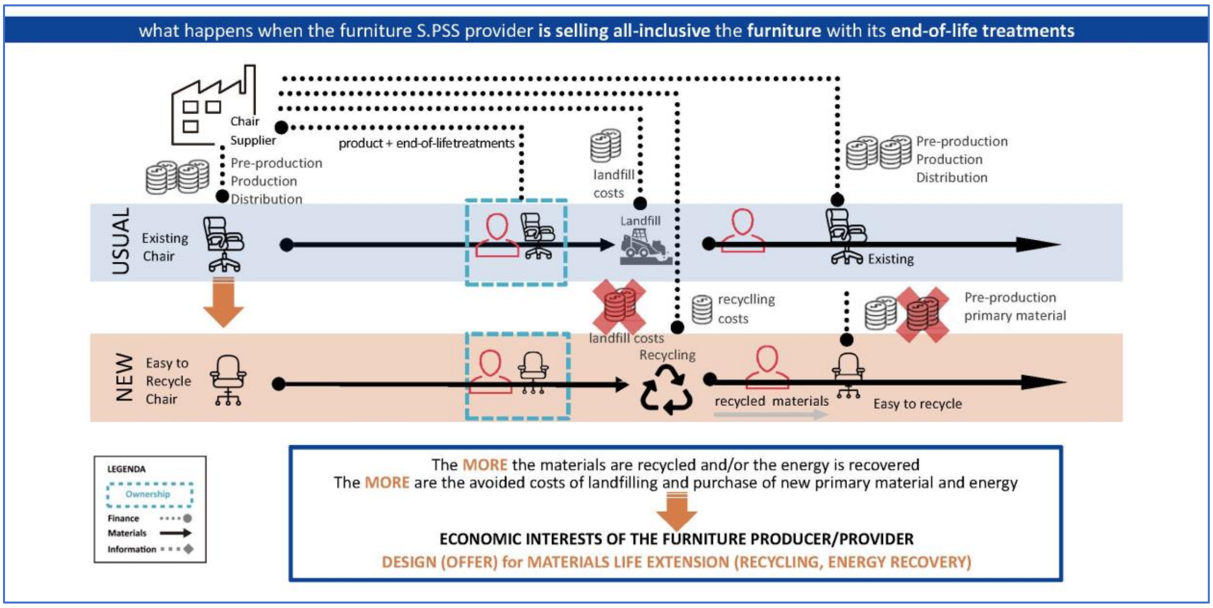


Figure 30 The win-win benefits of S.PSS for furniture (material life extension)

6.2.4 S.PSS for furniture facilitates resource consumption minimization

What happens when the furniture S.PSS provider is selling all-inclusive access to furniture and is responsible for the resources (i.e., materials and energies) it consumes during its life cycle stages? The higher the resource efficiency in all furniture life cycle stages (resulting in environmental benefits), the higher the profit (leading to economic benefits), as illustrated in Figure 31. Hence, the furniture producer/provider is driven by economic interests to design/offer furniture and/or services that minimize resource consumption.

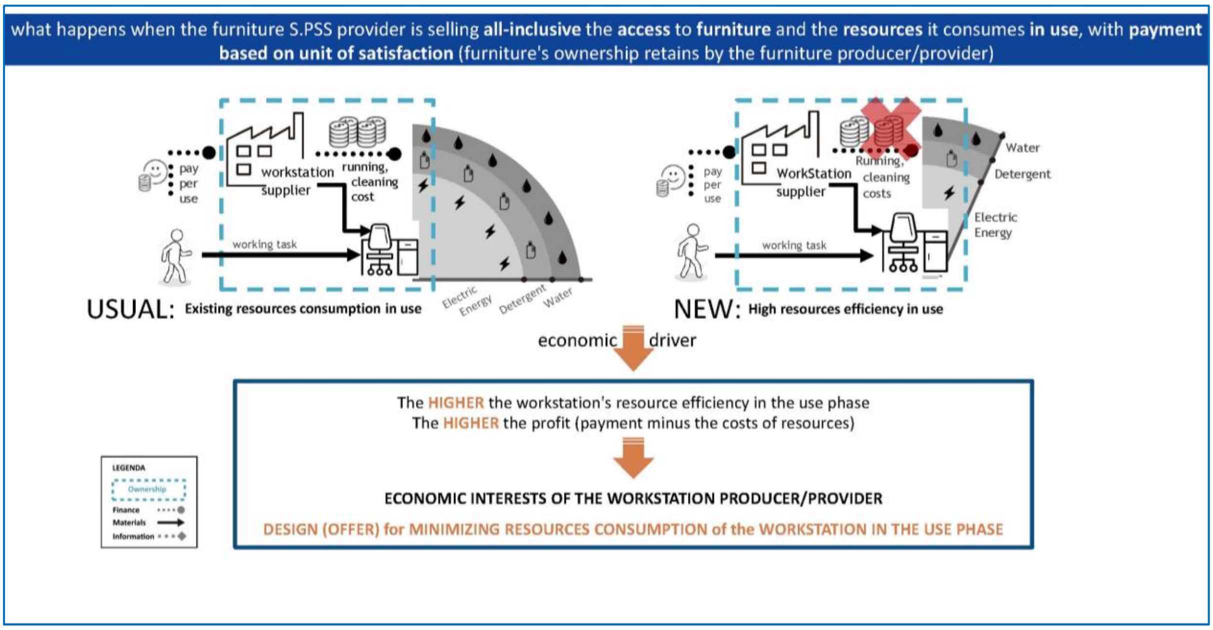


Figure 31 The win-win benefits of S.PSS for furniture (resource consumption minimization)

6.2.5 S.PSS for furniture facilitates resource renewability/biocompatibility

What happens when the furniture S.PSS provider is selling access to the workstation with all-inclusive the energy, with payment per period/time/satisfaction (e.g., furniture and energy production unit)? The higher the proportion of passive/renewable sources (resulting in environmental benefits), the higher the profit, i.e., the payment minus (among other costs) the costs of sources (leading to economic benefits). Hence, the furniture producer/provider is driven by economic interests to design (offer) for resource renewability. See Figure 32.

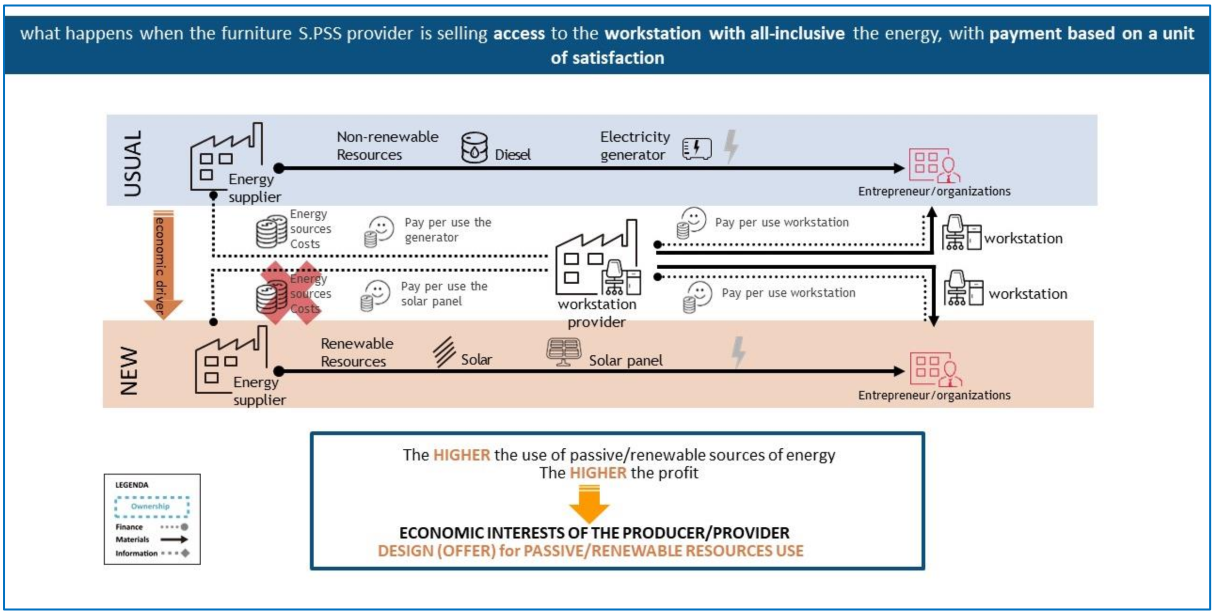


Figure 32 The win-win benefits of S.PSS for furniture (resources renewability/ biocompatibility)

In summary, Sustainable Product-Service Systems (S.PSS) for furniture encompass two key aspects: 1) the design of a specific furniture satisfaction unit and all related furniture products and services, and 2) the design of interactions among stakeholders (i.e., offer model) within a particular furniture satisfaction system. Within the S.PSS for furniture framework, there is potential for providers to consistently seek environmentally beneficial furniture solutions for economic reasons. In essence, the financial interests of furniture providers (manufacturers) serve as an incentive for the design of environmentally sustainable furniture products. These hypotheses are explored and substantiated in the subsequent chapters through case studies and semi-structured interviews.

6.3 Case Study and a semi-structured interview: existing characteristics of Sustainable Furniture Product Service Systems[23]

The theory regarding the application of S.PSS in sustainable furniture design is limited. Some proposed furniture PSSs are not primarily focused on sustainability but rather on new market opportunities. In this research, the Case study method is chosen as it is coherent for studying new areas and issues where little theory is available (Eisenhardt, 1989; Yin, 2014). Since evidence from multiple case studies is often considered more robust (Herriott & Firestone, 1983), multiple case studies are conducted in this paper. Selection criteria for cases and the format for information analysis are defined. A total of 44 furniture S.PSS cases have been thoroughly analyzed. Subsequently, a cross-case analysis is conducted to verify the similarities and differences of S.PSS offer models among cases. Afterwards, semi-structured interviews were carried out to verify cases, discuss companies' application of furniture S.PSSD approaches, methods, and tools, and confirm the win-win benefits observed during their practical implementation.

The case study and semi-structured interviews have several objectives. Firstly, it aims to identify the key elements and characteristics of furniture S.PSS. Secondly, it aims to verify and characterize S.PSS's win-win economic and environmental benefits for furniture systems, thus verifying the hypotheses made in chapter 6.2. This involves examining whether and under what conditions applying the S.PSS approaches to furniture design and offering makes the provider economically interested in improving furniture's environmental

[23] Within this chapter, the method and results of the furniture S.PSS case study analysis refers to the authors publication entitled "A Case Study Analysis of the Furniture System From Sustainable Product-Service System Design Perspective" (Vezzoli & Yang, 2021).

performance. Both objectives seek to identify common characteristics of furniture S.PSS. Thirdly, the study aims to draw a comprehensive archetypal S.PSS map for furniture that represents a sustainable furniture system. Lastly, the study aims to understand the need for furniture-specific S.PSS design approaches, methods, and tools.

6.3.1 Method

Sampling Strategy: Similar to the furniture product case study, the case analysis of furniture S.PSS adopted a maximum variation sampling (Miles & Huberman, 1994) and data triangulation strategy (Yin, 1994). Information sources for the case studies included companies' reports and websites, interviews with furniture companies, and scientific papers about the cases, reports from international organizations mentioning the cases, as well as news and articles from websites. The use of various data sources and methods, including desk research, literature review, and semi-structured interviews, enhances reliability and validity by providing a comprehensive and diverse perspective on the subject.

Case Collection: The research on S.PSS applied to furniture is conducted through literature review and desk research. Initially, a literature review is carried out using keywords such as 'furniture' or 'furniture design'; 'sustainable' or 'sustainability' or 'design for sustainability' or 'Product-service system'; 'case study' or 'case analyses' or 'case' with the Google Scholar tool to identify relevant furniture cases. Subsequently, desk research is conducted across three European Union-funded furniture projects, three research institutions' websites, over 42 furniture companies' websites, and five online interviews or videos. Through the literature review and desk research, 44 sustainable furniture PSS cases are identified, originating from 15 scientific papers, one book, one furniture project (Katch-e), and three research institutions (LeNS network, Ellen Macarthur Foundation, and Wrap). All these cases align with the general definition of Sustainable Product-Service System, as presented in chapter 6.1.

Case Analysis: A structured case study format (see Figure 33, also in Annex 1) has been designed for the collection and analysis of case information. This format encompasses various aspects, including the offered furniture products and services (referred to as the satisfaction unit), stakeholder configuration, sustainable benefits, and more. The case study format is organized into the following sections:

- General information: Brand, location, contacts, start year, project state, video (interview or introduction), and source of case's information;
- Furniture product analysis: (i) Furniture characteristics, including category, main materials, and life cycle design strategies; (ii) Furniture description; (iii) Sustainable benefits;
- Furniture PSS analysis: (i) System characteristics, including providers, customer, S.PSS type, satisfaction unit, offered products, offered services; ownership of products, and payment methods; (ii) System description; (iii) Sustainable benefits of the system, covering environmental, socio-ethical, and economic benefits; (iv) Stakeholders' interaction, illustrated with a system map;
- Limits and barriers of the system (if any);
- Pictures: Visual representation of the systems.

For each case, a comprehensive case analysis is undertaken to compare S.PSS configurations for furniture, satisfaction unit, offered product, the ownership, service providers, payment methods, and the sustainable win-win benefits, see Figure 33. An example of the Gispen case analyzed using this format is provided in the results section to demonstrate the application of the format.

CASE STUDY / PROJECT, LOCATION **1**

PROJECT, LOCATION

Source:

1. GENERAL INFORMATION

Brand name	-
Producer/provider /alliance of providers	-
Company location	-
Main contact	-
E-mail	-
Website	-
Start (year)	-
State	-
Link to video	-
Source of information	-

2. FURNITURE PRODUCTS ANALYSIS

2.1 FURNITURE CHARACTERISTIC

FURNITURE SERIES (NAME):	
category	-
Main materials	-
LCD STRATEGIES:	Analysis what design strategies are used in furniture design
Furniture use extension/ intensification	-
Material consumption reduction for furniture	-
Material Life Extension for furniture	-
Toxicity reduction for furniture	-
Energy Consumption Reduction for furniture	-
Resources conservation/biocompatibility for furniture	-

2.2 SHORT DESCRIPTION OF FURNITURE PRODUCTS

2.3 CHARACTERISTICS OF THE REDUCTION OF ENVIRONMENTAL IMPACTS

LeNS lab POLIMI | DESIGN AND SYSTEM INNOVATION FOR SUSTAINABILITY

3. FURNITURE PRODUCT SERVICE SYSTEM ANALYSIS

3.1 SYSTEM CHARACTERISTICS

SYSTEM CONFIGURATION:	
Provider/s (role)	-
Customer/s (type)	-
S.PSS CHARACTERISTICS:	
Type of S.PSS	-
Unit of satisfaction	-
Offered product/s (related producer/s)	-
Ownership of the offered product/s	-
Offered service/s (related supplier/s)	-
Access payment	-
DE system configuration (if make sense)	-

3.2 SYSTEM DESCRIPTION (max 500 characters - spaces included)

How does the S.PSS offer work?
Who is the provider/s and customer/s of the offer?
What is the offer to the customer?
What and how is paid within the service?

DESCRIPTION (if any longer than the short)

3.3 SUSTAINABLE BENEFITS OF SYSTEM

Environmental Benefits
Describe environmental benefits starting from the following categories.
System life optimization
Transportation/distribution reduction
Resource reduction
Waste minimization/valorization
Conservation/biocompatibility
Toxicity reduction.

Socio-ethical Benefits
Describe socio-ethical benefits starting from the following categories.
Improve employment/working conditions
Improve equity and justice in relation to stakeholders
Enable a responsible/sustainable consumption
Favor/integrate the weaker and marginalized
Improve social cohesion
Empower/enhance local resources.

CASE STUDY / PROJECT, LOCATION 3

Economic Benefits
Describe economic benefits starting from the following categories.
Market position and competitiveness: are there many competitors in your field?
Profitability/added value for companies: is the offer more economically beneficial?
Added value for customers: this reduces the initial investment and reduces the life responsibility.
Long term business/development risks; are there any business/development risks you expected?
Partnership/cooperation:
Macro-economic effect.

3.4 SYSTEM MAP (not compulsory)

4. DESCRIPTION OF HOW FURNITURE LCD SUPPORT S.PSS

5. LIMITS AND BARRIERS

6. PICTURES (not compulsory)
Images (possibly of good quality) can be related to:
- product or service in its complexity
- drawings, exploded views, etc.
- environmental characteristics (for example details, methods of use, etc.)

Images must be saved and printed individually.

The source must be indicated (if a magazine or a book indicates the author of the article or text, the name of the magazine or the title of the book, the publisher, and the relative page number).

LeNS lab POLIMI | DESIGN AND SYSTEM INNOVATION FOR SUSTAINABILITY

Figure 33 Case study format

Semi-structured interview. Semi-structured interview. A systematic approach was followed, encompassing the stages of planning, contact with potential interviewees, question preparation, documentation planning, and reflection on the interviews. A total of 22 furniture companies underwent thorough investigation through desk research, with subsequent in-depth interviews conducted with 10 selected companies. During the planning phase, outreach was made to 22 furniture companies, providing them with comprehensive background information, objectives, processes, tools, and anticipated durations. Subsequently, 10 of these companies were detailed interviewed. To ensure an organized and focused discussion during the interviews, an interview manuscript was sent in advance, containing questions aligned with the study's objectives. Each interview lasted approximately one hour. To enhance accuracy and comprehensiveness, audio recordings were made during the interviews, and these recordings were later fully transcribed and analyzed.

6.3.2 Result

44 cases have been thoroughly analyzed using the established case study format, within which 22 cases were further investigated with extensive desk research and / or during semi-structured interviews. Except for the application of S.PSS models in these furniture companies, the application of design strategies, methods and tools were investigated, the economic and environmental benefits derived from implementing furniture S.PSS were verified. The subsequent section provides an overview of one representative Furniture Sustainable Product-Service System (S.PSS) cases (from Gispen), illustrating the outcomes derived from the comprehensive analyses. Upon cross-referencing all investigated companies, common insights were subsequently extracted.

General information (Gispen)

Brand name	-Gispen
Producer/provider /alliance of providers	-Gispen
Company location	-The Netherland
E-mail	- info@gispen.nl
Website	- https://www.gispen.com/en/
Start (year)	-1916
State	-ongoing
Link to video	- https://www.youtube.com/watch?v=XxQwZtVGu-k
Source of information	- KATCHE project, (Bosch et al., 2017; Pergande et al., 2012; Zancul et al., 2011)

Furniture products analysis (Gispen)

(1) Furniture characteristic

Furniture series (name):	Triennial seats
category	- chair
Main materials	-steel, textile, wood, foam
LCD strategies:	
Furniture use extension/ intensification	-use standard components and modular structure; design for easy disassembly;
Material consumption reduction	-none
Material Life Extension for furniture	-mono-material strategy; design for easy disassembly
Toxicity reduction for furniture	-none
Energy Consumption Reduction for furniture	-none
Resources conservation/biocompatibility	-none

(2) Short description of furniture products

All of Gispen's furniture is well-suited for Furniture-as-a-Service (FaaS), particularly the modular collections, such as the Triennial seats. The Triennial seat is constructed using 75% standard components that are universally applicable to other furniture groups. For instance, the backrest of a chair can also be utilized for a bar stool. This design enhances the versatility of each component for future life cycles. The series is specifically engineered for straightforward disassembly. The backrest can be easily replaced or exchanged on-site by a single person within 10 minutes, facilitated by a single screw connection. The textile cover is secured with a zipper, ensuring easy on-site upgrades. Material blends are minimized, with the frame (steel) and cover (fabric) detachable from the seat (wood and foam).

(3) Characteristics of environmental impacts reduction

The furniture products are designed for disassembly, promoting an extended lifespan through potential repair and upgrades. The emphasis on design for disassembly and mono-material design contributes to the material's life extension, facilitating further recycling.

Furniture Product-Service System analysis (Gispen)

(1) System characteristics

System configuration:	B2B or B2C
Provider/s (role)	-Gispen
customer/s (type)	-business or individual
S.PSS characteristics	
Type of S.PSS	-result-oriented, product-oriented, care-oriented
Unit of satisfaction	-users have access to design furniture and all-inclusive life cycle services
Offered product/s (related producer/s)	-office furniture
Ownership of the offered product/s	-Gispen
Offered service/s (related supplier/s)	- delivery, installation, maintenance (annual check-ups, regular cleaning), repair, upgrade, replacement, and reconfiguration (when the users’ needs change), take back, and so on.
Access payment	-pay per month/ pay for furniture with services

(2) System description

Gispen offers various plans (including offices furniture and different services) for the final users. Firstly, Gispen sells office furniture accompanied by additional services, including (1) planned and unplanned maintenance, covering preventive (periodic checkups and maintenance) and corrective measures (repair, cleaning services); (2) value retention through component additions or removals to enhance functionality or design; (3) a furniture management system incorporating QR codes or RFID tags for monitoring and registering furniture details (info like location, brand, product type, age, purchase price, replacement cost, picture, colors and dimensions); (4) take-back services for remanufacturing; (5) furniture refurbishment; (6) office furniture relocation; and (7) circular product design, focusing on revival and remaking. Users can tailor these services within their contracts. This is afterwards defined as product-oriented furniture S.PSS.

Secondly, Gispen has other offers in which Gispen retain the ownership of furniture and provide services like the furniture management system which is managed by end-users themselves. This is afterwards defied as care-oriented furniture S.PSS.

Thirdly, Gispen offers a 'Furniture as a Service (FaaS)' solution, providing users with a subscription model for leasing office furniture and associated all-inclusive services through a fixed monthly fee. Gispen retains ownership and delivers well-designed furniture, suitable for refurbishing and remaking, accompanied by comprehensive services such as delivery, installation, maintenance (annual check-ups, regular cleaning), repair, upgrade, replacement, reconfiguration (as users' needs change), take-back, and more. The stakeholder interaction is illustrated in Figure 34. Customers pay based on the period of use.

(3) Environmental benefits of the system

Gispen's furniture S.PSS yields both environmental and economic win-win benefits observed during case analysis and were confirmed during the interview. As Gispen retains ownership and receives payment monthly, there is an economic incentive for Gispen to design furniture for life extension, as the longer the furniture lasts, the greater the benefits. Additionally, designing for material life extension, including recycling, becomes economically beneficial for Gispen by reducing the costs associated with purchasing new materials. The offer also supports minimization of resource consumption. Specifically, the furniture management system prevents furniture idleness, while the use of recycled materials reduces raw material consumption and smart logistics minimize energy consumption during transportation.

In this case, the furniture products are intentionally designed with modularity and easy assembly/disassembly. Furthermore, each piece of furniture is equipped with a QR code that displays crucial information such as material source, composition, and expected lifespan. These design characteristics create the foundation for an all-inclusive service model, encompassing maintenance, repair, upgrades, replacements, reconfigurations, and take-back for refurbishment or reuse. The win-win economic and environmental benefit arises from the simplicity and economic viability of reusing or refurbishing furniture. The disassembly structure and integrated IoT information make it easy to repair or upgrade furniture by exchanging specific components. This economic incentive for the provider to opt for reuse/refurbishment over new production extends the life of the furniture system and conserves materials.

A total of 41 case cards were developed with a designed format and made available with open access ethos, see annex 4.

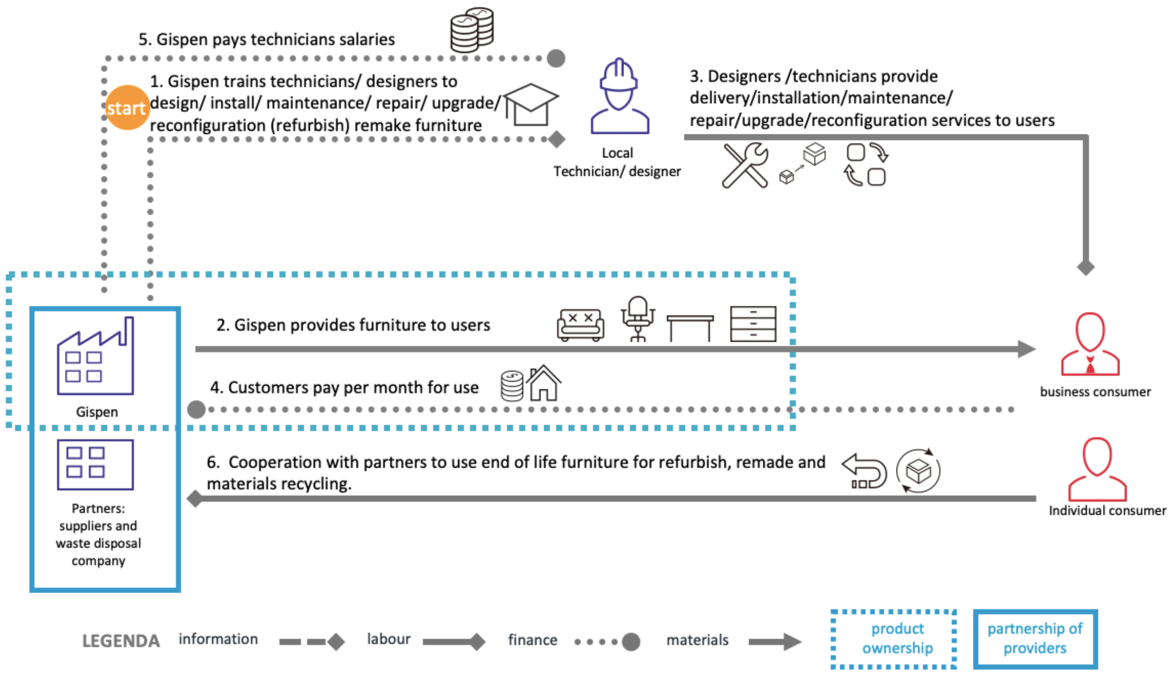


Figure 34 Stakeholders interaction for Gispen case (system map)

The application of S.PSSD methods and tools (Gispen)

To develop these offers (or furniture S.PSSs), Gispen adopts different design methods and tools. About design method, Gispen adopts the Dynamics Methodology to formulate the

Furniture Sustainable Product-Service System (S.PSS) or business model. This methodology involves the following steps: (1) Defining the most crucial central Key Performance Indicators (KPIs); (2) Identifying relevant variables within the causal-context model; (3) Establishing and quantifying relationships between central KPIs and variables in the model; (4) Validating the model structure and behavior at both levels (Bosch et al., 2017). In the S.PSS design process, Gispen utilizes the Vensim© tool.

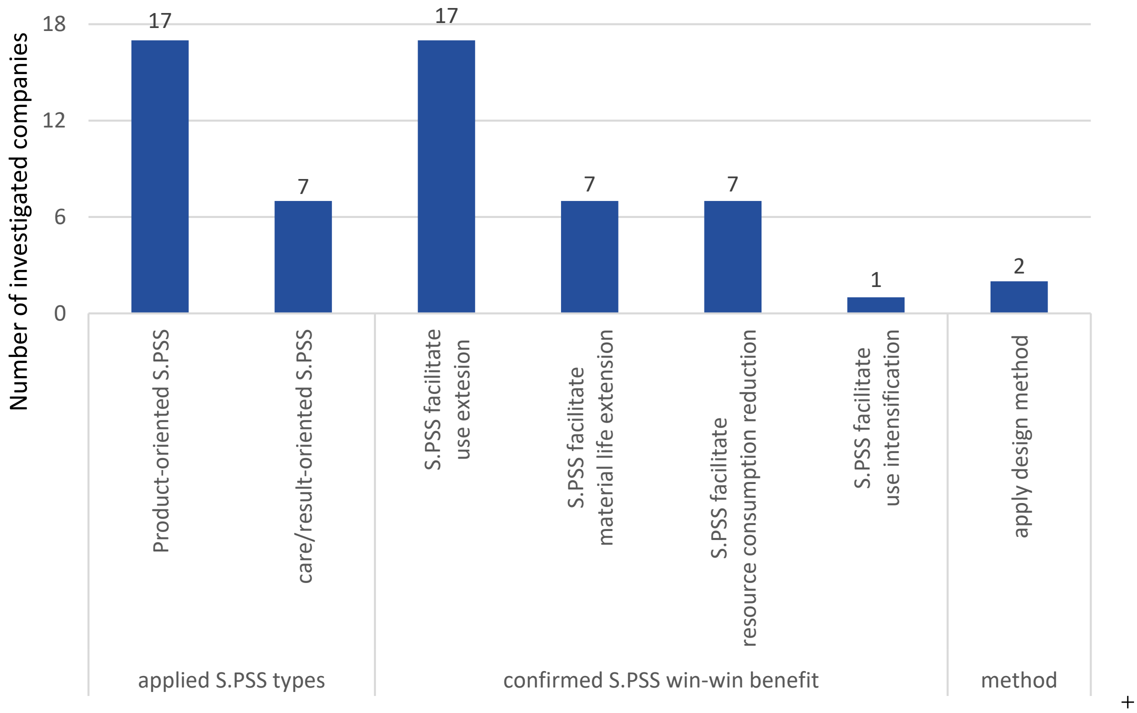
6.3.3 The nowadays application of S.PSS knowledge and know-how in furniture companies

Gispen was demonstrated as a prime example of applying S.PSSD approaches, methods, and tools. Through cross-comparing all cases, the study identified a deficiency in knowledge and know-how for furniture S.PSSD in contemporary furniture companies.

The application of furniture S.PSSD. The application of furniture S.PSSD reveals that out of 22 furniture companies analyzed (refer to Table 29), 17 were implementing product-oriented S.PSS, while 7 were adopting care-oriented or result-oriented S.PSS. These companies engaging in furniture S.PSS confirmed the assumed win-win economic and environmental benefits for furniture. While product-oriented S.PSS, added value to the furniture's life cycle, is widely embraced by furniture companies, the adoption of care-oriented S.PSS (enabling furniture care platforms for customers) and result-oriented S.PSS (providing access to furniture and full services) remains limited. Despite the higher potential in environmental impact reduction with the latter two models (Tukker, 2004), their application is not as well-developed.

The application of method and tools to design furniture S.PSS. Regarding the design of furniture S.PSS, one company utilized the business model canvas, although it is not relevant to sustainability. Conversely, one company employed the dynamics methodology, which is relevant to sustainability. The current situation revealed a deficiency in appropriate and comprehensive approaches, methods, and tools to steer the furniture S.PSSD process toward sustainable solutions, with designers primarily relying on their individual knowledge. Specifically, there is an absence of a knowledge base and know-how specific to Furniture S.PSSD, including strategies, design methods, supporting tools for strategic analysis, S.PSSD idea generation, S.PSS description, and qualitative evaluation.

Table 32 The application of S.PSSD types, achieved win-win benefits and methods among interviewed companies



6.3.4 Characteristics of furniture S.PSS and a conceptual framework

6.3.4.1 key elements of furniture S.PSS and characteristics

The offered furniture products in these exemplary cases are diverse, encompassing primarily office furniture, household furniture, a combination of office and household furniture, 3D printing products, furniture machines, co-housing/co-working spaces, and houses.

Furniture Product types. The range of offered office furniture varies, encompassing general ones found in an office setting, a package of office furniture with facilities and office spaces, locally crafted office furniture, remanufactured/refurbished/second-hand office furniture, and ergonomic chairs. Household furniture offerings include general household furniture, furnishings, appliances, second-hand household furniture, and furniture made from specific materials like plastic. 3D printing products comprise both furniture and various small items. Furniture machines are included among the offerings, providing users access to furniture machines for creating their own furniture, either independently or through a nearby third party. Co-housing and co-working spaces fall under the offered products, with co-housing spaces facilitating shared furniture use and co-working spaces enabling shared office furniture use and the utilization of furniture machines for crafting. Houses are also part of the offerings, providing inspirational ideas in two specific cases.

Furniture product characteristics. In certain cases, furniture products are intentionally designed for sustainability, while in others, sustainability considerations may not be as prominent. Notably, sustainably designed furniture products exhibit key characteristics such as 3D printing, ease of disassembly, flat-packaging, integration of Internet of Things (IoT) technology, utilization of local materials, modular design, and customization.

Services. The services offered within these furniture S.PSS models span all stages of stakeholder interaction, including design, pre-production, production, distribution, use, and end-of-life. In the design phase, a platform owner facilitates the connection between end-users and designers, ensuring the distribution of quality design work at fair prices. Additionally, design work-checking services are provided to ensure the final quality of 3D printing products, along with quoting services. For refurbished/remanufactured furniture to align with the surrounding environment, providers offer interior design and layout planning services. Some providers also involve users in the design process, allowing them to co-create final products based on customized demands.

During the pre-production stage, certain providers offer services to assist users of 3D printing furniture in procuring materials. In the production stage, a platform owner facilitates the connection between end-users and local producers to enable local furniture production. Some providers extend co-production services, including furniture-making training, to involve end-users in the production stage. This involvement is aimed at creating specific memories associated with using the furniture, contributing to emotionally durable design. Additionally, some providers grant access to furniture machines and offer maintenance services for these machines. At times, distribution is offered as an additional service. Throughout the distribution process, services such as online purchasing and order tracking functions are provided.

The use stage involves a variety of services. Consultancy services, including training in ergonomically use of task chairs and correction of sitting gestures, are provided to users. Some providers offer apps to provide additional useful information, such as maintaining healthy sitting positions. Additional tools may be provided for ergonomics adjustment or furniture inventory management to facilitate continued use. Services such as installation, regular cleaning, and maintenance are offered to keep the furniture in good condition, along with repair or replacement services to extend its use. Aesthetics, technological retrofits, culture/aesthetic/function/technology upgrades, reconfiguration, refurbishing, relocation, and removal services are also provided. For co-working offers, staff reception services may be included. Some of these services fall under warranty.

At the end of the furniture's life, some providers offer comprehensive services such as take-back, buy-back, furniture checking and reselling, and furniture exchange. See the following table.

Table 33 The numerosity of service types within the 44 furniture S.PSS cases analyzed

stages	services	Number of cases
design, finding collaborators	connection (user with designer), design (co-creation), design (interior), design supporting (analysis, fixing the 3D file, preview), design work, platform (open access), quote design works	8 (#1, #24, #25, #27, #28, #38, #40, #43)
PP	material procurement	3 (#25, #30, #38)
P	co-production (furniture-making training), connection (users with local craftsmen/3D printer owners), maintenance (spaces and machines)	5 (#28, #29, #33, #34, #37)
DIS	Delivery, online services for purchasing, tracking	11 (#4, #14, #16, #17, #22, #23, #24, #25, #26, #30, #38)
USE	Consultancy services (ergonomics training, sitting gesture correction), mobile APPs for information, additional tools to enable users of ergonomics adjustment or furniture inventory management, installation, regular cleaning or maintenance, repair or replacement, aesthetic/technologic Retrofits, culture/aesthetic/function/technology upgrades, reconfiguration, refurbishing, relocation, remove, staff reception	24 (#1, #2, #3, #4, #5, #6, #7, #9, #11, #12, #13, #14, #15, #16, #17, #18, #22, #23, #24, #26, #27, #32, #34, #41)
EOL	take-back, buy-back, furniture checking and reselling, furniture exchange	9 (#1, #5, #14, #17, #18, #19, #20, #39, #44)

Note: PP – Pre-production, P – Production, DIS – Distribution, EOL – End of life. #N refers to the number of a case, see Annex 8 _Case study_furniture S.PSS_coding

Stakeholders. To provide the diverse range of furniture products and services, various stakeholders are involved in the system, including: furniture remanufacturers, furniture producers, co-working space owners, furniture retailers, second-hand furniture sellers, customized furniture producers, platform constructors, furniture machine owners, sitting consultants, furniture training institutions, designers, etc.

Business models. Despite all being classified as furniture S.PSS, these cases present distinct business models. These models encompass extended warranty services, co-housing or co-working ventures, distributed networks for furniture production and sales, do-it-yourself (DIY) furniture or on-site assembly, furniture as a service (FAAS), furniture remanufacturing, furniture renting, second-hand furniture selling or exchanging, prosumer models (where the producer is also a consumer), and pre-determined demand strategies. See.

Table 34 The numerosity of business types within the 44 furniture S.PSS cases analyzed

Business models	**Cases numbers**
Extended warranty	2 (#2, #9)
co-housing or co-working business	3 (#15, #18, #41)
distributed furniture producing and selling network	11 (#25, #27, #28, #29, #30, #35, #36, #38, #43, #33, #34)
Do-It-Yourself (DIY)	3 (#26, #33, #34)
Furniture As a Service (FAAS)	4 (#4, #5, #6, #14)
furniture remanufacturing	5 (#1, #7, #13, #14, #39)
furniture renting	3 (#16, #17, #32)
second-hand furniture selling or exchanging	6 (#19, #20, #21, #22, #23, #39)
prosumer (the producer is the consumer) or pre-determined demand	3 (#24, #37, #40)
Flexible house	2 (#8, #10)

Note: #N refers to the number of a case, see Annex 8 _Case study_furniture S.PSS_coding

5.3.4.2 Definition, Classification of Furniture S.PSS

Several researchers (Manzini et al., 2003; Tukker, 2004; Vezzoli, 2007; UNEP and Delft University of Technology, 2017) have categorized Product-Service Systems (PSSs) into three groups: product-oriented PSS, user-oriented PSS, and result-oriented PSS. Based on insights from previous furniture S.PSS cases analysis, it becomes apparent that a more specific classification is necessary to adequately capture the diversity of offerings in the furniture sector. Consequently, the classification of S.PSS for furniture is being refined as follows (Table 35)(Vezzoli & Yang, 2021):

- Product-oriented S.PSS for furniture is defined as "S.PSS adding value to the furniture's life cycle". In this offer, a company or an alliance of companies offers furniture along with supplementary services (some of the following services such as furniture and interior layout co-design, delivery, installation, cleaning, maintenance, repair, reconfiguration, refurbishment, upgrading, substitution, ergonomic adjustments, take-back or exchange services, and end-of-life treatment, among others); or enabling services (such as training, advice, and consultancy to facilitate user activities such as delivery, installation, adjustment, assembly, maintenance, repair, upgrading, substitution, reconfiguration and refurbishment). The aim is to ensure the furniture's life cycle environmental performance for the customer. While the customer owns the furniture, the responsibility is diminished during usage and end-of-life stages. The customer pays an all-inclusive fee covering the furniture and associated services, as exemplified by the Rype office take-back service case.
- Care-oriented S.PSS for furniture can be defined as "S.PSS enabling furniture care platforms for customers." In this context, a company or an alliance of companies provides access to furniture and/or essential tools or platforms, accompanied by training, advice, and consultancy services. These services aim to facilitate user activities such as delivery, installation, adjustment, assembly, maintenance, repair, upgrading, substitution, reconfiguration, refurbishment, and end-of-life treatment, including the facilitation of second-hand furniture selling. Unlike product-oriented S.PSS, in this scenario, the customer does not own the furniture and/or furniture care tools but operates them to achieve a specific level of furniture use/care 'satisfaction.' Payment is made based on the usage of the furniture and/or furniture care tools, as seen in the BMA case.
- Result-oriented S.PSS for furniture can be defined as 'S.PSS provides furniture and full services to customers.' In this context, a company or an alliance of companies provides access to furniture with all-inclusive life cycle services. These services encompass aspects such as furniture and interior layout co-design, delivery, installation, cleaning, maintenance, repair, reconfiguration, refurbishment, upgrading, substitution, ergonomic adjustments, take-back or exchange services, and end-of-life treatment, among others. The customer does not own the furniture; instead, the provider carries out life cycle services, being paid per satisfaction unit. This model is exemplified by the Gispen/Regus case.

Key concepts in these definitions include enabling services, additional services, and all-inclusive services.

- Enabling services include (1) providing training, advice, and consultancy services to facilitate user delivery, installation, adjustment, assembly, maintenance, repair, upgrading, substitution, reconfiguration, refurbishment, and end-of-life treatment, among others. Additionally, they enable users to operate ergonomic furniture for improved utility and facilitate second-hand furniture selling. (2) providing essential tools or platforms required for these operations.
- All-inclusive services encompass a wide range of offerings, including but not limited to furniture and interior layout co-design, delivery, tracking, installation, cleaning, maintenance, repair, reconfiguration, refurbishment, upgrading, substitution, ergonomic adjustments, take-back or exchange services, and end-of-life treatment, among others.
- Additional services are part of the mentioned all-inclusive services.

Table 35 The comparison among 3 types of S.PSS for furniture

3 Furniture S.PSS types	**Product-oriented S.PSS for furniture**	**Care-oriented S.PSS for furniture**	**Result-oriented S.PSS for furniture**
Definition	S.PSS is adding value to the furniture's life cycle	S.PSS enables furniture care platforms for customers	S.PSS provides furniture and full services to customers
Offer	Furniture and supplementary/enabling services	Furniture and/or furniture care tools with enabling services	Furniture with all-inclusive services
Payment (Ownership)	Pay for furniture (customer ownership)	Pay to access (provider ownership)	Pay to shared/individual access (provider ownership)
Life cycle responsibility	Shared by customer and provider	Enabling customers to care for furniture	By provider
Examples	i) Additional take back service (Rype Office); ii) On-site assembly (IKEA)	i) Enable users for ergonomics needs/Leasing (BMA)	i) Co-living; ii) Co-working; iii) furniture as a service/leasing (Gispen)

Based on the analysis and proposals presented in the preceding chapters, a refined definition of S.PSS as applied to furniture could be articulated: "S.PSS for furniture is an offering model that provides an integrated mix of furniture and services capable of fulfilling a specific customer/user demand (to deliver a 'unit of satisfaction'). This is achieved through innovative interactions among the stakeholders of the value production system (satisfaction system), where the ownership of the furniture and/or the life cycle services costs/responsibilities remain with the provider/s. Consequently, the same provider/s continually seek environmentally and/or socio-ethically beneficial new solutions, with economic benefits" (Vezzoli et al., 2021b; Vezzoli & Yang, 2021)

In conclusion, when compared to traditional furniture offerings, these furniture S.PSS models exhibit common elements. Firstly, there is a shift from merely selling furniture products to providing satisfaction units. The innovation focus extends beyond technological advancements to encompass configuration innovation among stakeholders. Additionally, the transition in customer value is moving from individual ownership to access. As illustrated in Figure 35.

Figure 35 The characteristics of furniture S.PSS in comparison to furniture traditional offerings

6.3.4.3 Furniture S.PSS's win-win benefits and a conceptual framework

In Chapter 6.2, the study formulated hypotheses regarding furniture S.PSS, proposing five win-win economic and environmental benefits. Through case analysis, these hypotheses were validated with examples, encompassing Furniture use extension/intensification, reduce material consumption of furniture, Furniture materials life extension, Reduce energy consumption of the furniture system, Resources conservation/biocompatibility for furniture, as illustrated in the following table.

Table 36 The numerosity of sustainable benefits within the 44 furniture S.PSS cases analyzed

Environmental benefits	**Case number**
Furniture use extension/intensification	30 (#1, #2, #3, #4, #5, #6, #7, #8, #9, #10, #11, #12, #13, #14, #15, #16, #17, #18, #19, #20, #21, #22, #23, #24, #32, #33, #34, #39, #41, #4
Reduce material consumption of furniture	10 (#1, #8, #10, #14, #24, #25, #32, #37, #43, #44)
Furniture materials life extension	2 (#4, #5)
Reduce energy consumption of the furniture system	13 (#25, #26, #27, #28, #29, #30, #33, #34, #35, #36, #38, #40, #43)
Resources conservation/biocompatibility for furniture	1 (#40)

Note: #N refers to the number of a case, see Annex 8 _Case study_furniture S.PSS_coding

During the semi-structured interview and desk research, these benefits were further verified with furniture companies. 17 companies have affirmed that furniture S.PSS proves to be economically advantageous when offering furniture with extended use. Additionally, 7 companies confirmed the economic benefits of employing furniture S.PSS for material life extension. Another 7 companies acknowledged the economic advantages of utilizing furniture S.PSS for minimizing resource consumption. Furthermore, one case confirmed that furniture S.PSS provides economic benefits in facilitating the intensification of furniture use.

Through semi-structured interviews and desk research, these benefits were further validated with furniture companies. Seventeen companies affirmed that furniture S.PSS proves to have economically advantageous of facilitating furniture use extension. Additionally, seven companies confirmed the economic benefits of employing furniture S.PSS for material life extension. Another seven companies acknowledged the economic advantages of utilizing furniture S.PSS for minimizing resource consumption. Furthermore, one case confirmed that furniture S.PSS provides economic benefits by facilitating the intensification of furniture use. Although no companies mentioned the win-win economic benefits of facilitating toxicity reduction, the study list it as a potential opportunity, as illustrated in Figure 36.

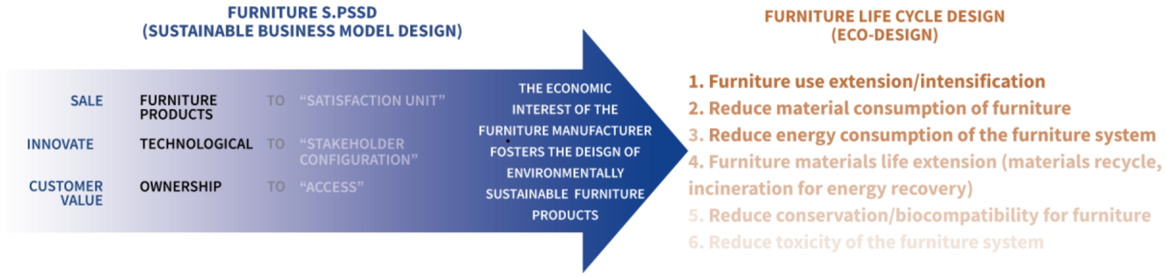


Figure 36 Furniture S.PSS facilitates environmental benefits (furniture Life Cycle Design)

Note: Figure 36 illustrates the win-win benefits of furniture S.PSS, wherein the economic interest of the furniture manufacturer promotes the design of environmentally sustainable furniture products through the adoption of furniture life cycle design strategies, which have been validated through case studies and semi-structured interviews. The darker the orange color, the greater the number of verifications from case studies and semi-structured interviews.

Through a cross-analysis of various elements, the study revealed a significant interconnection among the characteristics of furniture products, the offered services, the business model, and the resulting sustainable benefits. The well designing of all elements can ultimately lead to a final win-win scenario, providing both economic and environmental benefits with high efficiency.

While all the researched cases exhibit win-win benefits in the aspects mentioned earlier, not every furniture case can be deemed a thoroughly well-conceived S.PSS. Consideration should be given to the following key elements: (1) **Ownership and Payment Methods:** In S.PSS for furniture offerings, ownership of the furniture and/or life cycle responsibility is retained by the provider, who receives payment per satisfaction unit. This economic benefit incentivizes the provider to engage in furniture Life Cycle Design (LCD) strategies. (2) **Role of Producer and Provider:** In cases where the same furniture manufacturer retains the ownership or takes life cycle responsibility of furniture, there is a vested economic interest in offering furniture with a low environmental impact. Moreover, they possess the direct opportunity and capability to intervene in furniture design processes (e.g., furniture leasing in the Gispen case), enabling the adoption of specific LCD strategies.

Considering these strengths and weaknesses identified from case studies and semi-structured interviews, the research further developed an archetypal furniture Sustainable Product-Service System (S.PSS) map, encompassing 20 promising furniture S.PSS models. The detailed development process is illustrated in the following chapter.

6.4 Developing an archetypal furniture S.PSS map

The Furniture Sustainable Product-Service System (S.PSS) has emerged as a promising model for realizing both environmental and economic benefits. A thorough analysis was undertaken, involving 44 cases that encompassed a diverse range of products, services, and business models. This study introduced a comprehensive archetypal furniture S.PSS map with 20 distinct models capable of capturing the essential dimensions characterizing S.PSS applied to furniture.

The development process comprised several key steps (Emili et al., 2016), including the analysis of 44 furniture S.PSS cases (refer to chapter 6.3.4), identification of furniture S.PSS and product characteristics (covered in chapter 6.3.4), creation of a classification system (outlined in chapter 6.4.1), positioning of cases on the classification map (discussed in chapter 6.4.2), and the clustering and identification of archetypal models (as detailed in 6.4.2).

6.4.1 The archetypal furniture S.PSS classification system

The archetypal furniture S.PSS map was constructed with two dimensions: one representing furniture usage contexts, and the other indicating furniture S.PSS types. Through case analysis, six types of furniture usage contexts were identified and grouped as follows, see Figure 37:

- **Home Living:** In this context, household furniture producers and sellers act as providers, offering household furniture to individuals.
- **Home Working:** In this context, office furniture producers and sellers serve as providers, offering office furniture to individuals, freelancers, or employees through their companies.
- **Co-Living:** This context involves household furniture producers collaborating with small space owners, offering household furniture with living space to individuals.
- **Co-Working:** Within this context, office furniture producers and small space owners serve as providers, offering office furniture with working space to individuals or companies.
- **Centered Living:** In this context, hotel furniture producers cooperate with hotel owners, providing furniture with living space to individuals or companies.
- **Centered Working:** This context involves office furniture producers and large space owners serving as providers, offering office furniture with working space to companies.

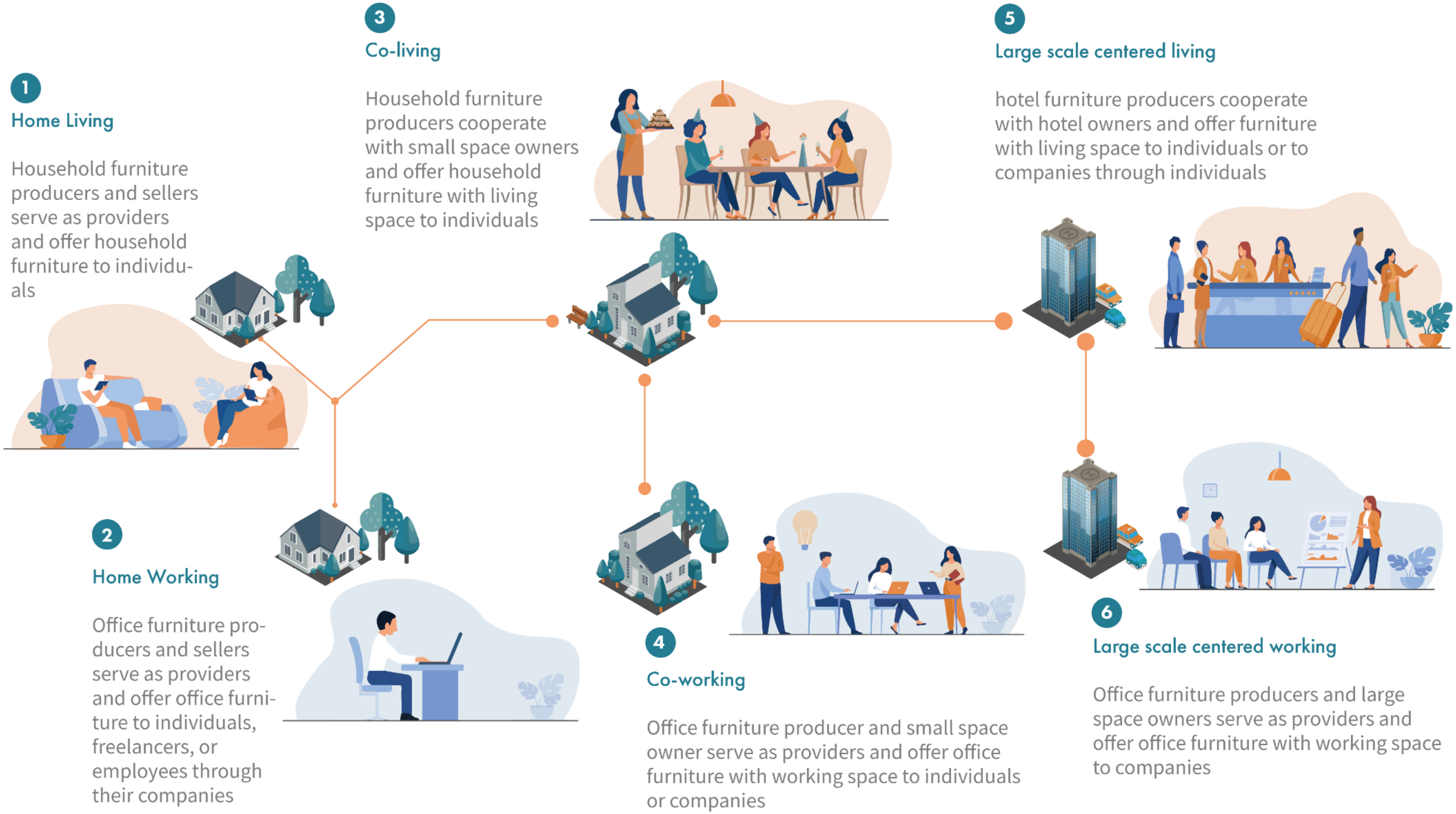


Figure 37 6 furniture application contexts

As indicated in chapter 6.3.4.2, various PSS classifications presented in the past have generally agreed on three main PSS categories: product-oriented, use-oriented, and result-oriented (S.)PSSs. (Tukker, 2004; UNEP, 2002; Vezzoli, 2007). The strength of this classification lies in its generic nature, making it applicable to various domains. However, its generality makes it less suitable for providing an exhaustive overview of PSS models in a specific application (Emili et al., 2016). In the context of this study, this classification proves inadequate for describing the diverse range of furniture S.PSS models. Therefore, furniture S.PSSs have been categorized as product-oriented, care-oriented, and result-oriented S.PSS, with 5 sub-categories, which are:

- Product-oriented furniture S.PSS:
    - Pay to purchase with enabling services;
    - Pay to purchase with additional services;
- Care-oriented furniture S.PSS: pay to access with enable services;
- Result-oriented furniture S.PSS:
    - Pay per unit of satisfaction (shared use);
    - Pay per unit of satisfaction (individual access).

These two dimensions formed the foundation for the archetypal furniture S.PSS map, aiming to construct a comprehensive furniture S.PSS models for both current and future promising furniture applications. See Figure 38.

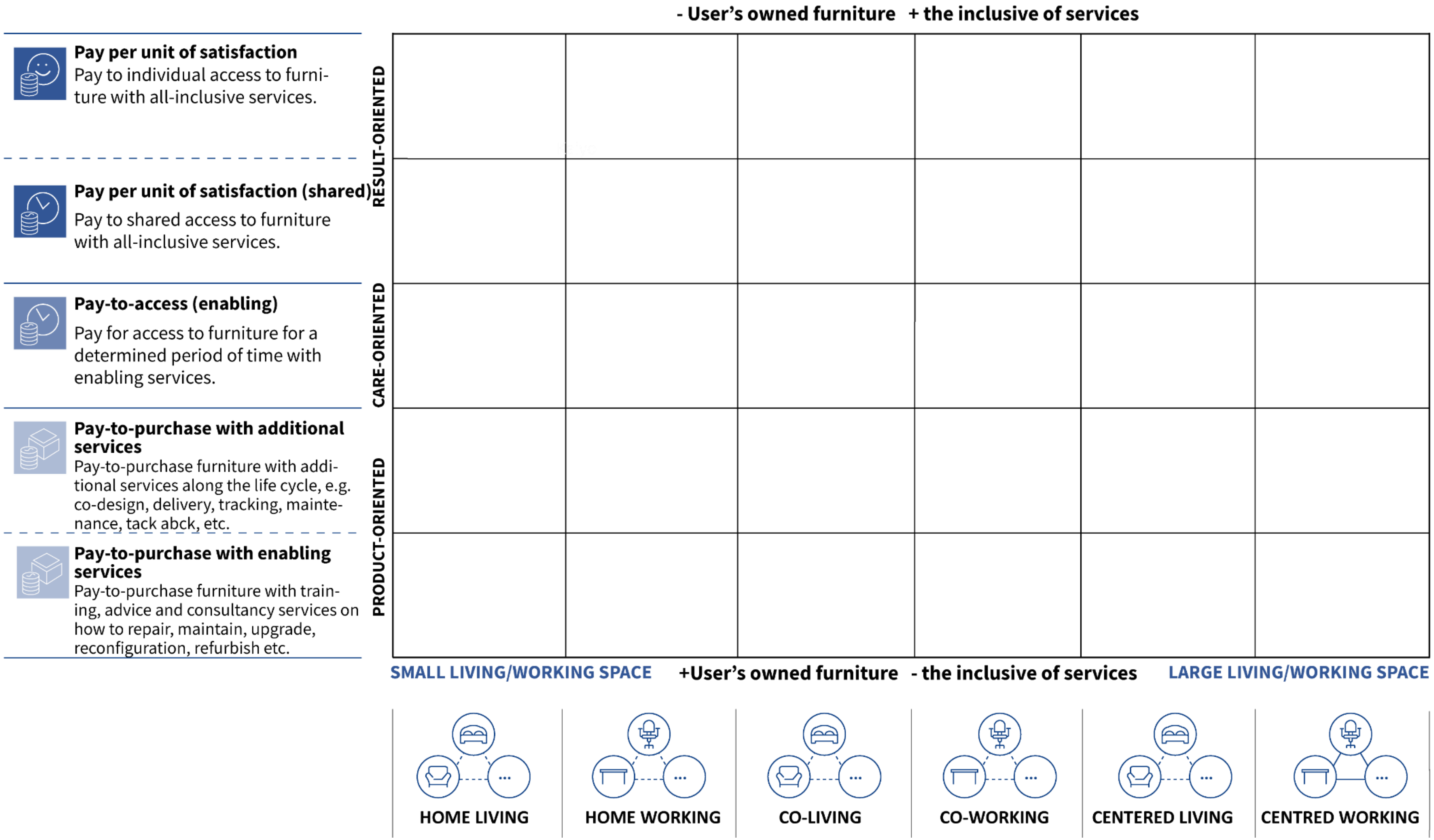


Figure 38 The classification system of furniture S.PSS

Note: FP is short for furniture producer

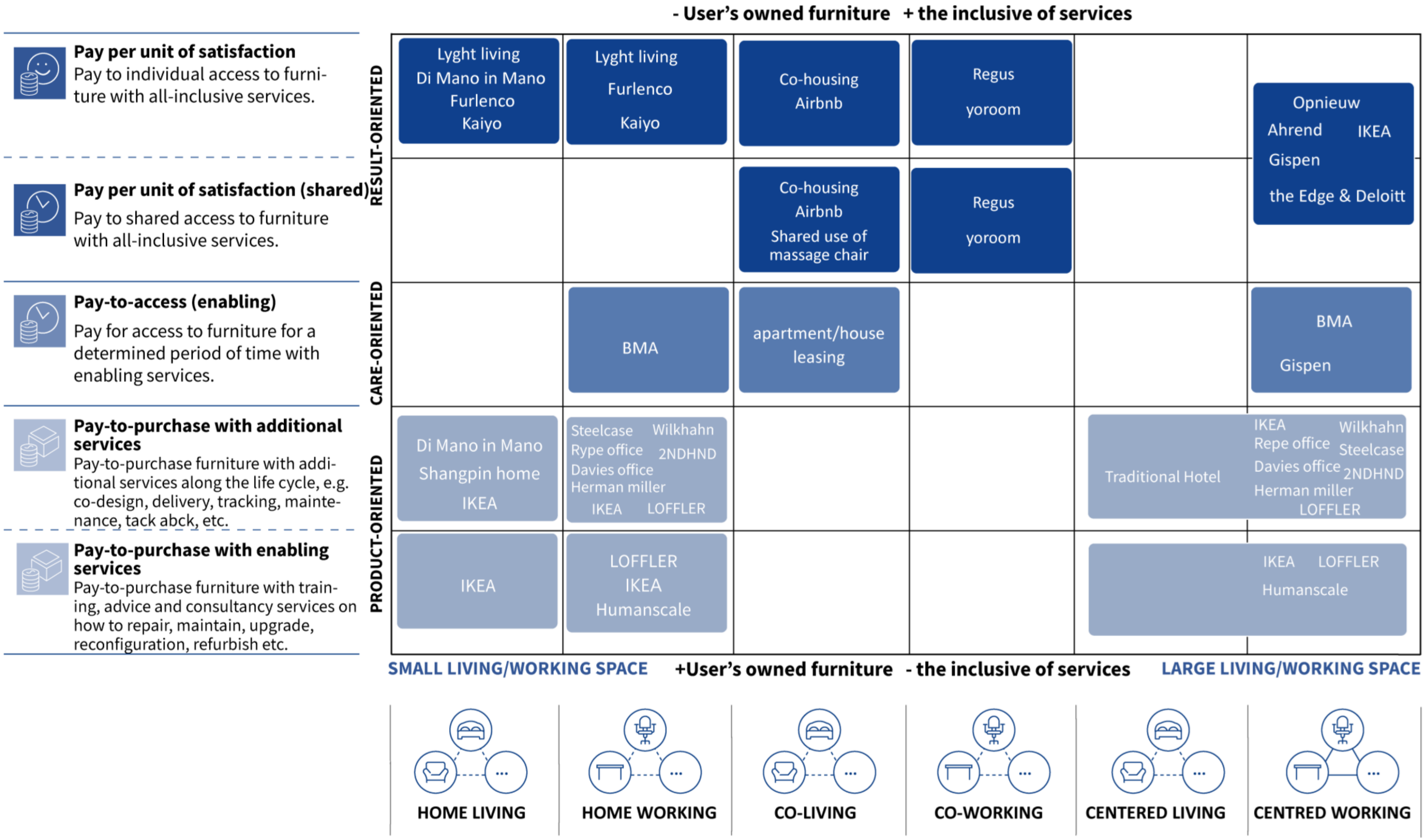


Figure 39 The position of cases on the developed furniture S.PSS classification system and clusters.

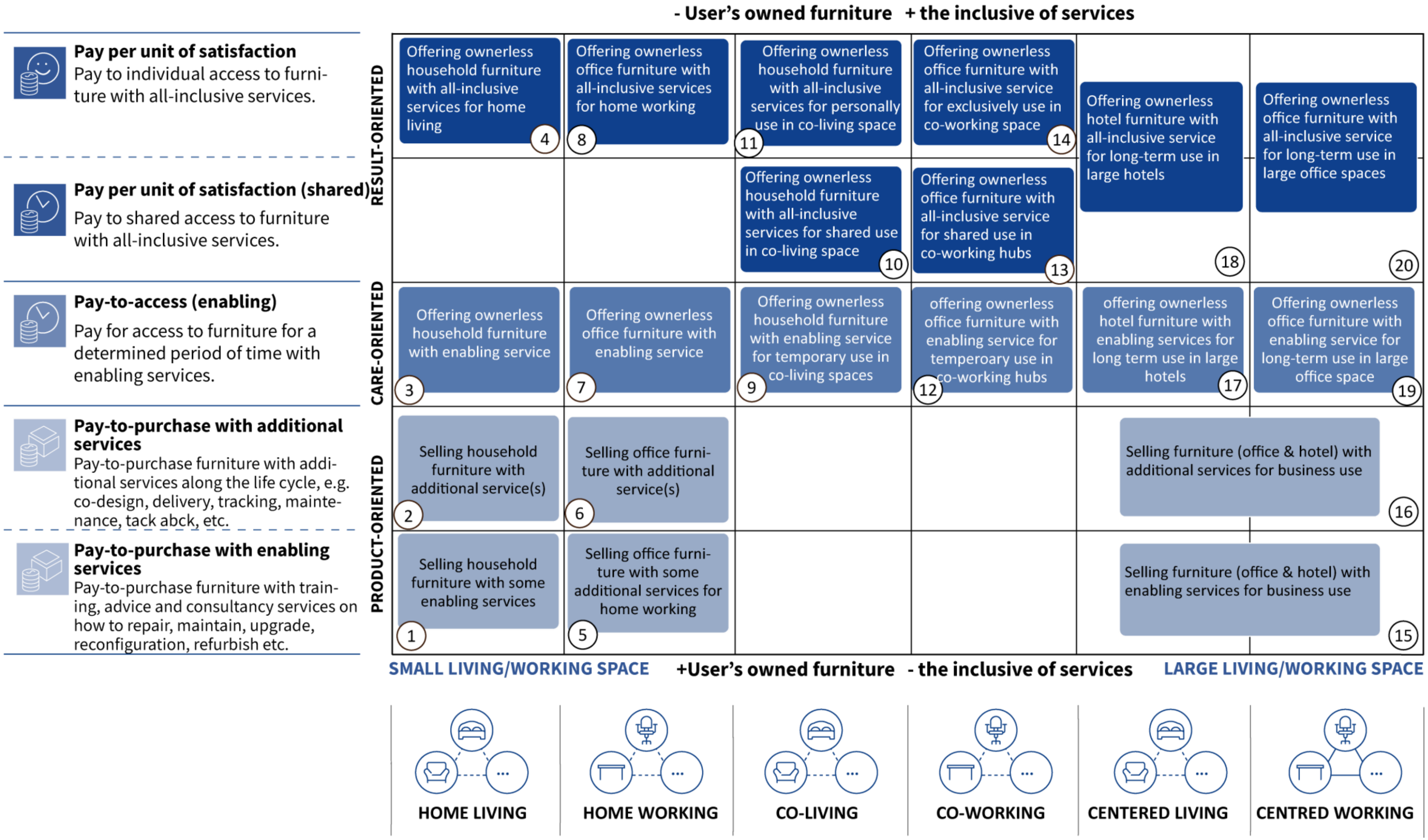


Figure 40 The archetypal furniture S.PSS classification system_20 archetypal models

6.4.2 Position of furniture S.PSS cases and development of furniture S.PSS archetypal map

Upon constructing the classification system, this study positioned furniture S.PSS cases within it and grouped similar cases into 16 clusters (refer to Figure 39). Each cluster signifies one promising model of furniture S.PSS. Although cases within each cluster are not identical, sharing fundamental traits like the business model and services are similar, their secondary characteristics, such as product types (such as remanufactured furniture, second-hand furniture, or new furniture), may vary.

Simultaneously, some empty spaces have emerged with no cases positioned, revealing new opportunities (4 models) that appear promising. Figure 40 provides an overview of all 20 identified or developed archetypal models for furniture S.PSS.

The developed archetypal models of furniture S.PSS are outlined below, accompanied by their main characteristics. Each model is complemented by a system map - a visualization depicting the actors involved in the PSS offer and their interactions.

Model 1. Selling household furniture with some enabling services. This model integrates furniture sales with enabling services, encompassing training, advice, consultancy services, and necessary tools. These services empower users to undertake activities such as assembly, operation (e.g., ergonomic furniture usage), repair, maintenance, upgrade, reconfiguration, and refurbishment of the furniture. Customers take ownership of the furniture post-purchase and are responsible for its entire lifecycle. Refer to Figure 41. A prominent exemplar of this model is IKEA, where users receive assistance in onsite furniture assembly through tools, printed instructions, and online video guidance.

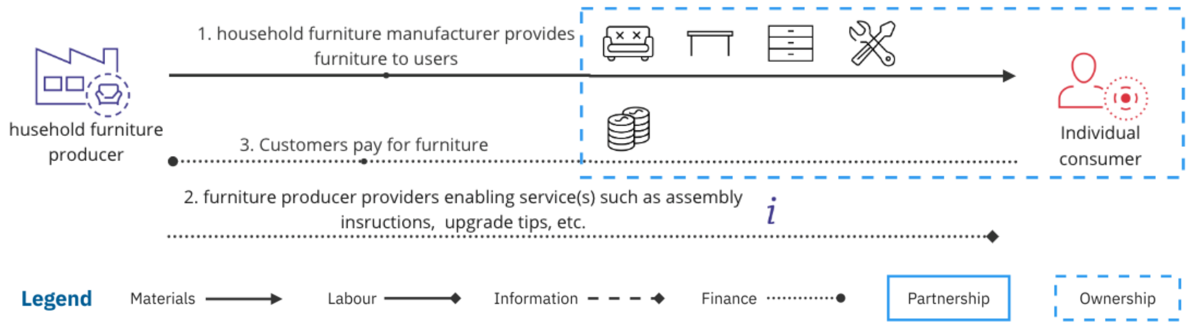


Figure 41 Furniture S.PSS archetypal model 1: Selling household furniture with some enabling services

Model 2. Selling household furniture with additional service(s). This model involves selling household furniture but introduces additional services facilitated by local service providers. These supplementary services include co-design, repair, maintenance, upgrading, reconfiguration, take-back, and others aimed at optimizing the system's environmental performance. The incorporation of these additional services requires collaboration with new stakeholders possessing expertise and local accessibility. Refer to Figure 42. A notable example of this model is Shangpin Home Co-design Service, a customized furniture producer and provider where all orders are co-designed with the end user. This model's advantage lies in the collaborative production of various orders, maximizing material utilization and achieving a noteworthy 5% reduction in material consumption.

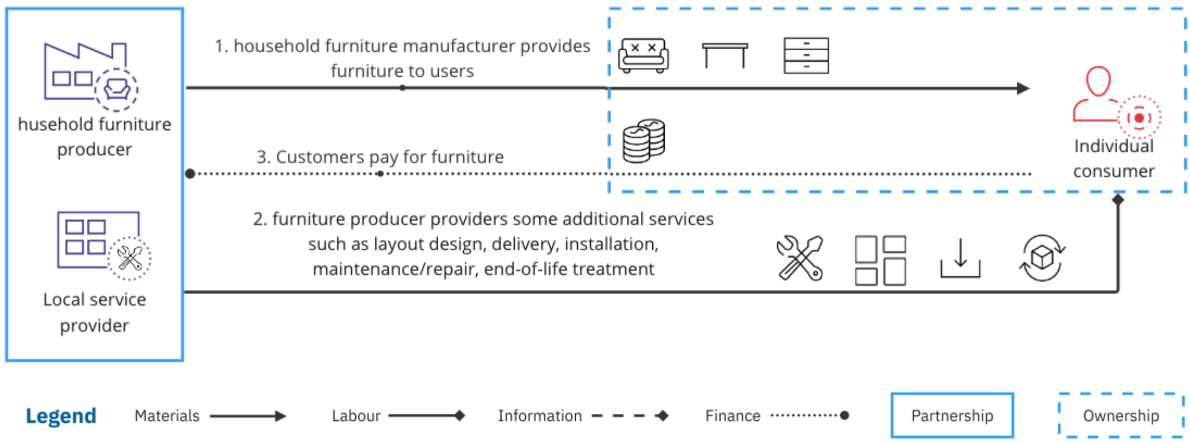


Figure 42 Furniture S.PSS archetypal model 2: Selling household furniture with additional service(s)

Model 3. Offering ownerless household furniture with enabling services. This model integrates providing household furniture with enabling services such as assembly instructions, upgrade tips, recycling guidance, and the provision of necessary tools. Notably, the provider retains ownership of the furniture, and certain life cycle services are conducted by the end user. Refer to Figure 43. This is a newly developed model without existing cases. An illustrative example could be IKEA offering flat-packaged furniture to users along with tools and instructions for transportation, assembly, disassembly, and upgrades, allowing users to carry out these services independently.

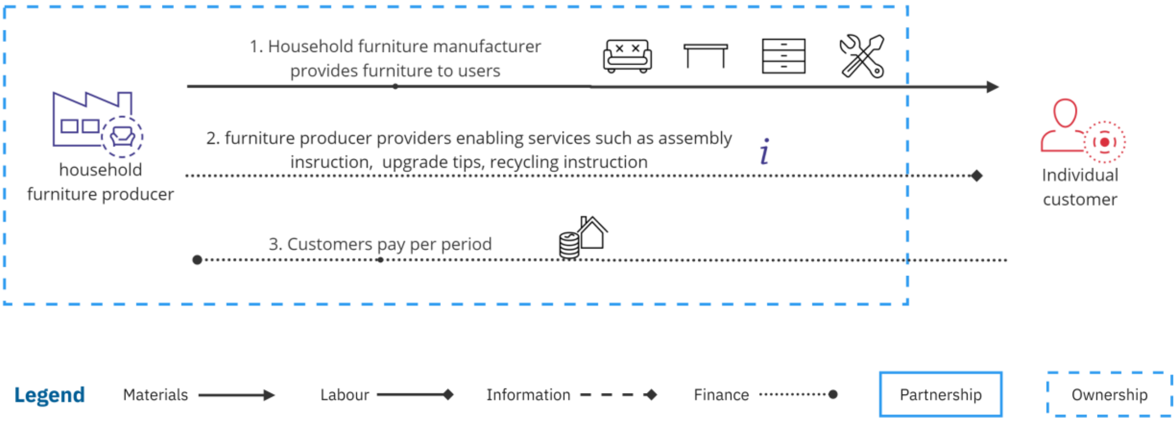


Figure 43 Furniture S.PSS archetypal model 3: Offering ownerless household furniture with enabling services

Model 4. Offering ownerless household furniture with all-inclusive services for home living. This model combines ownerless household furniture with comprehensive all-inclusive services tailored for home living. The suite of services includes co-design, repair, maintenance, upgrading, reconfiguration, take-back, and other services aimed at enhancing the system's environmental performance. The provision of these all-inclusive services requires collaboration with new partners to deliver lifecycle services and end-of-life treatment. An exemplary case of this model is Kaiyo, a second-hand furniture provider that offers a comprehensive suite of all-inclusive services.

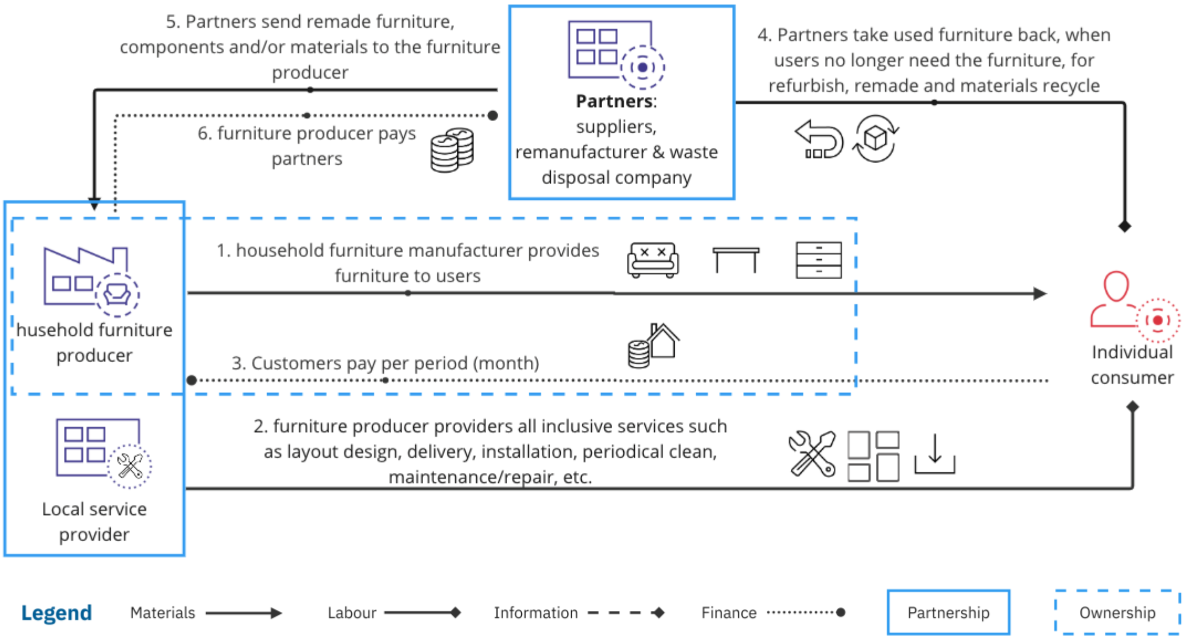


Figure 44 Furniture S.PSS archetypal model 4: Offering ownerless household furniture with all-inclusive services for home living

Model 5. Selling office furniture with enabling services for home-working. This model centers on selling office furniture, with services specifically tailored enabling services for office furniture. Enabling services may encompass consultancy, such as ergonomics consulting aimed at improving sitting posture. The customers may transition from individual users to employing companies, particularly those supporting remote work. Refer to Figure 45. An example of this archetype is BMA, which empowers users to adjust ergonomic chairs using a controller and a mobile app.

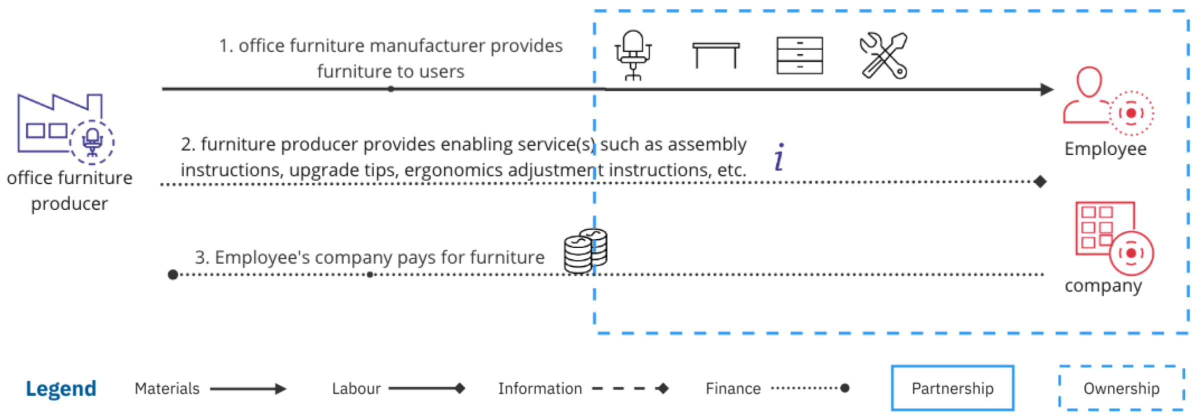


Figure 45 Furniture S.PSS archetypal model 5: Selling office furniture with enabling services for home-working

Model 6. Selling office furniture with additional service(s). This model involves selling office furniture with additional services facilitated by local service providers. The payer can be either the individual user or their company, particularly if the company advocates for remote working and requires office furniture solutions (refer to Figure 46). An illustrative example is Rype Office, a furniture remanufacturer that takes back furniture from users at the end of its lifecycle for subsequent furniture production.

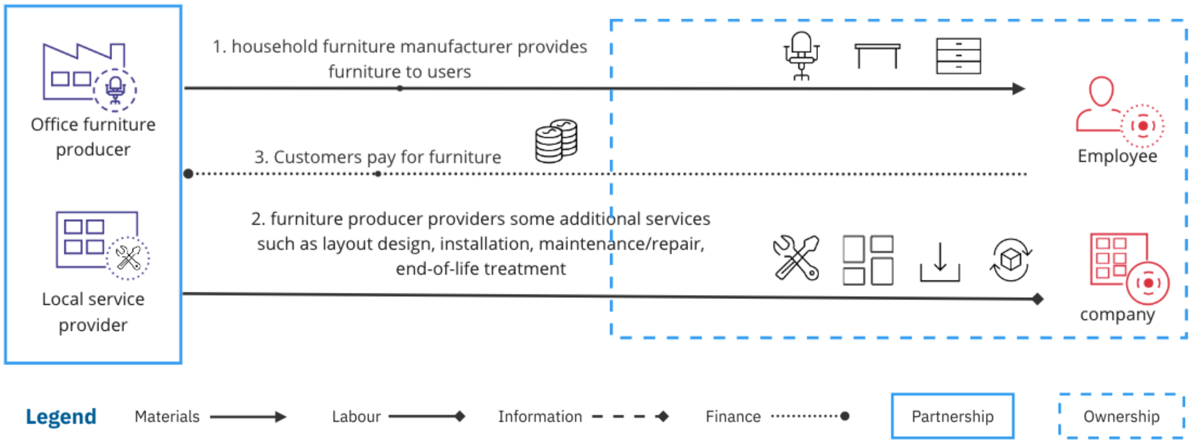


Figure 46 Furniture S.PSS archetypal model 6: Selling office furniture with additional service(s).

Model 7. Offering ownerless office furniture with enabling service. This model integrates providing office furniture with enabling services such as training, advice, and consultancy, accompanied by enabling tools. Importantly, the provider retains ownership of the furniture, and certain life cycle services are carried out by the end user (refer to Figure 47). An example of this model is the BMA ownerless ergonomics Axia chair. With this offering, BMA provides ergonomics training services for users, enabling them to adjust their sitting gestures independently with the support of a controller.

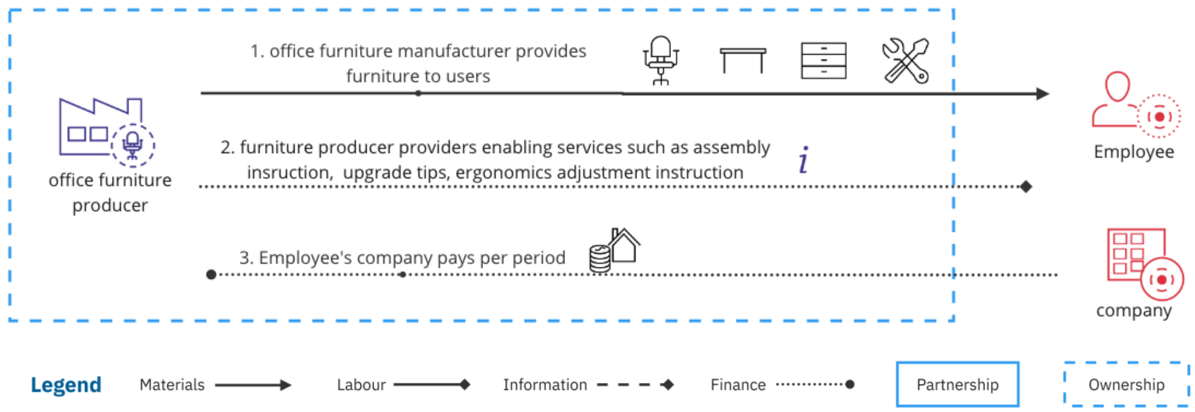


Figure 47 Furniture S.PSS archetypal model 7: Offering ownerless office furniture with enabling service

Model 8. Offering ownerless office furniture with all-inclusive services for home working. This model centers on ownerless office furniture specifically tailored for home working purposes. The The payer can be either the individual user or their company (refer to Figure 48). An illustrative example is Furlenco, a furniture rental company that offers comprehensive all-inclusive services.

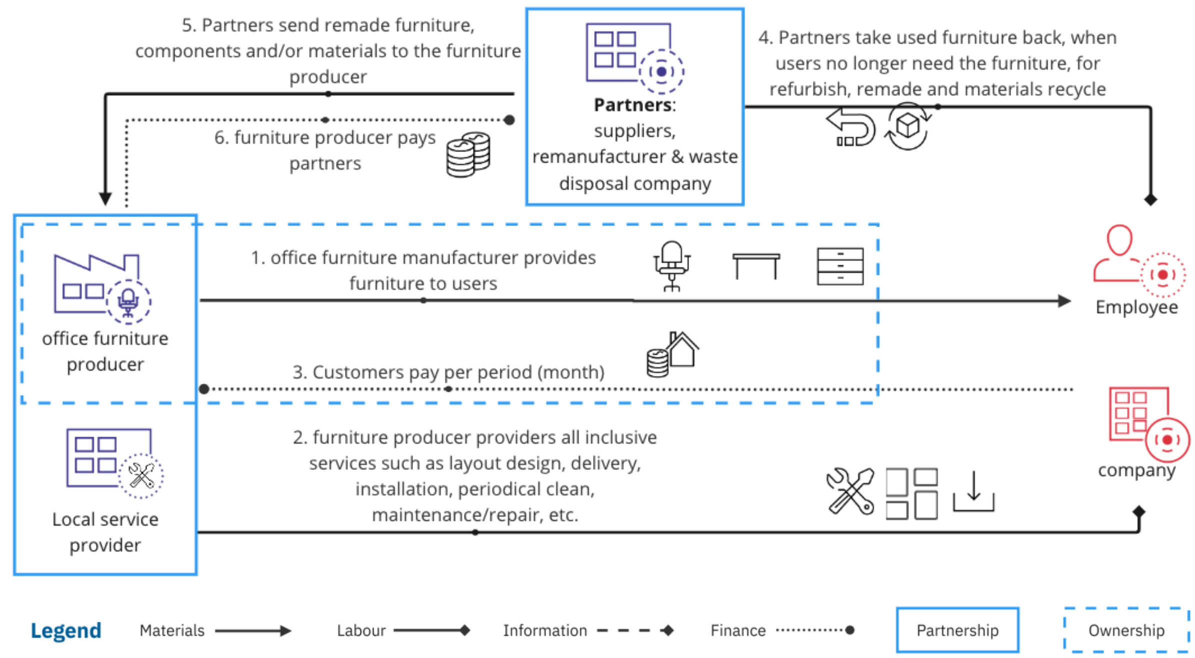


Figure 48 Furniture S.PSS archetypal model 8: Offering ownerless office furniture with all-inclusive services for home-working

Model 9. Offering ownerless household furniture with enabling service for temporary use in co-living spaces. In this model, the furniture provider furnishes furniture to the co-living space, which, in turn, provides furniture, co-living space, and enabling services to the end users. Stakeholder interactions are illustrated in Figure 49.

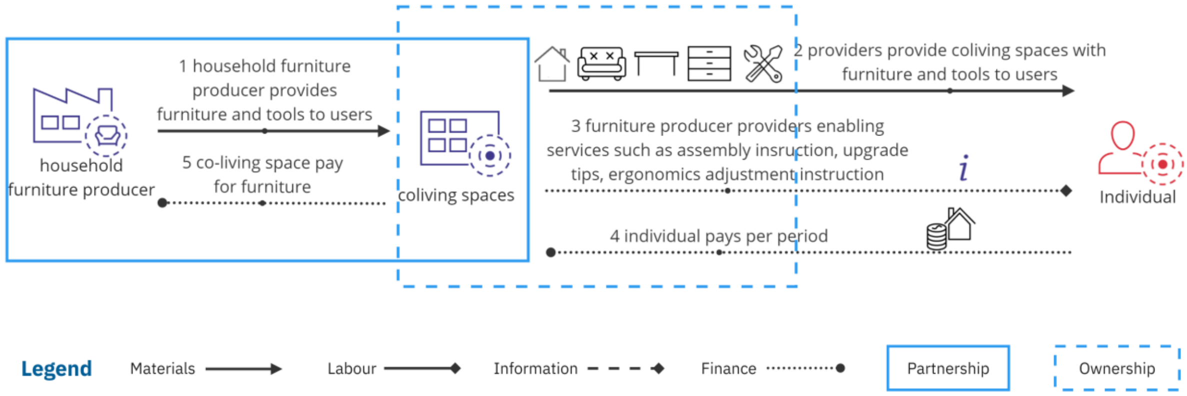


Figure 49 Furniture S.PSS archetypal model 9: Offering ownerless household furniture with enabling service for temporary use in co-living spaces

Model 10. Offering ownerless household furniture with all-inclusive services for shared use in co-living space. Household furniture producers collaborate with co-living space owners. They provide furnished co-living spaces with all-inclusive services as a result for end users. These spaces and furniture are shared among users, such as living areas or kitchens. Stakeholder interactions are illustrated in Figure 50.

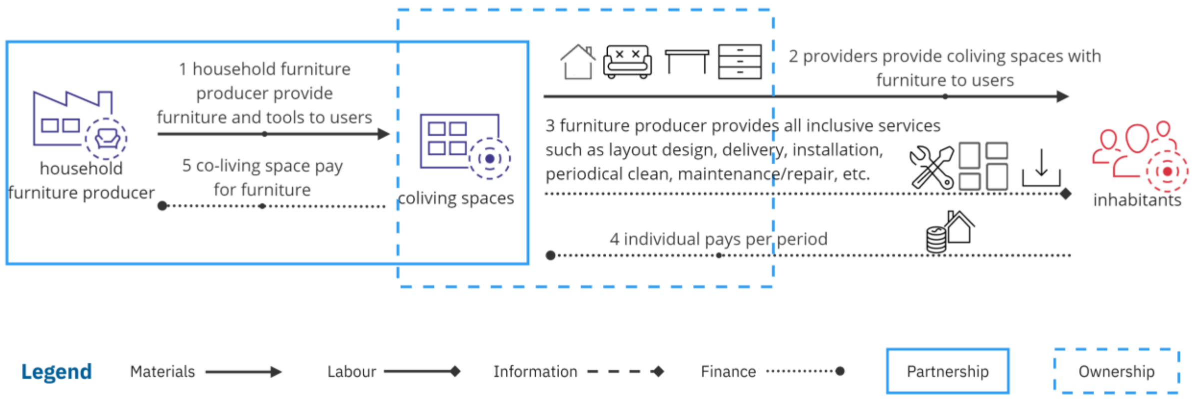


Figure 50 Furniture S.PSS archetypal model 10: Offering ownerless household furniture with all-inclusive services for shared use in co-living space

Model 11. Offering ownerless household furniture with all-inclusive services for individual use in co-living space. This model emphasizes providing users with ownerless household furniture and all-inclusive services for individual use within the co-living arrangement.

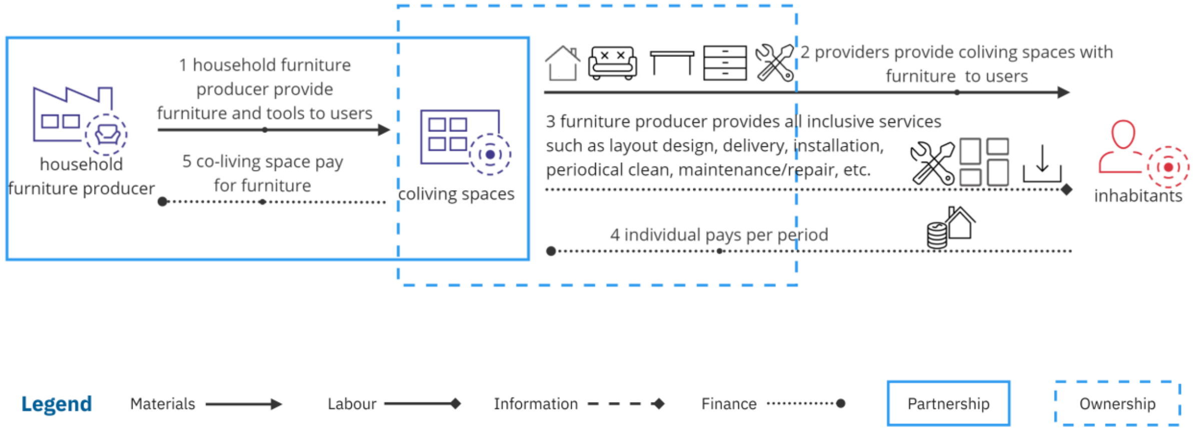


Figure 51 Furniture S.PSS archetypal model 11: Offering ownerless household furniture with all-inclusive services for individual use in co-living space

Model 12. Offering ownerless office furniture with enabling service for temporary use in co-working spaces. In this model, the furniture provider provides furniture to the co-working space, which, in turn, offers furniture, co-working spaces, and enabling services to end users. Stakeholder interactions are depicted in Figure 52.

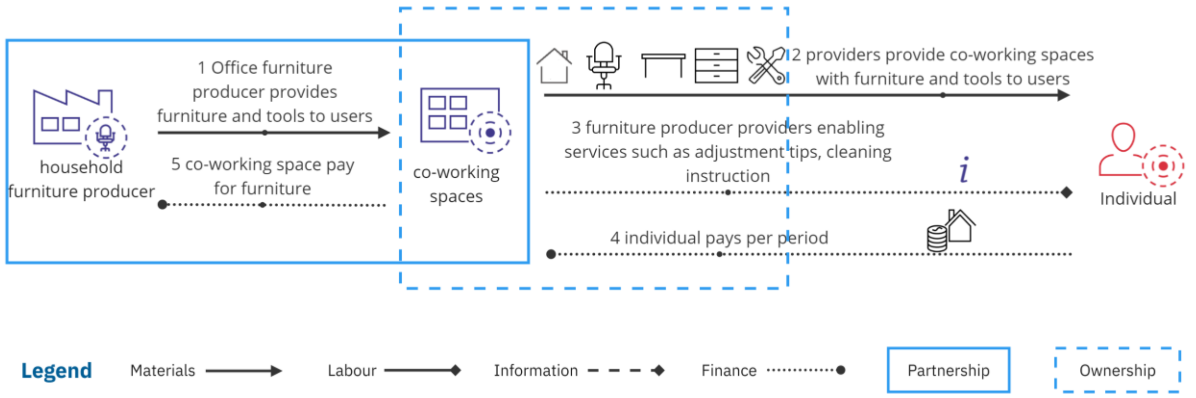


Figure 52 Furniture S.PSS archetypal model 12: Offering ownerless household furniture with all-inclusive services for personally use in co-living space

Model 13. Offering ownerless office furniture with all-inclusive service for shared use in co-working hubs. In this model, co-working hubs provide ownerless office furniture and shared co-working spaces. Individual users can access both spaces for a fee, typically based on time or hours of use. Stakeholder interactions are illustrated in Figure 53. An example of this model is Yoroom/Regus, where users can book co-working spaces for hours or days

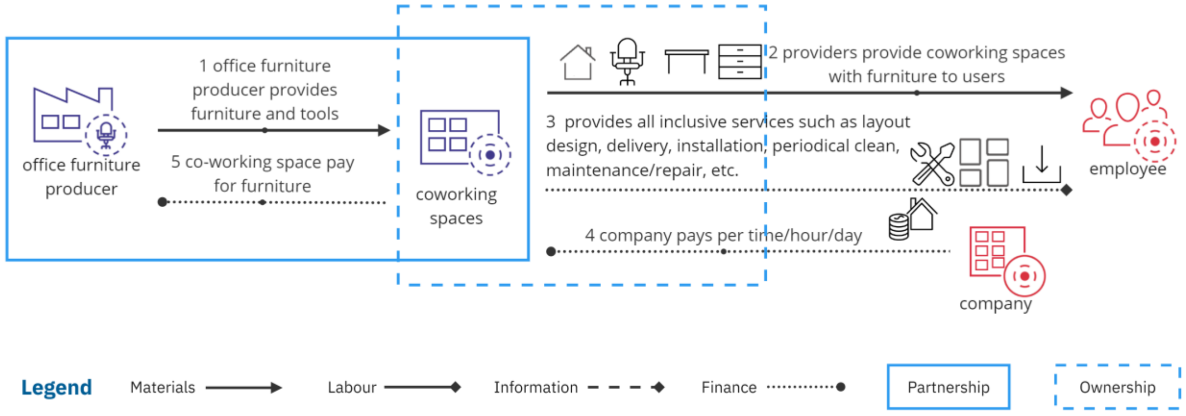


Figure 53 Furniture S.PSS archetypal model 13: Offering ownerless office furniture with all-inclusive service for shared use in co-working hubs

Model 14. Offering ownerless office furniture with all-inclusive services for exclusive use in co-working space. In this model, the co-working space provides ownerless office furniture, dedicated space, and all-inclusive services to a company. Under this arrangement, employees (users) have exclusive use of the space, and the company pays a recurring fee per month or year to the co-working space. Stakeholder interactions are depicted in Figure 54. An exemplar of this model is Yoroom/Regus, where companies can rent a certain size of co-working space for specific durations.

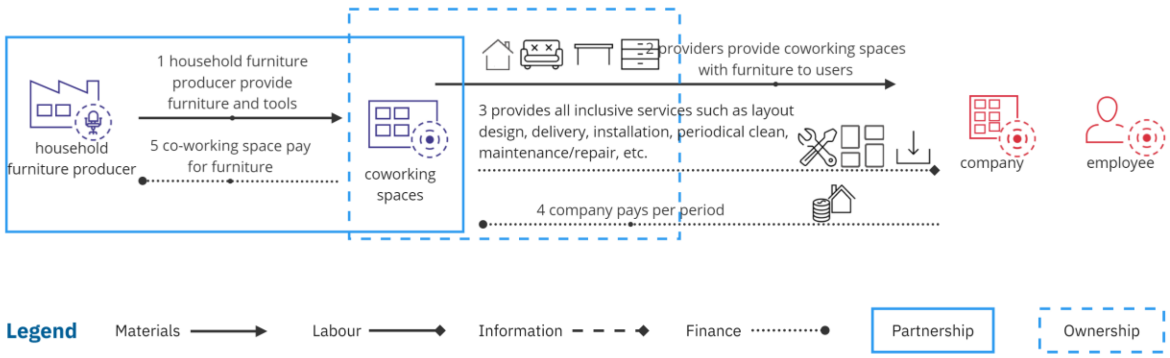


Figure 54 Furniture S.PSS archetypal model 14: Offering ownerless office furniture with all-inclusive service for exclusive use in co-working space

Model 15. Selling furniture (office & hotel) with enabling services for business use. This model functions as a business-to-business (B2B), where the furniture provider supplies furniture and enabling services to business organizations. The objective is for the business organization to offer this furniture and associated services to their end users, such as employees or hotel guests. Stakeholder interactions are depicted in Figure 55.

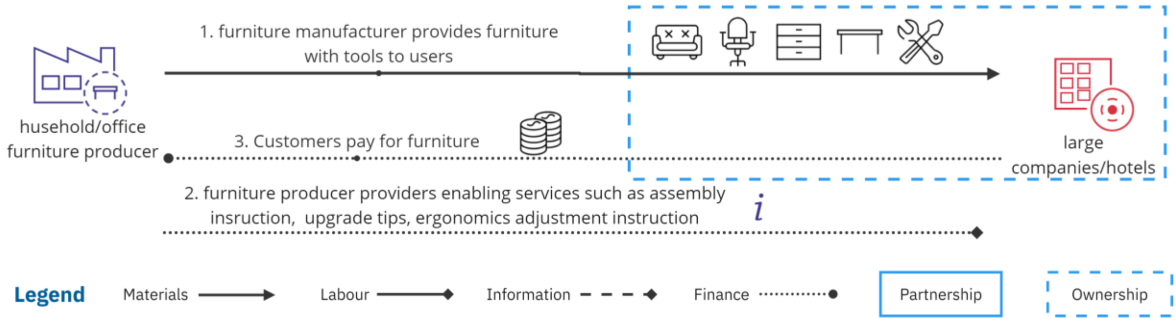


Figure 55 Furniture S.PSS archetypal model 15: Selling furniture (office & hotel) with enabling services for business use

Model 16. Selling furniture (office & hotel) with additional services for business use. In this B2B model, the furniture provider collaborates with local partner(s) to offer additional services aimed at enhancing the performance of the furniture for business organizations. Stakeholder interactions are illustrated in Figure 56.

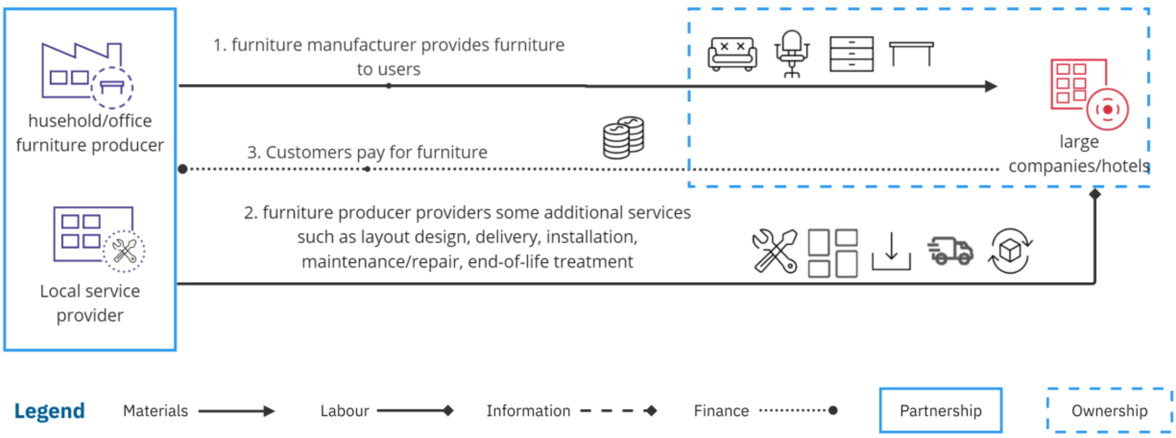


Figure 56 Furniture S.PSS archetypal model 16: Selling furniture (office & hotel) with additional services for business use

Model 17. Offering ownerless hotel furniture with enabling service for long-term use in large hotels. This model entails collaboration between furniture providers and large hotels to offer end users ownerless hotel furniture along with enabling services for long-term use.

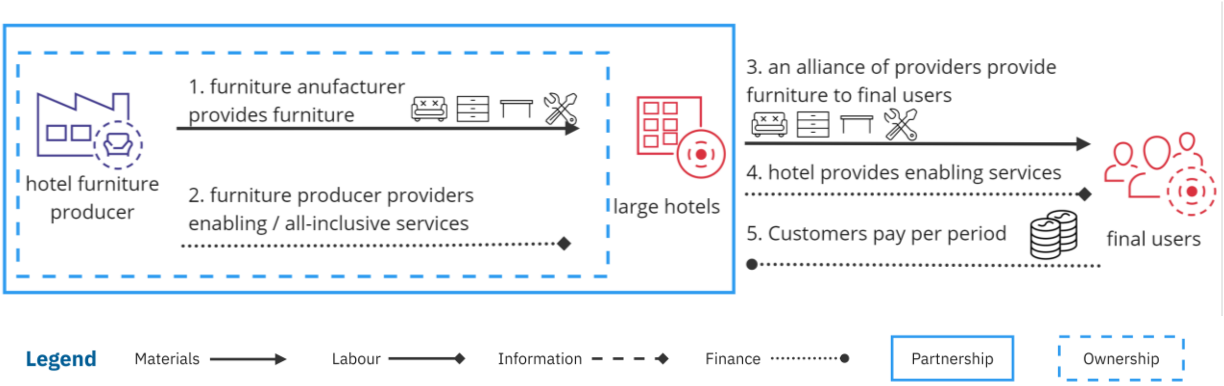


Figure 57 Furniture S.PSS archetypal model 17: Offering ownerless hotel furniture with enabling service for long-term use in large hotels

Model 18. Offering ownerless hotel furniture with all-inclusive service for long-term use in large hotels. In this model, the furniture provider collaborates with local service providers and end-of-life remanufacturers to offer all-inclusive services to hotels throughout the furniture's lifecycle. The hotel then provides a final integrated result, combining furniture with all-inclusive services for end users.

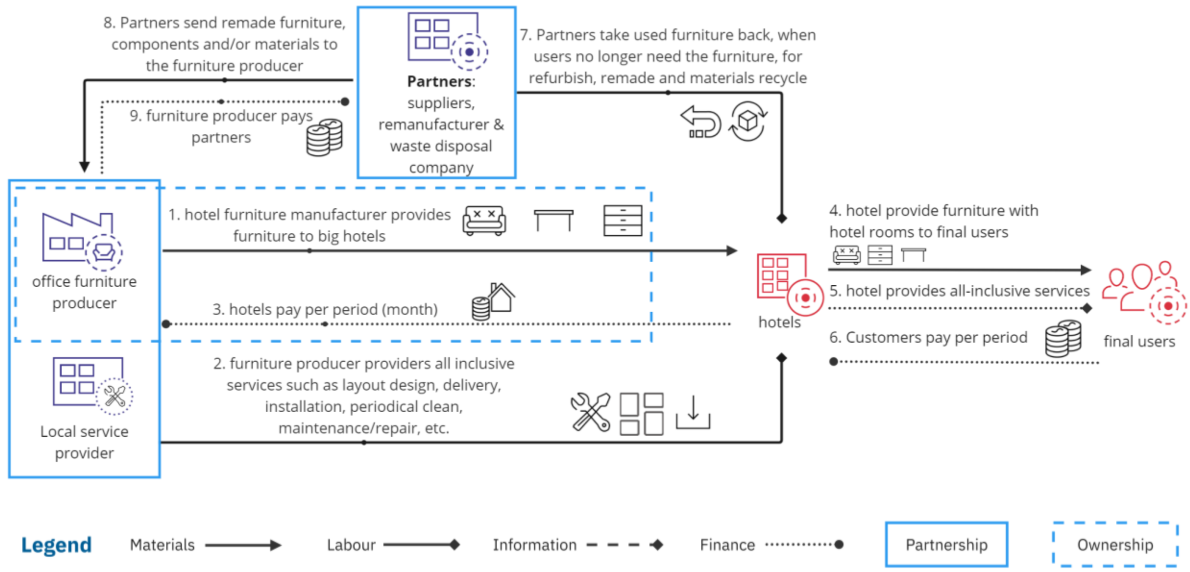


Figure 58 Furniture S.PSS archetypal model 18: Offering ownerless hotel furniture with all-inclusive service for long-term use in large hotels

Model 19. Offering ownerless office furniture with enabling service for long-term use in large office space. This B2B model involves the furniture provider offering ownerless office furniture along with enabling services for long-term use within large office spaces.

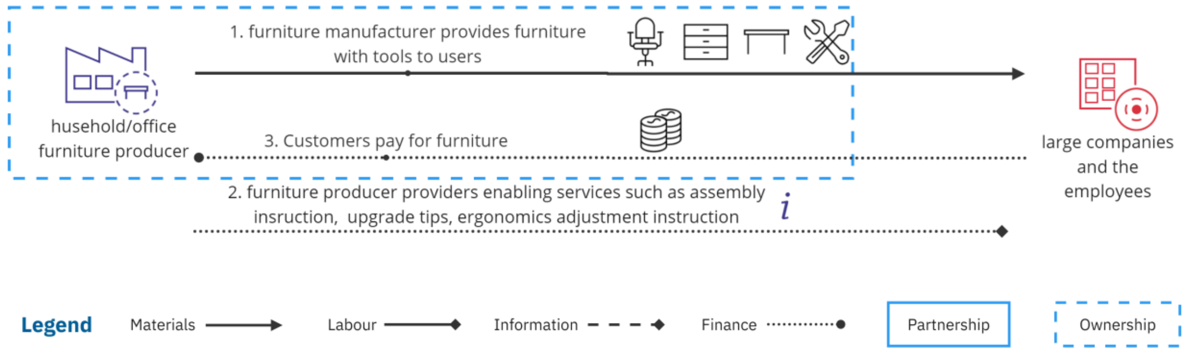


Figure 59 Furniture S.PSS archetypal model 19: Offering ownerless office furniture with enabling service for long-term use in large office space

Model 20. Offering ownerless office furniture with all-inclusive service for long-term use in large office spaces. This B2B model involves the furniture provider collaborating with local service providers and end-of-life remanufacturers to offer all-inclusive services to companies throughout the furniture's lifecycle.

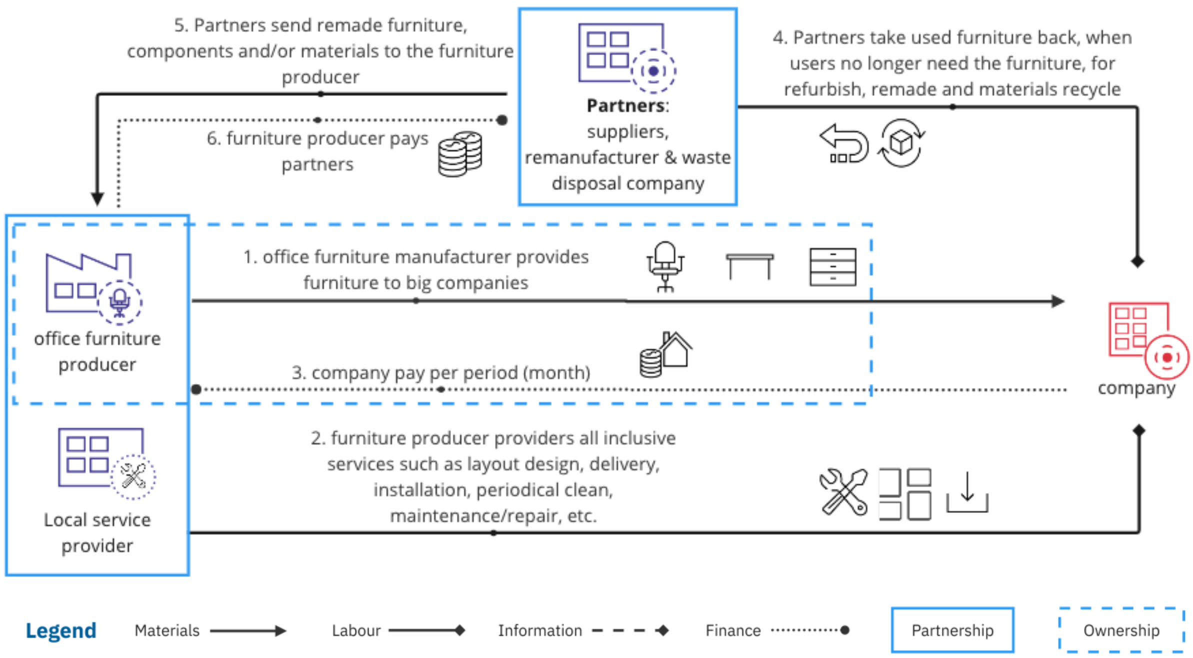


Figure 60 Furniture S.PSS archetypal model 20: Offering ownerless office furniture with all-inclusive service for long-term use in large office spaces

6.5 Conclusions

The design may play a crucial role in envisioning a new generation of sustainable furniture systems within the former framework. This case study analysis mainly verifies and characterizes five main win-win environmental and economic benefits of S.PSS in furniture systems. The S.PSS for furniture offer models need to be designed by adopting S.PSS design approaches and tools.

- Adopting a “satisfaction-system” approach to design a particular “furniture satisfaction unit” and its related furniture and services.
- Adopting a “stakeholder configuration” approach to design the interactions of the stakeholders of a particular furniture satisfaction system.
- Adopting a “system sustainability” approach to design such stakeholder interactions (offer model) that providers continuously seek after both environmentally and socio-ethically new beneficial furniture solutions for economic reasons.

Finally, to enhance our understanding of these opportunities, it is very relevant to develop an archetypal furniture S.PSS map - an essential part of the reference framework for promising furniture S.PSS. The archetypal furniture S.PSS map comprises 20 models, representing comprehensive and promising possibilities for furniture system design. Each model signifies a sustainable win-win configuration, promoting solutions with low environmental impact and high economic value.

In conclusion, taking into account the characteristics of S.PSS furniture in comparison to traditional furniture offerings, as well as win-win economic and environmental benefits of furniture S.PSS, the conceptual framework of S.PSS furniture could be illustrated as depicted in Figure 61.

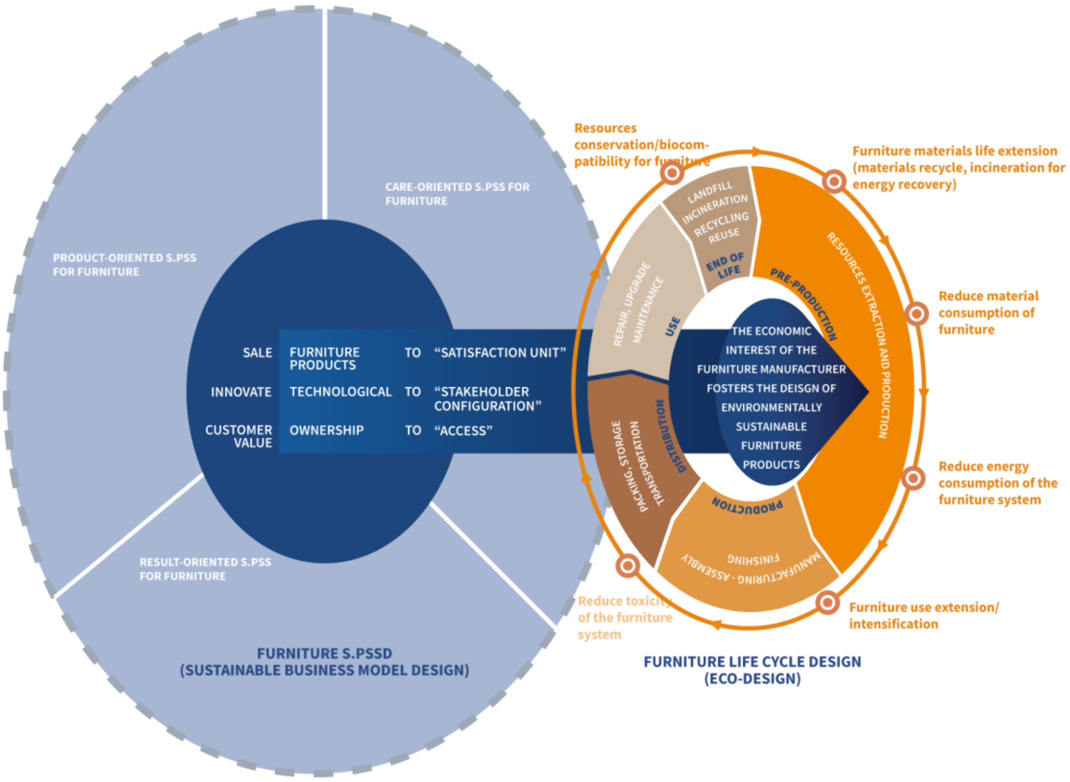


Figure 61 The conceptual framework of furniture S.PSS.

In addition to this knowledge development, a set of available S.PSS tools can be applied for furniture system design (as analyzed in Chapter 2.4). However, certain tools require further research for specification to be effectively used in the furniture sector, highlighting a deficiency in tools for furniture S.PSSD. The literature review also identified a scarcity of qualitative evaluation tools for furniture S.PSS and furniture-specific S.PSS design tools. From a practical standpoint, as outlined in Chapter 6.3.3, the study identified a lack of knowledge base and know-how for furniture companies to design furniture S.PSS. Specifically, there is an absence of furniture-specific S.PSS design strategies, design methods, furniture-specific tools for strategic analysis, S.PSSD idea generation, description, and qualitative evaluation. This study aims to address these gaps in the following chapters.

Part III How to design a sustainable furniture system

This part describes the activities undertaken as part of the prototyping and evaluation stage, aiming at answering RQ 2: What new knowledge is needed to design environmentally Sustainable Furniture Systems? RQ 2.1: What new competencies, skills, methods, and tools are needed for environmentally sustainable furniture Life Cycle Design (product level)? RQ 2.2: What new competencies, skills, methods, and tools are needed for environmentally Sustainable furniture Product-Service System Design (PSS level)?

The fundamental insights for this part lie in the former researchers. The desk research and literature review of existing general DfS approaches/methods/tools (chapter 2.4), and the desk research and semi-structured interview of the application of DfS approaches/ methods /tools in furniture companies found the lack of knowledge and know-how for sustainable furniture system design (chapter 5.3.3 and chapter 6.3.3). The conceptual framework built in former parts contributes insights for this stage of research during the development of a furniture-specific knowledge base and know-how.

The activities and results described in this chapter are summarized below:

- The development of furniture-specific Product Life Cycle Design strategies and guidelines (chapter 7.1 The development of furniture-specific product life cycle design guidelines). This chapter follows the established methodology (L. I. Chaves, 2008; Vezzoli & Sciama, 2006) that guides the development of product type-specific guidelines from general ones. Insights from Part II (especially chapter 5) nutrients the process. A workshop with experts was conducted involving experts to develop the draft version of furniture-specific LCD guidelines (with 3 levels of details: strategy, guideline, and sub-guideline). Based on the LCA results, the priority for each strategy was defined based on its potential to reduce the environmental impact along the furniture's life cycle. Last, these guidelines were then revised, evaluated by internal and external experts, and finalized.
- The development of furniture-specific sustainable Product-Service System strategies and guidelines (chapter 7.2 The development of furniture-specific Sustainable Product-Service System Design (S.PSSD) guidelines). This chapter follows the same

methodology (L. I. Chaves, 2008; Vezzoli & Sciama, 2006) that guides the development of type-specific guidelines from general ones. Insights from Part II (especially chapter 6) nutrients the process. After developing the draft version of furniture-specific S.PSS design guidelines by the candidate, a workshop with experts was conducted involving experts to examine the draft version and develop the first version of furniture-specific S.PSS design guidelines (with 2 levels of details: strategy and guideline). These guidelines were then revised, evaluated by internal and external experts, and finalized.

- The adoption of a method for environmentally sustainable Furniture System Design (chapter 7.1). This chapter adopted the general Method for Sustainable System Design and Method for Sustainable Product Design and developed the Method for Sustainable Furniture System Design considering the furniture product and system design.
- The prototyping of furniture-specific LCD tools (chapter 8.2). This chapter shows the development of furniture-specific LCD tools. All knowledge acquired in the former parts (chapter 7.1 and chapter 5) was integrated into these tools.
- The prototyping of furniture-specific S.PSSD tools (chapter 7.3). This chapter shows the development of furniture-specific S.PSSD tools. All knowledge acquired in the former parts (chapter 7.2 and chapter 6) was integrated into these tools.
- The evaluation of furniture-specific system design tools (Chapter 9) involved an iterative testing and refinement process for all developed tools/toolkits, including the ICSxFurniture toolkit, SDOxFurniture toolkit, Innovation DiagramxFurniture S.PSS, Concept SheetxFurniture S.PSS, and System MapxFurniture S.PSS. This evaluation engaged 70 furniture designers and experts in furniture design and/or design for sustainability. The assessment activities encompassed evaluations within a project, during a workshop, through a series of interviews, within a focus group, and a questionnaire sent to the LeNS community.

This part developed a knowledge base and know-how for Sustainable Furniture System Design, considering both furniture Life Cycle Design and Sustainable Furniture Product-Service System Design. As a closure to this part, furniture-specific LCD guidelines with priorities, furniture-specific S.PSSD guidelines, a new methodology for environmentally sustainable furniture system design, and series of design for sustainable furniture tools that integrated all necessary knowledge were developed and evaluated.

One key word in this part is furniture-specific, which means the knowledge base and know-how were developed specifically for the furniture sector. Although a general knowledge base and know-how (for example, guidelines for general products) have been developed, it is not said that they are efficient or even proper for specific product sectors, in this case, furniture. This is proved through a semi-structured interview (chapter 5.3.3 and chapter 6.3.3). To be effective in a specific context, knowledge base and know-how should inspire and indicate design decisions and solutions that have the major potential to be sustainable as precisely as possible; they should "provide specific advice and strategies on how to reduce impacts" (Vezzoli & Sciama, 2006); Actually, focusing tools on a specific sector or product is one of the approaches that design for sustainability has adopted to enhance the effectiveness of its application (L. I. Chaves, 2007).

Other researchers take the same position. Results from broadly contextualized research methods may prove too global and abstract to be useful in many settings (Cobb, 2001; Cobb et al., 2003; E. Baumgartner & Bell, 2002). They may prove ineffective when used alone, but they can be modified, replaced, or adapted by others, provided the system itself remains unaffected. Thus, researchers attempt to analyze the relationship between principles (e.g., the order of implementing them and the interdependencies between them) so that the design procedures they employ in the original setting will likely prove effective in new settings (Brown & Campione, 1996). Guidance for applying generated principles is needed to increase the adaptability and, ultimately, the generalizability of the research. Dewey warned that although general ideals and principles are of value in the direction and enlargement of conduct, they are also dangerous: They tend to be set up as fixed things in themselves, apart from reference to any particular case (Dewey, 1967) as cited in (Boydston, 1971). With this Epistemology, this part aims to develop the furniture-specific knowledge base and know-how.

Chapter 7 The development of specific guidelines for sustainable furniture system design

7.1 The development of furniture-specific product life cycle design guidelines [24]

Given the serious environmental impact of the furniture system, the role of design in innovating furniture products toward sustainability is increasingly recognized as a key leverage, as acknowledged by the European Union's Circular Economy Action Plan in 2020. The need for sustainable design knowledge to address environmental issues caused by the life cycle of furniture products – a fundamental part of the furniture system – has now been prioritized.

Within this framework, the paper presents furniture-specific LCD guidelines to guide sustainable furniture design. These guidelines were developed through an established methodology involving scholars and specialists on both Design for Sustainability and Furniture Design and were the results of a research project funded by the Italian Ministry of Education (MIUR), aimed at developing and disseminating innovative design strategies and guidelines to foster a sustainable and circular economy within the furniture industry. In this sense, these guidelines will promote long-term open innovation and technological transformation of furniture products, allowing designers and organizations to support the implementation of sustainable options from the beginning of the design process.

[24] This chapter, 7.1, refers to the publication of the author entitled Designing sustainable furniture: guidelines to promote furniture Life Cycle Design (D. Yang & Vezzoli, 2023).

7.1.1 Method

The development of product type-specific LCD guidelines based on general ones has a well-established foundation. A span of more than two decades encompassing research and consultancy endeavors conducted by the LeNS lab at Polimi has gradually formulated a structured and validated methodology (L. I. Chaves, 2008; Vezzoli & Sciama, 2006), which was employed within this study, as depicted in Figure 62. The data presented in orange signifies external competence, denoting knowledge, data and information that have been sourced outside of the LeNS lab. Examples include contributions from partners in the GIOTTO project (COSMOB, Cluster Arredo, and UNICAM). The cyan elements represent internal competence, reflecting the knowledge, data, information, and research outcomes generated within the LeNS lab. Lastly, the green-colored data encapsulates a synergy of internal and external competencies, intertwining the insights and outcomes from both LeNS lab endeavors and external collaborations.

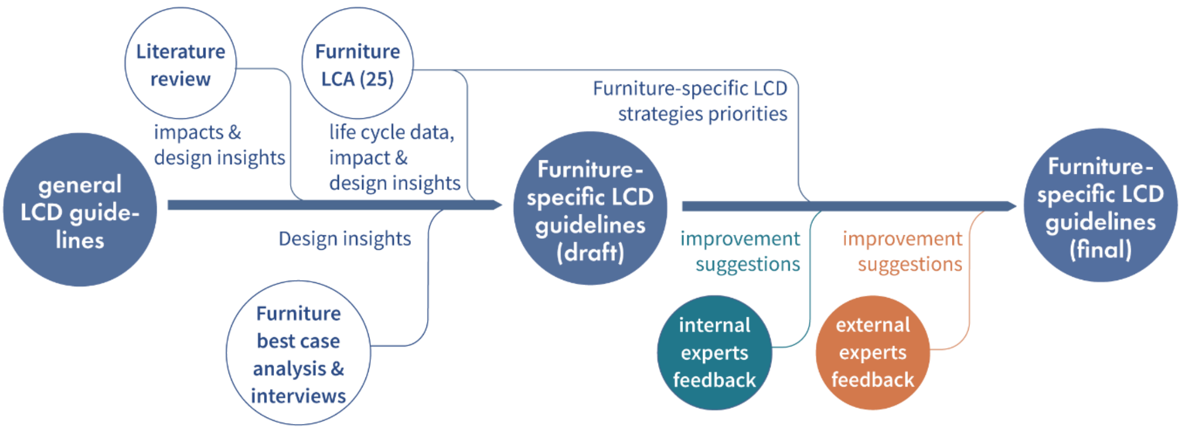


Figure 62 Prior knowledge and steps to develop furniture-specific product LCD and S.PSSD strategies/sub-strategies/guidelines, adapted from (L. I. Chaves, 2008; Vezzoli & Sciama, 2006)

Note: White text with orange background represents external competence (e.g. knowledge and know-how from GIOTTO project partners (COSMOB, Cluster Arredo, and UNICAM). White text with cyan background represents internal competence (inside the LeNS Lab where the PhD candidate is involved). Blue text with blue frame represents research activities made by the PhD candidate and the original data, information comes from other researchers (literature), furniture companies (reports, interviews, websites), or practitioners (interviews).

7.1.1.1 1st stage: Preliminary study (chapter 5)

The project started with a preliminary phase of desk research to uncover the most updated knowledge about the environmental impact of the furniture life cycle (chapter 5.1). On one side, a critical review of available literature was conducted to analyze previous evaluations of furniture's environmental impact, i.e. Life Cycle Assessment. On the other hand, a detailed Life Cycle Assessment was conducted to identify the environmental impact along different furniture's life cycle. In addition, a detailed analysis of best practices and semi-structured interviews from an environmental standpoint (chapter 5.2 - chapter 5.3) was conducted to provide inspiration for subsequent collaborative sessions when elaborating on furniture-specific LCD guidelines. Results from these research activities formed the framework to facilitate the successive step within the GIOTTO project, aimed at moving from general LCD strategies and guidelines toward the definition of furniture-specific version to reduce the overall environmental impact along furniture's life cycle.

7.1.1.2 2nd stage: workshop

The specification process was carried out through a collaborative workshop that involved scholars and experts on Design for Sustainability and Furniture Design, with the goal of generating a preliminary version of furniture-specific LCD guidelines. The Workshop was conducted at the LeNSLab POLIMI.

The development of furniture-specific LCD guidelines finished with the following activities:

Step 1: Before the workshop, a report was sent to all participants to collect their opinions on whether the general guidelines are clear and relevant to furniture and facilitate the generation of furniture-specific LCD guidelines, see an example in Figure 63.

Step 2: At the initial stage of the workshop, results from the preliminary research stage (environmental impacts and design insights from practical LCAs and academic literature review, sustainable furniture product characteristics [25] from case study and semi-structured interviews) were presented to participants. The process to be followed for the workshop was also presented to participants.

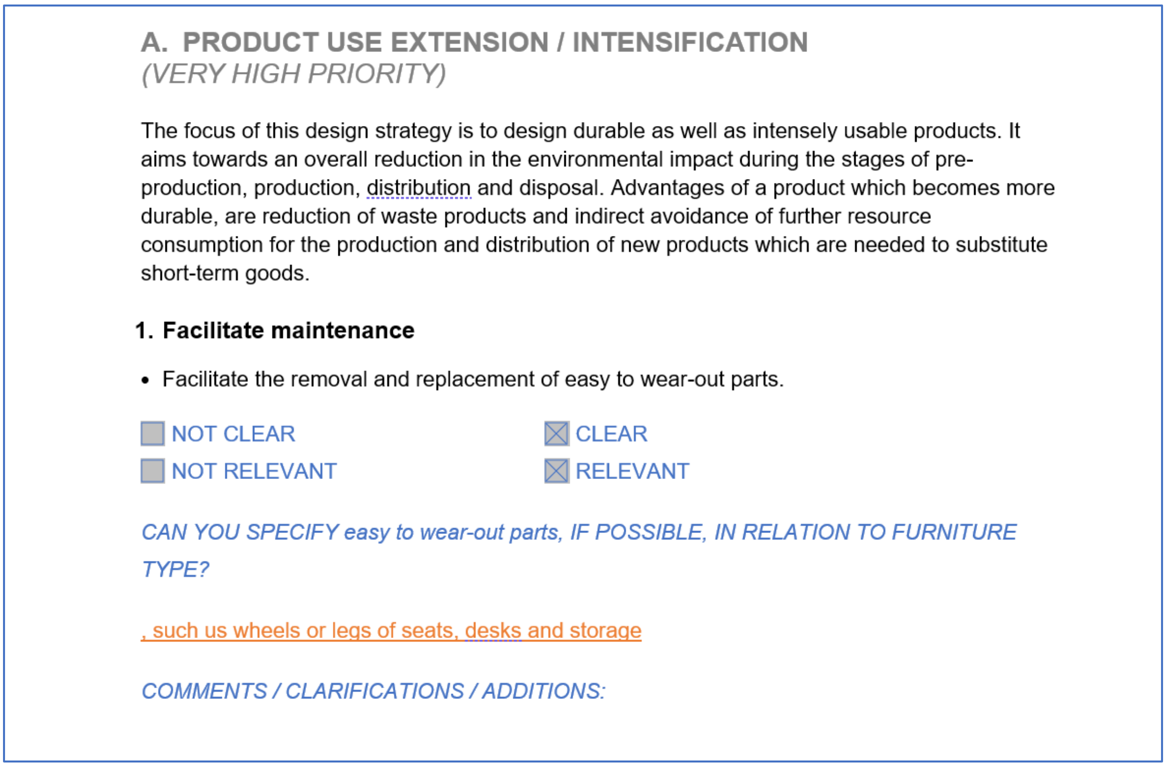
Step 3: During the workshop, each of the general guidelines were presented, all participants' comments before/during the workshop were recapped/recorded, discussed and polished. During this phase, a structured process was implemented for each general guideline, allowing participants to perform a variety of specification actions such as: integrating a general guideline related to furniture products or typology; adding a new guideline that deals with a certain environmental impact related to particular furniture products or typology; adding notes related to particular furniture product or typology; and erasing a guideline if irrelevant. The outcome of the workshop was a draft of furniture-specific guidelines, which was further reviewed and refined for final improvements. Please see Table 37 and Figure 64 for a more specific example of the shift from general to furniture-specific Life Cycle Design guidelines. The workshop's main activity, the guidelines specification, was then completed.

Step 4: After the workshop, each guideline was polished considering participants' comments. The draft version of furniture-specific LCD guidelines was developed.

Step 5: The draft version of the furniture-specific LCD guidelines was sent to internal experts from LeNSLab POLIMI for improvement and finalization.

Step 6: Then the new draft version was sent to external experts from the GIOTTO project for further improvement and finalization to form the final version of furniture-specific LCD guidelines.

[25] Since the best cases analysis activity is iterative, new cases emerged as the research progressed. Therefore, not all design insights were presented to participants at this stage. However, all design insights were taken into account for the final version of the furniture-specific LCD guidelines.



A. PRODUCT USE EXTENSION / INTENSIFICATION
(VERY HIGH PRIORITY)

The focus of this design strategy is to design durable as well as intensely usable products. It aims towards an overall reduction in the environmental impact during the stages of pre-production, production, distribution and disposal. Advantages of a product which becomes more durable, are reduction of waste products and indirect avoidance of further resource consumption for the production and distribution of new products which are needed to substitute short-term goods.

1. Facilitate maintenance

- Facilitate the removal and replacement of easy to wear-out parts.

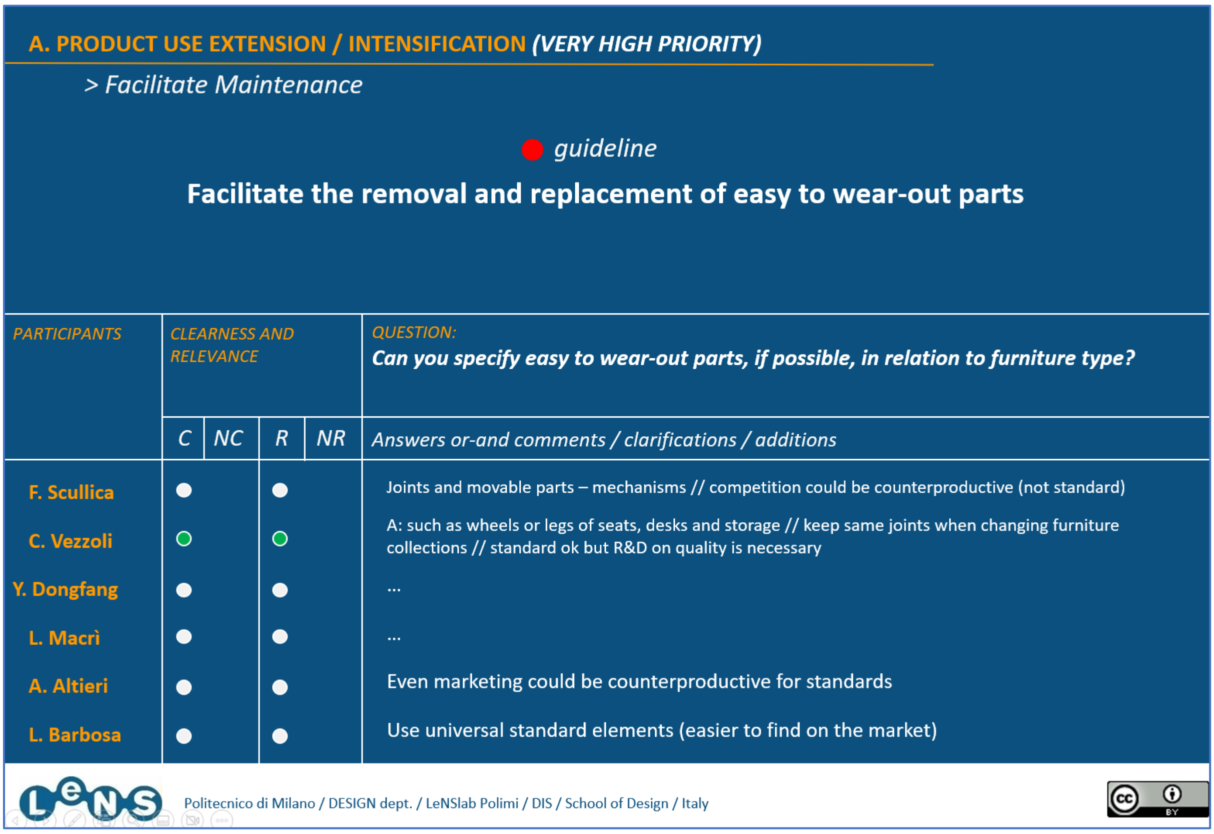
☐ NOT CLEAR ☒ CLEAR
☐ NOT RELEVANT ☒ RELEVANT

CAN YOU SPECIFY easy to wear-out parts, IF POSSIBLE, IN RELATION TO FURNITURE TYPE?

, such us wheels or legs of seats, desks and storage

COMMENTS / CLARIFICATIONS / ADDITIONS:

Figure 63 Step 1: An image indicates the report sent to participants before the workshop.



A. PRODUCT USE EXTENSION / INTENSIFICATION *(VERY HIGH PRIORITY)*

> Facilitate Maintenance

guideline

Facilitate the removal and replacement of easy to wear-out parts

PARTICIPANTS	*CLEARNESS AND RELEVANCE*				*QUESTION:* ***Can you specify easy to wear-out parts, if possible, in relation to furniture type?***
	C	*NC*	*R*	*NR*	*Answers or-and comments / clarifications / additions*
F. Scullica	●		●		Joints and movable parts – mechanisms // competition could be counterproductive (not standard)
C. Vezzoli	●		●		A: such as wheels or legs of seats, desks and storage // keep same joints when changing furniture collections // standard ok but R&D on quality is necessary
Y. Dongfang	●		●		…
L. Macrì	●		●		…
A. Altieri	●		●		Even marketing could be counterproductive for standards
L. Barbosa	●		●		Use universal standard elements (easier to find on the market)

Politecnico di Milano / DESIGN dept. / LeNSlab Polimi / DIS / School of Design / Italy

Figure 64 Step 3: An image indicates the presentation of each general guideline, and the recap and recording of all participants' comments.

Note: Participants were initially asked to assess the clarity and relevance of each guideline to the furniture sector. Subsequently, their comments were recorded and discussed during the workshop.

Table 37 An example of developing furniture specific guidelines from general ones

General strategy/sub-strategy/guidelines	**Furniture-specific strategy/sub-strategy/guidelines**
Strategy: Product lifespan optimization Sub-strategy: Facilitate upgrading and adaptability	**Strategy:** Furniture use extension/intensification Sub-strategy: Facilitate furniture upgrading, extension and adaption
Guideline 1: Enable and facilitate software upgrade	**Activity:** erasing irrelevant guidelines
Guideline 3: Design modular and dynamically configured products to facilitate their adaptability for changing environments	**Activity:** adding characteristics relevant to specific furniture products or typologies **Guideline 1:** Design reconfigurable furniture that is able to adapt to different spaces/situations, such as modular desk and storage structures that can be used for both the transformation of a given office space or for a new function (e.g. an individual working station that can be transformed into a collective one, and that can also be rearranged if the office moves to a new location).
Guideline 5: Design products that can be upgraded and adapted onsite	**Activity:** integrating a general guideline related to specific furniture products or typologies **Guideline 7:** [Office seats] Design modular and on-site upgradable seats, allowing the user to substitute (with standard tools) fixed feet with wheels and/or fixed components to adjustable ones.
	Activity: adding new guidelines related to particular furniture products or typologies **Guideline 11:** Include multiple connection possibilities on tables and storages, e.g. electricity cables, joints to combine table surfaces, etc.

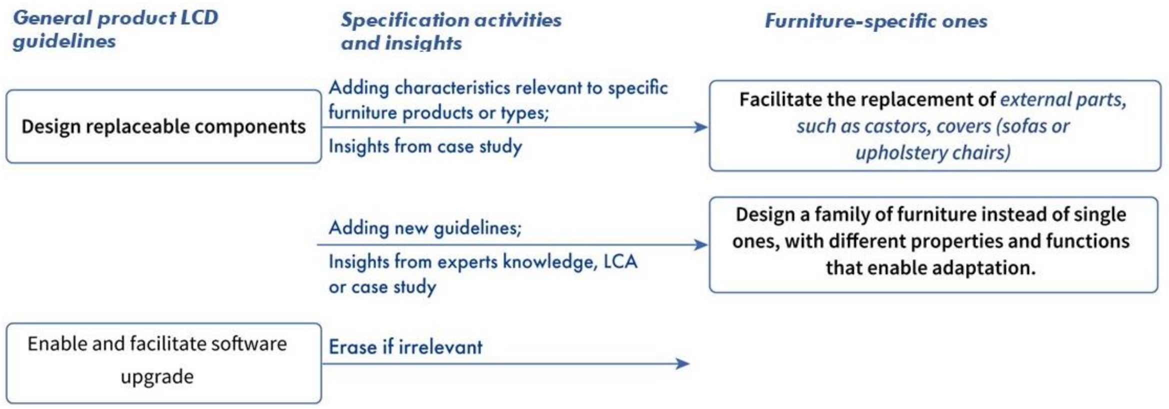


Figure 65 An example of developing furniture specific guidelines from general ones

Sampling. Participants were selected based on the following criteria since the aim was to generate furniture-specific LCD guidelines. 1) Heterogeneity. Participants from different and relevant backgrounds should be involved, so participants come from fields including furniture design and engineering, design for sustainability, interior and furniture design, and 2) Expertise. Participants should have expertise in their fields.

7.1.1.3 3rd stage: Environmental LCD Strategies Priority Evaluation

(1) The importance of defining furniture-specific LCD strategies priorities

Although there are some general LCD guidelines, products groups or even each product has their characteristics (e.g. raw materials, production process, consumption of resources in use) which affect their life cycle impact and thus requiring different interventions (L. I. Chaves, 2008). The developed furniture-specific Life Cycle Design (LCD) strategies, along with their corresponding guidelines, constitute a valuable body of knowledge that can assist designers in creating environmentally sustainable furniture. These strategies facilitate a comprehensive consideration of all stages in the product's life cycle, leading to substantial reductions in environmental impacts. However, some strategies are more relevant than others and lead to greater reductions in environmental impact. On the other hand, designers often encounter situations where alternative solutions emphasize different sustainability aspects, necessitating a delicate balance (Byggeth & Hochschorner, 2006). In such a situation, designers require decision-making support. Gibson (2013) underscored the common approach of assuming that trade-offs are inevitable when different aspects of sustainability are at play. Within this perspective, it is considered good practice to explicitly acknowledge trade-offs, enabling better-informed choices.

In essence, conflicts can arise among guidelines, leading to scenarios in which adopting a particular design strategy or guideline inevitably results in a burden shift. For instance, when reducing the dimensions of furniture components, it becomes challenging to ascertain the extent to which environmental impacts decrease or even increase. This complexity arises from the fact that minimizing material consumption might simultaneously compromise the product's functional longevity.

Effectively determining the priorities of LCD strategies, while taking functional considerations into account, is pivotal in guiding design endeavors. It is posited that certain strategies hold greater precedence than others for each product category, be it furniture, automobiles, or other items. For instance, in the context of furniture, extending the product's lifespan holds more significance than energy consumption reduction, whereas for automobiles that consume energy during operation, prioritizing resource consumption reduction becomes more pertinent.

(2) How to define furniture-specific LCD strategies priorities

Two pivotal factors are involved in determining the design priority for each furniture-specific LCD strategy: the strategies' relevance to the maximum avoidable environmental impact in theory and the estimate of improvement in practice. The strategy's relevance can be defined by answering the question: "From the LCA result of an existing furniture, how relevant is the strategy/sub-strategy, or what is the maximum avoidable environmental impact (in comparison to the total) by fully pursuing a given LCD strategy (or sub-strategy)?" This can be answered with a level of "high', 'middle', 'low' and 'no'. Different strategies can influence various life cycle stages and environmental categories. To answer this query, it's necessary to (1) assess the environmental impacts of a furniture piece across its life cycle stages, spanning pre-production, production, distribution, usage, and end-of-life stages, and (2) evaluate impacts for each environmental category.

On the other hand, given the real-world limitations that often prevent complete strategy implementation, another pivotal factor is introduced: the estimate of improvement in practice. This factor is qualitative hypotheses provided by users or experts, often quantified with an average value. This can be defined by answering a question "From the characteristics of the existing furniture and its functional unit, what extent of improvement can we assume by fully pursuing this strategy? This can be answered with a level of 'radical improvement', 'incremental improvement', 'no improvement'.

In this study, this method is employed to ascertain the priorities of individual furniture-specific Life Cycle Design (LCD) strategies. The main objective is to establish the most and least relevant strategies for various furniture products and give a general trend. The priority indicators are classified into distinct levels: high, middle, low and none. The subsequent sections present the overall trend of the priorities defined for each furniture-specific LCD strategy.

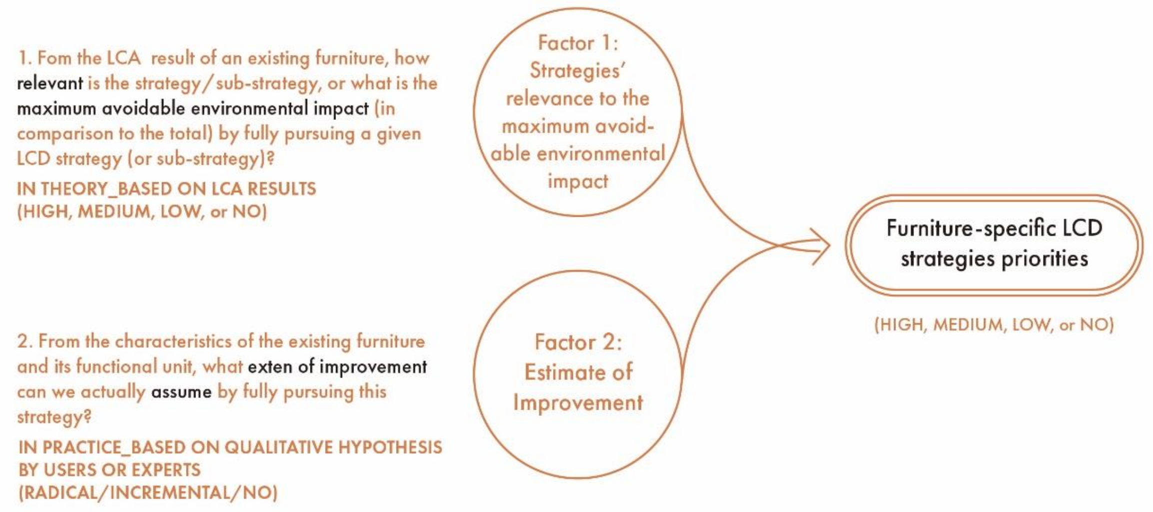


Figure 66 The method of define the priority for each furniture-specific LCD strategy

(3) Sampling

The underlying assumption is that furniture products, whether chairs, desks, or other specific types, share common characteristics. Consequently, they are likely to exhibit similar trends in priorities concerning furniture-specific Life Cycle Design (LCD) strategies. Another assumption is that incorporating a greater number of categories and cases will yield more accurate outcomes. The Furniture-specific LCD strategies priorities definition was identified based on these 25 furniture pieces detailed in Chapter 5.1.

In Chapter 5.1, the study conducted an environmental analysis of 25 furniture pieces spanning 8 distinct furniture product categories, utilizing the Life Cycle Assessment (LCA) method. This comprehensive analysis encompassed various items, including 3 task chairs, 5 desks, 4 sofas, 2 stools, 2 coffee tables, 3 storage units, 5 chairs, and a workspace. These assessed objects served as references, aiming to unveil common trends in the priorities of furniture LCD strategies.

7.1.1.4 4th step: iterative revision and improvement of these guidelines

Following the conclusions of the workshop and the subsequent identification of priorities, an initial draft of furniture-specific guidelines was created. This preliminary draft was subjected to revision primarily by the project coordinator and other participants who had taken part in the workshop. This collaborative effort resulted in the initial version of the furniture-specific Life Cycle Design (LCD) guidelines.

Subsequently, this initial version of the guidelines underwent a secondary review by three additional partners affiliated with the GIOTTO project. This review process led to the development of the second version of the guidelines. The culmination of these revisions and refinements led to a more comprehensive and refined set of guidelines.

Following the revision process, the study was presented at the Cumulus conference and subsequently accepted to be published. The presentation at the conference provided an opportunity for peer review and scholarly critique, further enhancing the robustness of the guidelines. It is noteworthy that no additional revisions were deemed necessary following the peer review process.

7.1.1.5 The involvement of the author and other participants

Design-based research is a systematic, yet flexible methodology aimed at enhancing practices through iterative analysis, design, development, and intervention implementation. It relies on collaboration among researchers and practitioners in real-world settings, resulting in contextually sensitive design principles and theories.

The present contribution forms part of the outcomes of the research project titled "The Circular Economy for the Competitiveness of the Made in Italy Industry - GIOTTO." This project, conducted in collaboration with eleven national organizations and funded by the Italian Ministry of Education and Research (MIUR), sought to develop and disseminate innovative design guidelines and tools, to foster a sustainable and circular economy within the competitive value chains of the Made in Italy industries, including furniture, food, and fashion. Through a multidisciplinary and collaborative research consortium, GIOTTO empowered small and medium enterprises with innovative approaches to minimize the environmental impact of their products across their entire life cycle.

In this context, LeNSlab Polimi spearheaded research activities to formulate targeted Life Cycle Design (LCD) strategies and guidelines for the development of environmentally sustainable furniture and fashion products. This paper introduces novel furniture-specific LCD guidelines, a result of LeNSlab Polimi's research spanning over two decades.

During the project, the author undertook the role of project manager for the furniture research component. Particularly, the author conducted preliminary research encompassing literature reviews, Life Cycle Assessments (LCAs), and case study analyses. This preliminary research was subsequently reviewed by the project coordinator, Prof. Vezzoli. For the workshop sessions, the author prepared necessary documents under the guidance of Prof. Vezzoli. These documents included a Word file for notetaking and idea generation by six participants and a presentation to guide the workshop’s activities.

During the workshop sessions, the author collaborated with other participants to facilitate discussions, recorded ideas from each participant and consolidated collective conclusion. Post-workshop, the author incorporated all participants' inputs to refine the furniture-specific LCD guidelines. These guidelines were further discussed with selected participants and the coordinator, leading to the initial version of the furniture-specific LCD guidelines. This version was shared with all project partners for final revision and refinement.

7.1.2 The priorities for furniture-specific Life cycle Design strategies and guidelines

As a result of the study, furniture-specific LCD guidelines were developed, which include, hierarchically organized, 7 strategies, 23 sub-strategies and 154 guidelines to stimulate and guide the generation of environmentally sustainable furniture LCD solutions. These guidelines have a hierarchical structure with each specific strategy containing several specific sub-strategies and each sub-strategies containing a set of specific guidelines. Design strategies and sub-strategies guide the design directions, providing a framework that orientates the design activities. Design guidelines are more detailed, and actionable providing clear instructions for generating ideas during the design process.

These 7 furniture-specific LCD strategies are:

- Furniture use extension/intensification
- Reduce material consumption of furniture
- Furniture materials life extension
- Reduce toxicity of the furniture system
- Reduce energy consumption of the furniture system
- Resources conservation/biocompatibility for furniture
- Design for furniture disassembly.

Each of the former strategies was assigned a priority indicator – high, medium, low or very low – which refers to the potential environmental burden reduction associated with each

LCD strategy, in relation to furniture systems. Since the last strategy - design for furniture disassembly is functional to both Furniture use extension/ intensification and Furniture materials life extension, the study did not assign it a priority.

(1) Furniture use extension/intensification

The meaning of 'Furniture use extension/intensification' is to design durable and/or intensely usable furniture. It leads to an overall reduction in the environmental impact of pre-production, production, distribution, and end-of-life phases. Given the same function, a furniture piece with shorter lifespan will create more waste at its end-of-life. The replacement of this furniture to provide the functions (functional unit) will have additional impact from the pre-production, production, distribution. Figure 67 compares the environmental impact of two furniture pieces with different lifespan and shows the avoided impacts of long-lasting furniture.

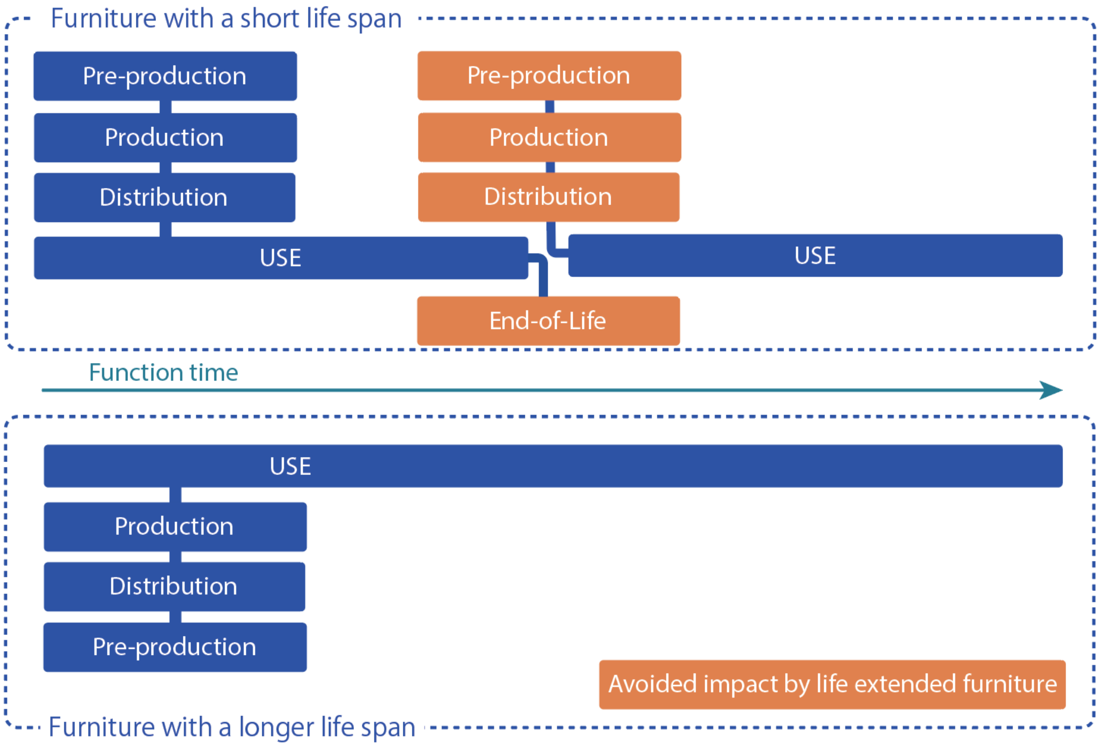


Figure 67 Environmental advantages of furniture with longer lifespan

To define the priority of 'Furniture use extension/intensification', the first step is to define the strategy's relevance to the maximum avoidable environmental impact, by asking "From the LCA results of the existing 25 furniture pieces, how relevant is the strategy, or what is the maximum avoidable environmental impact (in comparison to the total) by fully pursuing this strategy"? For all 25 cases, with this strategy, the maximum avoidable environmental impact of the pre-production, production, distribution, and end-of-life stages ranges from 99%-100%, which is HIGH compared to the overall impact.

The second step was to define the estimate of improvement by answering a question "From the characteristics of the existing furniture and its functional unit, what extent of improvement can we assume by fully pursuing this strategy"? For all 25 cases, the improvement estimate we can assume by fully pursuing the strategy is RADICAL.

These considerations lead to define the priority of the Furniture use extension/intensification strategy: HIGH.

(2) Reduce material consumption of furniture

This strategy facilitates environmental impacts reduction due to fewer materials being extracted and processed, consequently reducing impact from pre-production, production, distribution, use (transportation of furniture during use) and end-of-life. Figure 68 compares the environmental impact of two furniture pieces with different materials content and shows the avoided impacts of furniture with reduced materials.

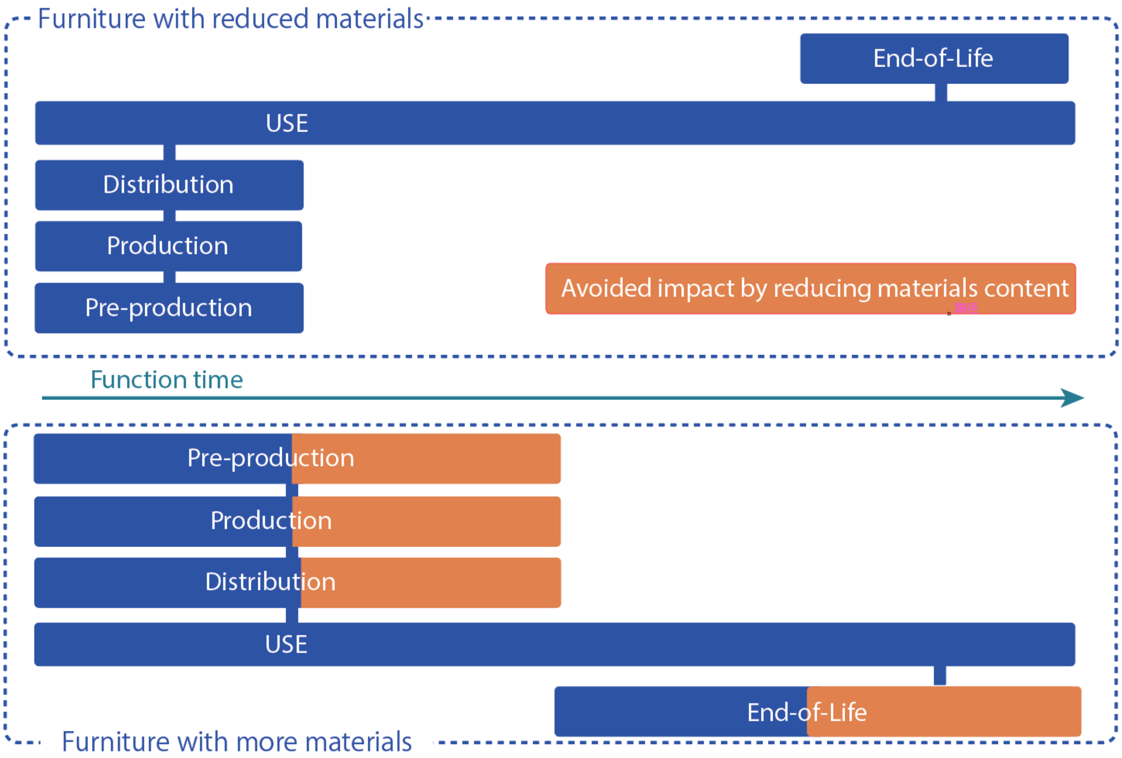


Figure 68 Environmental advantages of furniture with reduced materials content

To define the priority of ‘reduce material consumption of furniture’, the first step is to define the strategy’s relevance to the maximum avoidable environmental impact, by asking “From the LCA results of the existing 25 furniture pieces, how relevant is the strategy, or what is the maximum avoidable environmental impact (in comparison to the total) by fully pursuing this strategy”? For all 25 cases, with this strategy, the maximum avoidable environmental impact of the pre-production, production, distribution, use (transportation of furniture during use) and end-of-life stages ranges from 99%-100%, which is HIGH compared to the overall impact.

The second step was to define the estimate of improvement by answering a question “From the characteristics of the existing furniture and its functional unit, what extent of improvement can we assume by fully pursuing this strategy”? For all 25 cases, the improvement estimate we can assume by fully pursuing the strategy is RADICAL/ INCREMENTAL.

These considerations lead to define the priority of the reduce material consumption of furniture: HIGH.

(3) Furniture materials life extension

This design strategy is to design furniture with the purpose of increasing the value of materials at the end-of-life. Extension of material lifespan with recycling or “clean” energy recovery leads to less landfilling (end-of-life) and less resources extraction for primary (new) materials (pre-production). Figure 69 compares the environmental impact of furniture with extended and short material lifespan and shows the avoided impacts for materials life extended furniture.

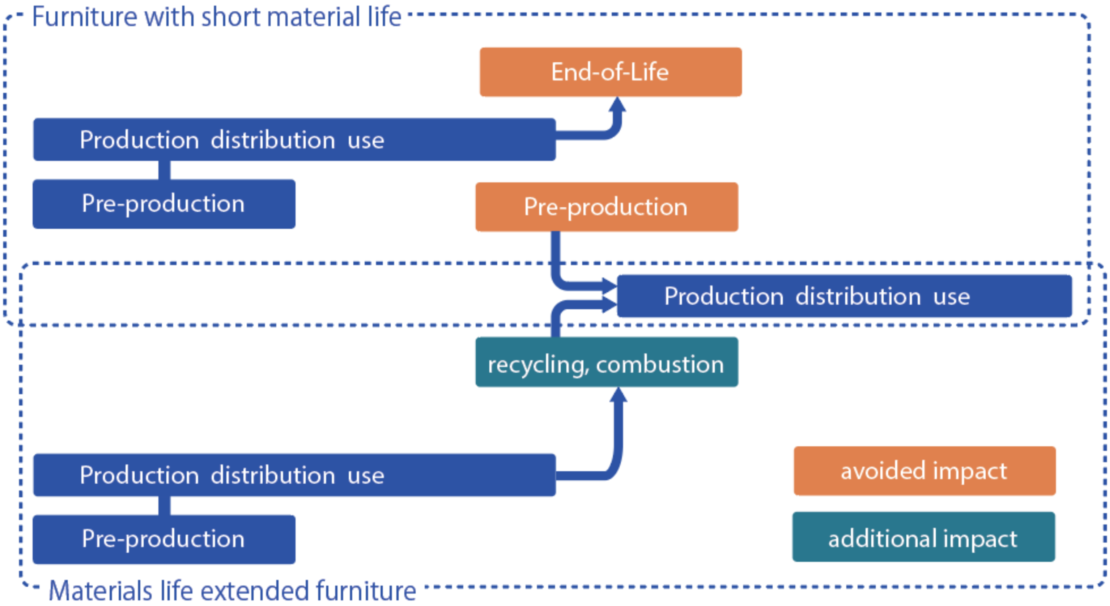


Figure 69 Environmental advantages of furniture with materials life extension

To define the priority of “Furniture materials life extension”, the first step is to define the strategy’s relevance to the maximum avoidable environmental impact, by asking “From the LCA results of the existing 25 furniture pieces, how relevant is the strategy, or what is the maximum avoidable environmental impact (in comparison to the total) by fully pursuing this strategy”? For all 25 cases, with this strategy, the maximum avoidable environmental impact of landfilling/incineration and pre-production of materials ranges from 54% - 94%, which is MIDDLE/HIGH compared to the overall impact.

The second step was to define the estimate of improvement by answering a question "From the characteristics of the existing furniture and its functional unit, what extent of improvement can we assume by fully pursuing this strategy"? For all 25 cases, the improvement estimate we can assume by fully pursuing the strategy is INCREMENTAL.

These considerations lead to define the priority of the Furniture materials life extension: MIDDLE.

(4) Reduce toxicity of the furniture system

Materials, additives with toxic and harmful emissions and energy resources with dangerous emissions should be avoided. To reduce toxicity of the furniture system, we need to avoid the use of toxic materials/energy.

To define the priority of "Reduce toxicity of the furniture system", the first step is to define the strategy's relevance to the maximum avoidable environmental impact, by asking "From the LCA results of the existing 25 furniture pieces, how relevant is the strategy, or what is the maximum avoidable environmental impact (in comparison to the total) by fully pursuing this strategy"? For all 25 cases, the maximum avoidable environmental impact lies in the environmental category of toxicity_cancer and toxicity_non cancer, which ranges from 1% - 10%. This is LOW compared to the overall impact.

The second step was to define the estimate of improvement by answering a question "From the characteristics of the existing furniture and its functional unit, what extent of improvement can we assume by fully pursuing this strategy"? For all 25 cases, the improvement estimate we can assume by fully pursuing the strategy is LOW.

These considerations lead to define the priority of the Reduce toxicity of the furniture system: LOW.

(5) Reduce energy consumption of the furniture system

To define the priority of "Reduce energy consumption of the furniture system", the first step is to define the strategy's relevance to the maximum avoidable environmental impact, by asking "From the LCA results of the existing 25 furniture pieces, how relevant is the strategy, or what is the maximum avoidable environmental impact (in comparison to the total) by fully pursuing this strategy"? For all 25 cases, the maximum avoidable environmental impact lies in the environmental impact from distribution (the transportation process) and use (energy for cleaning and transportation if any) which ranges from 0% - 9%. This is LOW compared to the overall impact.

The second step was to define the estimate of improvement by answering a question "From the characteristics of the existing furniture and its functional unit, what extent of improvement can we assume by fully pursuing this strategy"? The reduction of impact with design intervention can be done to a substantial extent through reducing materials consumption for furniture. For all 25 cases, the improvement estimate we can assume by fully pursuing the strategy is INCREMENTAL/RADICAL.

These considerations lead to define the priority of the Reduce energy consumption of the furniture system: LOW.

(6) Resources conservation/biocompatibility for furniture

This strategy recommends renewable and non-exhaustible materials and energy resources during the pre-production, production, distribution, and use phases as well as during transportation. The designer can especially intervene in materials and energy selection with low levels of resources depletion. For Resources conservation/biocompatibility for furniture, the relevant environmental impact lies in the environmental categories of resources use_fossils and resources use_minerals and metals.

To define the priority of “Resources conservation/biocompatibility for furniture”, the first step is to define the strategy’s relevance to the maximum avoidable environmental impact, by asking “From the LCA results of the existing 25 furniture pieces, how relevant is the strategy, or what is the maximum avoidable environmental impact (in comparison to the total) by fully pursuing this strategy”? For all 25 cases, the maximum avoidable environmental impact ranges from 11% - 33%. This is LOW compared to the overall impact.

The second step was to define the estimate of improvement by answering a question “From the characteristics of the existing furniture and its functional unit, what extent of improvement can we assume by fully pursuing this strategy”? The reduction of impact with design intervention can be done to a substantial extend through reducing materials consumption for furniture. For all 25 cases, the improvement estimate we can assume by fully pursuing the strategy is INCREMENTAL/RADICAL.

These considerations lead to define the priority of the Resources conservation/ biocompatibility for furniture: LOW.

In order to establish priorities for furniture-specific Life Cycle Design (LCD) strategies, it is essential to define the estimate of improvement which was ascertained through experts/users assumptions. While these assumptions might carry a degree of inaccuracy, the comparison of 25 furniture pieces yielded consistent trends in the results. Based on these results, we can draw the following conclusions:

- The strategy 'Furniture use extension/intensification' holds a 'HIGH priority’.
- 'Furniture materials life extension' is accorded a 'Middle priority'.
- 'Reduce material consumption of furniture' is categorized as having a 'HIGH priority'.
- 'Reduce energy consumption of the furniture system' is assigned a ‘LOW priority'.

- The aspect of 'Resources conservation/biocompatibility' is rated as having a ' LOW priority'.
- Lastly, the factor of 'Reduce toxicity of the furniture system' is ranked as a ‘LOW priority'.

7.1.3 The furniture-specific LCD guidelines

Furniture Life Cycle Design (LCD) strategies

- Furniture use extension/intensification (HIGH priority)
- Reduce material consumption of furniture (HIGH priority)
- Furniture materials life extension (MIDDLE priority)
- Reduce toxicity of the furniture system (low priority)
- Reduce energy consumption of the furniture system (low priority)
- Resources conservation/biocompatibility (low priority)
- Design for furniture disassembly[26]

Strategy 1: Furniture use extension/intensification (high priority)

The focus of this design strategy is to design durable as well as intensely usable furniture at an overall reduction in the environmental impact of pre-production, production, distribution and end-of-life phases. Longer lasting furniture reduces by-product waste and indirectly avoids further resource consumption for the production and distribution of new products needed to substitute short-term ones.

Sub-strategies

- Sub-strategy a1. Facilitate furniture maintenance
- Sub-strategy a2. Facilitate furniture upgrading and adaptation
- Sub-strategy a3. Design furniture for reliability
- Sub-strategy a4. Facilitate/enable furniture re-use and remanufacturing
- Sub-strategy a5. Intensify furniture use

Guidelines:

Guidelines for sub-strategy a1. Facilitate furniture maintenance

- Facilitate the removal and replacement of easy to wear-out parts, such as mechanisms and joints for movable parts, e.g. wheels or legs of seats, desks and storages.
- Use universal standard elements for mechanisms and joints for movable parts.

[26] Design for furniture disassembly is strictly related to the Furniture use extension/intensification strategy and Furniture materials life extension.

- Keep the same joints when changing furniture collections.
- Facilitate access to parts in order to simplify cleaning, avoiding narrow interspaces, slots and holes, e.g. by designing round internal edges of drawers and shelves for quick and easy cleaning.
- Use stainless steel with semi-gloss treatment; select surface material and finishing processes for furniture that avoid the need of toxic detergent for maintenance.
- [Office seats] Properly cover office chair mechanisms to prevent dust and dirt from accumulating and limiting their functioning, e.g. height adjustment mechanisms.
- [Office desks] Properly cover desk height adjustment mechanisms to prevent dust and dirt from accumulating and limiting their functioning.
- [Office storage] Install compensation boards at the top/bottom/side of storage furniture to avoid dust from getting under/on the top/side.
- Consider using surfaces that are resistant to dust and dirt, such as sleek surfaces, dust/dirt-repellent surfaces or textiles.
- Design products that allow maintenance with easily available tools, e.g. use screws with standard hexagonal heads in seats, desks and storage furniture.
- Provide a maintenance kit for cleaning, such as customized brushes to clean (unavoidable) narrow interspaces, slots and holes or surface specific staining removal detergent for seats, desks and storage furniture.
- Provide information on how to clean the product and multi-context maintenance tool kit.
- Facilitate alternative cleaning solutions or more automatic cleaning systems, such as steam cleaning or UV solutions.
- Reduce the need for maintenance operations/procedures, e.g. with textured seats cover to hide stains or with anti-dust surface treatments on seats, desk and storage products.
- Design modular products to facilitate the substitution/cleaning of parts instead of substitution/cleaning of the entire product.

Guidelines for sub-strategy a2. Facilitate furniture upgrading and adaptation.

- Design reconfigurable furniture that is able to adapt to different spaces/situations, such as modular desk and storage structures that can be used for both the transformation of a given office space or for a new function (e.g. an individual working station that can be transformed into a collective one, and that can also be rearranged if the office moves to a new location).

- Design a family of furniture instead of single ones, with different properties and functions that enable adaptation.
- Include add-on parts to transform and/or upgrade function and properties of the furniture.
- Design for changeable ergonomic positions, e.g. height adjustable desk and chairs.
- Avoid premature aesthetic obsolescence by designing furniture that can be customized (e.g. exchangeable seat covers) or personalized with a corporate identity via software to avoid add-on brand identification operations (printing, adhesive plates, etc.).
- Consider designing multi-functional furniture that can adapt to the user's development (physical and cultural), such as changeable shapes or dimensions of sofa or bed.
- [Office seats] Design modular and on-site upgradable seats, allowing the user to substitute (with standard tools) fixed feet with wheels and/or fixed components to adjustable ones.
- [Office desks] Design modular and on-site upgradable desks, allowing the user to add (with standard tools) drawers, change drawer's typology, add inner cabling cabinets, etc.
- [storage] Design modular and on-site upgradable storage, allowing the user to add (with standard tools) shells, change drawer's typology, etc.
- Co-design furniture and connection platforms such as flooring, ceilings and walls.
- Include multiple connection possibilities on tables and storages, e.g. electricity cables, joints to combine table surfaces, etc.
- Provide website and/or app with instructions and tools to enable maintenance and repair by the user, such as periodic maintenance procedures, e.g. cleaning of hard surfaces (desk, storage), inspection, repair and lubrification (height-adjustable mechanism for office chairs or wheels).
- [Office desks] If related to tech devices, enable upgrading and design reconfigurable desks according to forecastable technology development, e.g. Wi-Fi system/wireless system of automated desks.

Guidelines for sub-strategy a3. design furniture for reliability

- Simplify the office furniture as much as possible, e.g. by reducing the number of components.
- Avoid weak connections, especially movable mechanisms such as fasteners joints between plastic components in chairs; use certified connectors (e.g. by CE).
- Design resistant furniture to prevent damage: use highly resistant materials for sensitive parts, e.g. edges of tables and cabinets, office seat back joints.
- Use highly resistant materials for handles, hinges and sliding mechanisms of drawers and storage furniture doors.
- [Office storage] If using glass doors, consider stratified glass.
- [Office desks] Avoid that table edges get quickly worn off.

Guidelines for sub-strategy a4. Facilitate/enable furniture re-use and remanufacturing.

- Facilitate the access for the removal of parts and components (such as expensive mechanisms) that can be remanufactured, e.g. use reversible connections or two-way snap-fits without glue within assemblies; use removable cover protection to interchange components between products by differentiating structural parts from surface ones.
- Facilitate the access for the removal of parts (especially expensive mechanisms) that can be re-used, such as chair (e.g. seats, wheels, tripod legs, covers) and storage locker components (e.g. hinges, metal, rubber feet, handles, locks).
- Use reversible connections or two-way snap-fits (avoiding whenever possible gluing in assembling processes), use removable cover protection to interchange components among objects (differentiate structure and surface).
- Facilitate disassembly, especially for parts that are easy to wear out such as task chair wheels and back, upholstery and desk surfaces, by using reversible connections or two-way snap-fits system.
- Facilitate the replacement of external parts, such as castors, sofa covers (clothes), upholstered chair.
- [Office desks] Facilitate the disassembly of tabletops from the supporting structure/legs.
- [Office seats] Facilitate the dismantling and substitution of upholstery/foam/ fabrics/leather of office seats.

- Design modular and interchangeable parts and components.
- Design standard parts and components that can be replaced, improve durability and facilitate easy repair, e.g. handles, screws, feet, shelves for storage lockers; wheels, bearings, screws, bolts, felt pads pillows, covers for chairs; pillows, felt, pads, feet for sofas.
- Increase the resistance of easy to wear-out or easy to damage parts by using more resistant materials.
- Increase the resistance of easy to wear-out or easy to damage parts by using protective removable layers, e.g. table edges, seat upholstery and fabrics, seat wheels, high adjustable mechanisms, armrest, table surfaces, storage shells; and by avoiding painting layers sensible to scratches.
- Foresee re-use of auxiliary parts, e.g. desktop divider as shelves, the protective cover of mechanisms as sofa pillows, writing board of conference chairs.
- Incorporate packaging that can be re-used by the manufacturer, e.g. by using packaging that can adapt to different products or by using foldable and more resistant packaging materials.
- Incorporate collapsible packaging.
- Design structural parts that can be easily separated from external parts, such as mechanisms and their protection parts, bookcases and doors.
- [Office seats] Facilitate the substitution of furniture upholstery fabrics/leather by designing easy removable slipcovers.
- Facilitate the substitution of movable parts, such as castors of furniture products, arm/backrest of chairs and height-adjustable mechanisms.
- Plan adequate tolerance or dimensioning at weak points, such as connection points or most used parts (e.g. storage corner joints, hinge and chair casters).
- Avoid self-tapping screws that can be screwed and unscrewed only a few times.
- Consider material abundance in points which are subject to wear and tear, e.g. abrasion of castors.
- Use a larger amount of finishing/coating materials on surfaces that tend to deteriorate rapidly (e.g. table or storage edges).

Guidelines for sub-strategy a5 intensify furniture use

- Design products with integrated functions, e.g. chairs that allow different positions, storage furniture with integrated locker.
- Design product-service systems for shared use.
- [Office storage] Consider storage furniture that is adaptable for different purposes, such as storage of personal belongings/eating (e.g. heating/cooling).
- [Office desks] Consider tables that are adaptable/customizable (e.g. exchangeable drawers for personal belongings).

Strategy 2 Reduce material consumption of furniture (HIGH priority)

In general, the designer has great influence on materials selection, giving him/her the responsibility to consider resources consumption when making such decisions. Regarding input flows, the strategy to reduce material consumption of furniture helps to save natural resources for future generations. The use of less materials also reduces environmental impacts due to fewer materials being extracted and processed, consequently saving also in terms of transportation and end-of-life.

Sub-strategies

- b1. minimize the material content of furniture
- b2. minimize scraps and waste
- b3. minimize or avoid furniture packaging
- b4. minimize material consumption during use

Guidelines:

Guidelines for sub-strategy b1. minimize the material content of furniture

- Dematerialize the furniture or some of its parts, such as handle systems in store component shapes with handle as "hole" embodied in locker door shape.
- Design suitable dimensions for structure parts, e.g. reduce the thickness of components according to material properties, resistance requirements and processing technology.
- Apply 3D printing in furniture, e.g. for chair backrest and handles.
- Avoid over-dimensioning by analysing the function, standard references and typical use of the furniture.
- Use reinforcing structures such as ribbed/honeycombed/rippled (e.g. for tabletop) structures or T-sections, hollow shapes (for rotationally moulded plastics and die-cast metals) to improve stiffness and avoid distortions.
- Take material reduction and structural reinforcement, such as rib reinforcements to reduce materials, into consideration especially regarding storage doors or desks.
- Avoid parts or components which are not strictly functional.
- Provide storage cabinets options with reduced components, e.g. with or without doors.

Guidelines for sub-strategy b2. minimize scraps and waste

- Prefer production processes that minimize scraps and waste, such as bent plywood instead of massive wood.
- Design tabletop, storage shelves and sides taking into consideration modularity and standardization to avoid leftovers.
- Select processing technology according to material properties and product requirements, such as die casting instead of moulding (e.g. for chair legs, etc.).
- Avoid waste in injection moulding plastic parts caused by excessive wall thickness.
- Apply 3D printing technologies when possible, e.g. for handles.

Guidelines for sub-strategy b3. minimize or avoid furniture packaging

- Use packaging material only where it is strictly necessary, e.g. protect with consistent packaging fragile parts of the furniture, such as glass tabletop, handles in locker storage, etc.

Guidelines for sub-strategy b4. minimize material consumption during use

- Design for the most efficient use of materials needed for maintenance, such as self-cleaning materials, materials that avoid/reduce the need of cleaning agents (e.g. water, soap, detergent), water repellent materials.

Strategy 3 Furniture materials life extension (MIDDLE priority)

The objective of this design strategy is to design products with the purpose of increasing the value of disposed materials. Extension of material lifespan due to recycling, composting or “clean” energy recovery leads to less landfilling as well as raw materials extraction for primary (new) materials production.

Sub-strategies:

- c1. Adopt the cascade approach for furniture
- c2. Select materials with the most efficient recycling technologies
- c3. Facilitate collection and transportation of disposed furniture
- c4. Identify furniture materials
- c5. minimize the number of non-compatible furniture materials and/or facilitate their separation

Guidelines:

Guidelines for sub-strategy c1. Adopt the cascade approach for furniture

- Facilitate and foresee closed-loop recycling of materials within components with lower aesthetic/formal requirements.
- Facilitate recycling of highly structural materials (e.g. wheels) into components with lower mechanical requirements (e.g. seat back).
- Facilitate recycling of massive wood into chipboard.
- Facilitate recycling of visible components into non-visible filling materials (e.g. chair or sofa pillows).
- Facilitate and foresee closed-loop recycling of materials within components with lower mechanical requirements.
- Avoid the use of contaminant materials, such as glued paper labels on the office furniture and glued natural fibres.
- Prefer label information that could be embedded in the injection process.
- Avoid painting or coating on polymers (e.g. for chair seat, arms, back) in favor of colored polymers.

Guidelines for sub-strategy c2. Select materials with the most efficient recycling technologies

- Select materials that recover more easily the original material characteristics after recycling.
- Adopt ribbed structures (or similar) to improve the stiffness of polymers instead of using reinforcing fibres, e.g. Nylon reinforced with glass fibres (PA-GF) as often involved in office chairs [office chair].
- Prefer thermoplastic polymers instead of thermosetting.
- Avoid composite materials such as sandwich laminates (e.g. for tables or storage shelves) or fiber-based components (e.g. for chairs) in favor of monomaterial solutions (metals or polymers).
- Avoid the use of fireproof additives by selecting thermoplastics that resist to high temperatures.

Guidelines for sub-strategy c3. facilitate collection and transportation of disposed furniture

- Design furniture considering the existing recycling systems, e.g. urban waste collection system.
- Reduce product dimension and foresee easy stocking of disposed furniture products.
- Facilitate the disassembly of furniture junctions.

- Design chair, tables and storage shapes according to stoking standards
- Design stackable chairs, foldable tables or compactable storage.
- Facilitate the design of components for easy stocking, e.g. tabletops, shelves.
- Reduce the weight of the furniture components/materials.
- Design furniture that is able and easy to be compressed when disposed.
- Inform the user about how the furniture or its parts can be disposed of.

Guidelines for sub-strategy c4. identify furniture materials

- Codify materials according to their type.
- Add information on material age, conducted recycling processes and additives use.
- Indicate the presence of toxic residues and contaminant materials.
- Apply identification codes in places visible during the disassembly, e.g. near joints, places not subjected to wear out, on flat surfaces.
- Use international standard identification systems, such as SPI codes, especially when open-loop recycling may occur.

Guidelines for sub-strategy c5. minimize the number of non-compatible furniture materials and/or facilitate their separation

- Use one single material on a furniture product or one single material to produce each one of its parts, if possible (mono-material strategy).
- Avoid the use of contaminant materials, such as adhesives for labels.
- If necessary, facilitate the removal of contaminant materials, such as water-based adhesives for labels.
- Use compatible materials that could be recycled together with the furniture or its subassembly (for polymers compatibility see Tab.1).
- Use joints made of the same or with compatible materials to the parts that need to be joined.
- Facilitate the sorting process in wood recycling.
- Facilitate the separation of bolts, nuts, screws and other small parts that are made of non-compatible materials, e.g. metal joints over plastic components.
- [Office seats] Consider castors with cores made of one material and that enable the easy disassembly of the outer rubber part.

Strategy 4 Reduce toxicity of the furniture system (LOW priority)

Materials and additives with toxic and harmful emissions should be avoided as well as energy resources with dangerous emissions.

Sub-strategies:

- d1. Select materials without or with the lowest toxicity/harmful potential
- d2. Select energy sources without or with the lowest toxicity/harmful potential

Guidelines:

Guidelines for sub-strategy d1. select materials without or with the lowest toxicity/harmful potential

- Avoid the use of toxic and harmful materials for office furniture products, such as toxic paintings, additives, adhesives or refinements for table-tops/edges, storage surfaces or chair joints.
- Prefer water-based varnishing, additives, adhesives or refinements for all components of furniture.
- Avoid the use of additives and adhesives causing toxic and harmful emissions.
- Avoid toxic and harmful finishing processes/materials, such us formaldehyde and chromium plating.
- Minimize the dispersion of toxic and harmful residues during furniture's use, such as Volatile Organic Compounds (VOC) emissions.
- Use low emission polyurethane or latex foam padding materials.
- Select Polyurethane foam complying with the requirements for VOC emissions.

Guidelines for sub-strategy d2. select energy sources without or with the lowest toxicity/harmful potential

- Select energy resources that minimize toxic/harmful emissions during pre-production and production, such as electricity coming from renewable sources instead of fossil fuels.
- Select energy resources that minimize toxic/harmful emissions during distribution, such as electric vehicles.
- Select energy resources that minimize toxic/harmful emissions in End-of-life treatments, e.g. avoid furniture moving mechanisms with heavy metals batteries.

Strategy 5 Reduce energy consumption of the furniture system (LOW priority)

This strategy aims to minimize energy consumption during the pre-production, production and use phases as well as during transportation (including transportation of the materials, transportation of the product and related processes). The designer can especially intervene in the selection of materials and production processes with low levels of energy consumption.

Sub-strategies:

- e1. minimize energy consumption in pre-production and production phases
- e2. minimize energy consumption in the transportation phase
- e.3 minimize energy consumption in the use phase

Guidelines:

Guidelines for sub-strategy e1. minimize energy consumption in pre-production and production phases

- Design for local-focused resources supply, such as energy generated by local renewable systems (e.g. photovoltaic systems, wind turbines, geothermal systems, hydroelectric systems).
- Design for energy consumption efficiency, such as planning a production process shared by different furniture components.
- Prefer materials with low energy consumption in pre-production and production, e.g., recycled aluminum instead of primary aluminum.
- Prefer packaging processing technologies with low energy consumption levels.

Guidelines for sub-strategy e2. minimize energy consumption in the transportation phase

- Design compact or compactable furniture, favoring high-density storage.
- [Office seats] Design stackable visitor chairs or components.
- Design for on-site furniture assembly.
- Minimize furniture’s weight, especially non-structural elements.
- Choose lighter materials compared to others with the same functional properties.
- Reduce packaging weight/volume to reduce resource consumption in transportation.

- Prefer container ships and trains rather than truck transportation for furniture distribution.
- Optimize logistics to reduce the distance between providers and users.

Guidelines for sub-strategy e.3 minimize energy consumption in the use phase

- Favour mechanical devices instead of electric-powered devices, e.g., for adjustable office seats.
- Prefer cleaning processes that avoid energy-consuming equipment.
- Avoid internet-based manuals and instructions for furniture assembling, maintenance, etc.

Strategy 6 Resources conservation/biocompatibility (LOW priority)

To save resources for future generations, prefer renewable and nonexhaustible materials and energy resources. Bio-compatible materials should also be considered as they reduce soil, water, and air contamination.

Sub-strategies:

- f1. Select renewable/nonexhaustible and/or biocompatible materials for furniture.
- f2. Select renewable/nonexhaustible and/or biocompatible energy resources for furniture.

Guidelines:

Guidelines for sub-strategy f1. Select renewable/nonexhaustible and/or biocompatible materials for furniture.

- Avoid materials from exhaustible resources.
- Favor the use of highly renewable materials.
- Choose certified timber for furniture production, such as FSC 28 and PEFC29.
- Use materials derived from other production processes, such as chip wood scraps from massive wood production (e.g., table-tops) or fabric for chair upholstery taken from furniture production waste (e.g., sofa).
- Use components from disposed products, such as handles, joints, and mechanisms, e.g., use height and armrest regulation of chairs/desks as cable holders for desks.

- Use recycled materials or recycled materials combined with new materials (e.g., mixtures for injection molding consisting of recycled plastic and recycled wood chips).

Guidelines for sub-strategy f2. Select renewable/nonexhaustible and/or biocompatible energy resources for furniture

- Select renewable/nonexhaustible energy resources.
- Select small-scale local energy resources.

Strategy: 7 Design for furniture disassembly

Sub-strategies:

- g1: Reducing and facilitating operations of furniture disassembly and separation
- g2: Design and/or co-designing special technologies and features for furniture separation

Guidelines:

guidelines for sub-strategy g1: reducing and facilitating operations of furniture disassembly and separation

- Prioritize the disassembly of toxic and dangerous components or materials
- Prioritize the disassembly of components or materials with higher economic value, such as metal mechanisms or wood panels.
- Prioritize the disassembly of more easily damaging or consumable components and materials, such as table tops, bookshelves, etc.
- Prefer modular structures, such as modular closets, sofas, etc.
- Construct the product into easily separable and manipulatable sub-assemblies, such as bookshelves/wardrobes with inner panels.
- Facilitate the removal of other components like handle.
- Minimize the overall dimensions of furniture.
- Minimize the number of different components.
- Minimize hierarchically dependent connections among components, such as the mechanisms of the task chair.

Guidelines for sub-strategy g2: design and/or co-designing special technologies and features for furniture separation

- Co-design cutting or breaking paths with appropriate separation technologies for separating incompatible materials.
- Suggest to the users how and with what device they could separate incompatible materials.
- Provide information to the user together with the furniture about the characteristics of crushing separation, such as providing video resources online (website, app).

All furniture-specific LCD guidelines were eventually integrated into one of the main outcomes of the GIOTTO project - the MIUR manual "Handbook for sustainable furniture system design", which was conceived as an operative tool to enhance the application of the furniture Life Cycle Design, specifically aimed at guiding designers and companies toward environmentally sustainable furniture design and innovation. The handbook is available and open access on LeNS International's 'tools' section (http://www.lens-international.org/).

7.1.4 Conclusions

The principal contribution of this research lies in the formulation of a comprehensive set of furniture-specific Life Cycle Design (LCD) strategies, sub-strategies, and associated guidelines that incorporate best practices (the incorporation shows within each case, see annex 2). The primary innovation centers on the creation of 23 furniture-specific sub-strategies and 154 guidelines, significantly mitigating environmental impact across the entire life cycle of furniture products.

A secondary innovation arises from the assignment of priorities to each strategy, reflecting the level of environmental impact reduction attainable through their implementation. This prioritization holds importance in improving the efficiency of the design process.

Currently, a handbook encompassing all these outcomes is being disseminated globally through the Learning Network on Sustainability (LeNS). LeNS is an international community connecting over 150 higher education institutions and organizations. Its overarching mission is to advance the discipline of Design for Sustainability (DfS) across worldwide curricula, guided by an ethos of openness, collaboration, and copyleft principles. Furthermore, the handbook is being integrated into international master courses while also undergoing refinements and enhancements aimed at fostering a collaborative and open innovation paradigm within the furniture industry.

While the concept of open innovation has become well-established and widespread across various domains (Gassmann et al., 2010), the same cannot be universally said for sustainable furniture knowledge innovation. This handbook holds the potential to serve as a vital resource for designers and organizations, offering support for the incorporation of sustainable choices during the preliminary stages of the design process.

It is important to note that while these strategies, sub-strategies, and guidelines have been devised for general furniture applications, the optimization of their effectiveness in real-world design practice may necessitate specific guidelines tailored to each furniture category. As the outcomes of this research are accessible through open access, other research groups and companies can devise more tailored guidelines for individual furniture types.

7.2 The development of furniture-specific Sustainable Product-Service System Design (S.PSSD) guidelines

Chapter 7.1 described the process and results of furniture-specific LCD guidelines. However, considering the increasing production and consumption values of furniture worldwide, it is not enough to design only sustainable furniture products. Like many other sectors, the transformation requires radical changes and a discontinuity in consumption and production patterns (L. I. Chaves, 2017). Specifically, even if a piece of furniture is very sustainable, if the Product-Service System is not well designed for sustainability, for example, the furniture is discarded after only a short period of time due to different reasons, the system is not sustainable. This could be dealt with using S.PSSD strategies and guidelines.

Within this framework, the paper presents furniture-specific S.PSSD guidelines which were developed through an established methodology involving scholars and specialists on both Design for Sustainability and Furniture Design as the product level. In this sense, these guidelines will promote long-term open innovation and technological transformation of furniture S.PSS, allowing designers and organizations to support the implementation of sustainable options from the beginning of the design process.

7.2.1 Method

This part of the research follows the same method as the product level, using the method for The development of type-specific guidelines based on general (L. I. Chaves, 2008; Vezzoli & Sciama, 2006), as depicted in Figure 62.

7.2.1.1 1st step: Preliminary study (chapter 6)

The study started with a preliminary phase of desk research to uncover the most updated knowledge about the environmental impact of the furniture system with a literature review (chapter 1.1). In addition, a detailed analysis of best practices and semi-structured interviews from an environmental standpoint (chapter 6) were conducted to provide inspiration for subsequent collaborative sessions when elaborating on furniture-specific S.PSSD guidelines. Results from these research actions formed the framework to facilitate the successive step, aimed at moving from general S.PSSD strategies and guidelines toward the development of the furniture-specific version to reduce the overall environmental impact of the furniture system.

7.2.1.2 2nd step: workshop

The specification process was carried out firstly by the Ph.D. candidate based on the general S.PSSD strategies and guidelines. New insights from literature review, case studies and semi-structured interviews were integrated along the process. Please see Figure 70 for a more specific example of the shift from general to furniture-specific S.PSSD guidelines. A draft version of furniture-specific S.PSSD strategies and guidelines was developed and reviewed and further developed through a collaborative workshop that involved scholars and experts on Design for Sustainability and Furniture Design, with the goal of validating this knowledge. The outcome of the workshop was the first version of furniture-specific guidelines, which was further reviewed and refined to integrate final improvements.

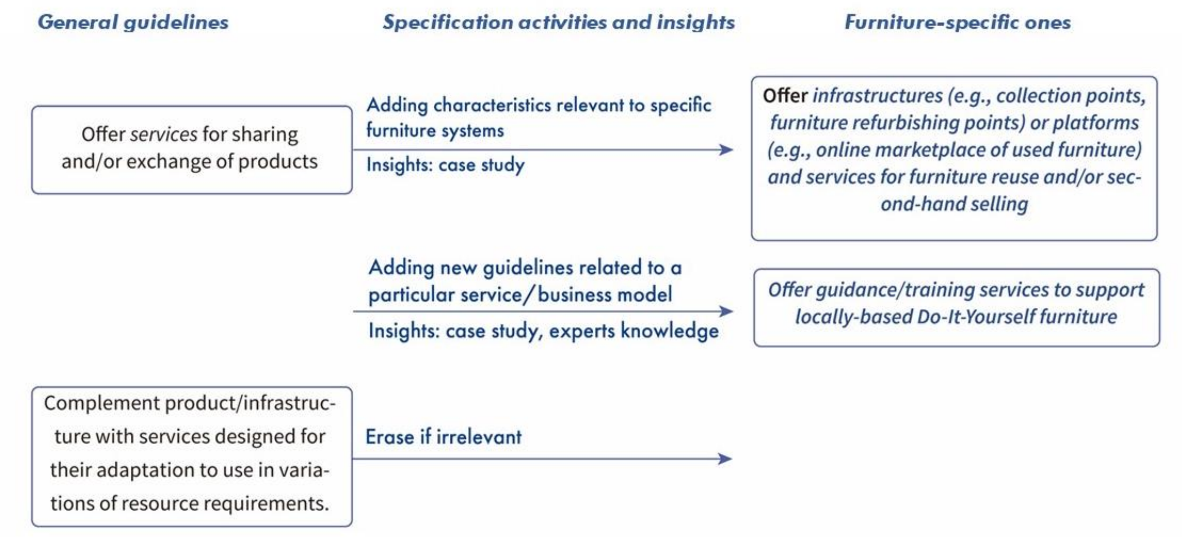


Figure 70 An example of developing furniture-specific guidelines from general ones

7.2.1.3 3rd step: iterative revision and improvement of these guidelines

Following the conclusions of the workshop, the first version of furniture-specific S.PSSD guidelines was created. This first version was subjected to revision primarily by experts in the field of Design for Sustainability and Furniture Design. This resulted in the final version of the furniture-specific S.PSSD guidelines.

Following the revision process, the guidelines were integrated into a toolkit (which is described in the next chapter). The application and evaluation of this toolkit provided an opportunity for peer review and scholarly critique of the toolkit and these guidelines, further enhancing the robustness of the knowledge.

7.2.1.4 The involvement of the author and other participants

Design-based research is a systematic, yet flexible methodology aimed at enhancing practices through iterative analysis, design, development, and intervention implementation. It relies on collaboration among researchers and practitioners in real-world settings, resulting in contextually sensitive design principles and theories.

The author conducted preliminary research encompassing literature reviews, case study analyses, and the development of the draft version of the furniture-specific S.PSSD guidelines. This study involved other researchers and practitioners for the reviewing and validation of the draft guidelines to form the final version.

7.2.2 Furniture-specific Sustainable Product-Service System Design Guidelines

- Furniture System life optimization
- Transportation/distribution reduction in the furniture system
- Minimize resource consumption in the production stage
- Furniture system waste minimization/valorization
- Resources conservation/biocompatibility in the furniture system
- Furniture system toxicity reduction

Strategy 1: Furniture System life optimization

- Complement furniture with all-inclusive services for design or co-design
- Complement furniture with all-inclusive services for maintenance and repair
- Complement furniture with all-inclusive services for temporary replacement and reconfiguration
- Complement furniture with management service to avoid furniture sitting idle
- Complement furniture with services for a technological upgrade, e.g., adjustable desks and task chairs, power and data hubs
- Complement furniture with services for ergonomics adjustment, e.g., task chairs
- Complement furniture with services for aesthetic/cultural upgrades, e.g., by providing refurbish services or providing design advice to help customers upgrade their furniture
- Complement furniture with services that enable the adaption in new locations/new interiors, e.g. through design and refurbishment services
- Complement furniture offers with all-inclusive take-back services aimed at re-using or re-manufacturing
- Offer services for shared use of ownerless furniture paid-per-period or paid-per-use, e.g. co-working and co-living
- Offer services for shared ownership of furniture or furniture system, e.g., collective purchase and use of furniture or furniture system in public space by multiple users
- Offer services for furniture sharing and/or exchanging

- Offer infrastructures (e.g., collection points, furniture refurbishing points) or platforms (e.g., online marketplace of used furniture) and services for furniture reuse and/or second-hand selling

Strategy 2: Transportation/distribution reduction in the furniture system

- Furniture producer/provider uses digital channels to offer information/guidance services for furniture purchase, installation, repair, maintenance, and upgrade
- Furniture producer/provider creates partnerships with locally-based furniture care service providers to offer all-inclusive services, including assembly, maintenance, repair, reconfiguration, upgrade, and end-of-life collection/treatment, etc.
- Furniture producer/provider creates partnerships with locally-based acknowledged suppliers of resources for furniture pre-production, production, distribution, maintenance, repair and upgrade
- Furniture developer/designer creates partnerships with local furniture manufacturers for local production and delivery (e.g., a decentralized manufacturers network)
- Merge the furniture offer with all-inclusive services, tools, and support for on-site assembly
- Furniture producer/provider creates partnerships with retailers and other stakeholders to reduce/avoid packaging, either tertiary, secondary, or primary
- Furniture producer/provider creates partnerships to reduce or avoid transportation/packaging of semi-finished products, e.g., partnerships with component suppliers and manufacturers
- Offer furniture with reusable/returnable packaging
- Merge furniture/semi-finished furniture with all-inclusive service for transportation to optimize distribution
- Offer remote support and status monitoring of activities and interventions to be carried out on-site by the user related to furniture maintenance, repair, upgrade, and/or end-of-life collection/treatment
- Offer guidance/training services to support locally-based Do-It-Yourself furniture

Strategy 3: Minimize resource consumption in the production stage

- Offer access to resource-saving furniture manufacturing spaces, equipment, and facilities (enabling platform) with advanced technologies through pay-per-period/pay for a specific function

- Create partnerships/networks to use/integrate/complement existing furniture infrastructures, e.g., 3D printers and CNC machines for furniture manufacturing
- Outsource activities when higher scale economies are feasible or higher specialization and technological efficiency of furniture components when available, especially standard components
- Offer furniture/semi-finished furniture based on pre-determined demand aimed at avoiding unsold inventory and/or surplus production

Strategy 4: Furniture system waste minimization/valorization

- Complement furniture offer with all-inclusive take-back services aimed at recycling
- Complement furniture offer with all-inclusive take-back services aimed at (low-impact) energy recovery
- Create local partnerships aimed at a symbiotic/cascade approach for recycling disposed furniture or waste into products with lower requirements in other sectors, e.g., sawdust as raw materials for fiberboard or for flower pot

Strategy 5: Resources conservation/biocompatibility in the furniture system

- Engage material suppliers for renewable materials in the furniture system
- Engage local energy suppliers who offer ownerless solutions with access to on-site renewable energy systems as well as all-inclusive services, including design, installation, maintenance, and repair, etc., for the functioning of the furniture system‘s pre-production and production phases
- Create partnerships that enable/increase the use of recycled materials in the furniture system from disposed products of other sectors

Strategy 6: Furniture system toxicity reduction

- Complement furniture material offered with services that minimize/treat toxic or harmful emissions of processes along furniture production, e.g., recycling of paints from the painting process
- Complement furniture offer with all-inclusive end-of-life treatments of toxic or harmful substances, e.g., treatment of painting components/glue-contained components
- Create partnerships with other producers to reuse or recycle toxic/harmful by-products

7.3 Who are these guidelines for?

The focus of DfS has progressively expanded from single indicator products to complex systems (Ceschin & Gaziulusoy, 2016). This has been accompanied by an increased development of knowledge.

In the furniture industry, some sustainable furniture product design strategies have been proposed (Krystofik et al., 2018), such as reducing material content (Ika Rinawati et al., 2018) and selecting resources with lower environmental impacts (Iritani et al., 2015). However, the focus remains mainly on single-indicator innovation, which is insufficient for addressing the complexity of sustainable challenges in the furniture industry. In other words, there is a lack of comprehensive furniture LCD approaches, strategies, and guidelines. Furthermore, there is limited research that provides solutions for the trade-offs among different LCD strategies, i.e., furniture-specific LCD strategy priorities. Regarding furniture S.PSSD, existing studies focus on either environmental sustainability or economic prosperity without considering win-win solutions that benefit both the economy and environment (Park et al., 2016). To develop sustainable win-win solutions for furniture S.PSSD, it is necessary to expand the knowledge base and know-how of DfS applied to furniture. In conclusion, while the importance of design and system innovation for sustainability is acknowledged, the approved knowledge base and know-how for DfS applied to furniture are quite limited.

These furniture-specific design guidelines featured in this chapter are partial outcomes of the research activities conducted during a Ph.D. program and consultancy experiences undertaken by the LeNS Lab POLIMI. The purpose of this research is to address the relationship between the practical industry and the academic field.

These guidelines aim to support various stakeholders involved in sustainable furniture system design, including researchers, teachers, students, designers, design studios, furniture companies, NGOs, and other interested organizations. Researchers working on sustainable furniture system design projects can adapt these guidelines to their specific contexts and objectives, whether focusing on a particular country, industry area, typology, furniture company, design studio, etc. For educational purposes, the guidelines and cases can help students gain a deeper understanding of sustainable furniture products and S.PSS.

Chapter 8 The Development of furniture-specific Design Know-how: method and tools

8.1 The Development of a Method for Environmentally Sustainable Furniture System Design

In order to develop environmentally sustainable furniture systems, it is necessary to have consolidated methods and tools that can help users understand the environmental priorities of existing systems and adopt appropriate design strategies and guidelines. Compared to general design process, incorporating environmental requirements makes the design process more complex but ultimately yields valuable results. Within this framework, designers require consolidated knowledge and decision-supporting tools to accomplish the following objectives:

- Assessing the environmental impact of the existing furniture system and identifying the priorities for the design interventions.
- Orientating the design innovations and decisions towards lower environmental impact solutions.
- Evaluating the potential environmental improvements of new solutions.

The development of Method for Environmentally Sustainable Furniture System Design referred to the Method for Product Design for Sustainability (MPDS) and the Method for System Design for sustainability (MSDS) since these two methods are consistent with ISO14046 and with many years of application and improvement in practical projects, as depicted in chapter 2.3.

The Method for Environmentally Sustainable Furniture System Design combines the typical product and PSS Design method (process) with furniture-specific sustainable design steps. The proposed method is defined along four stages of furniture product and furniture Product-Service System design:

Strategic analysis/design brief

This stage aims at collecting information to understand the existing context and processing it into insights to steer the exploration of promising furniture products/S.PSS solutions.

Concept design

This stage aims to develop and select the most promising furniture product and service concepts, identify innovative potential directions for the development of valuable solutions that involve/consider all stakeholders in the value production chain.

Detailed design (and engineering)

This stage aims at developing the details of the project to enable the implementation of the solution, such as detailed furniture production processes/materials and detailed interaction between stakeholders within the furniture S.PSS.

Communication

This stage aims at drawing up documents to communicate the sustainability characteristics of the final furniture system solution designed.

Along with the abovementioned process, the proposed Method for Environmentally Sustainable Furniture System Design presents processes for both the Product-Service System level (based on the Method for System Design for Sustainability, MSDS, Vezzoli et al., 2021) and the product level (based on the Method for Product Design for environmental Sustainability, MPDS, Vezzoli, 2008).

The Method for Sustainable Furniture System Design is a modular method. For a comprehensive Sustainable Furniture System Design project, users could start from the sustainable furniture product design process (left part marked with orange color) or the furniture S.PSS design process (right part marked with blue color). For a specific project that focuses on either sustainable furniture products or furniture S.PSS design, users could conduct one process.

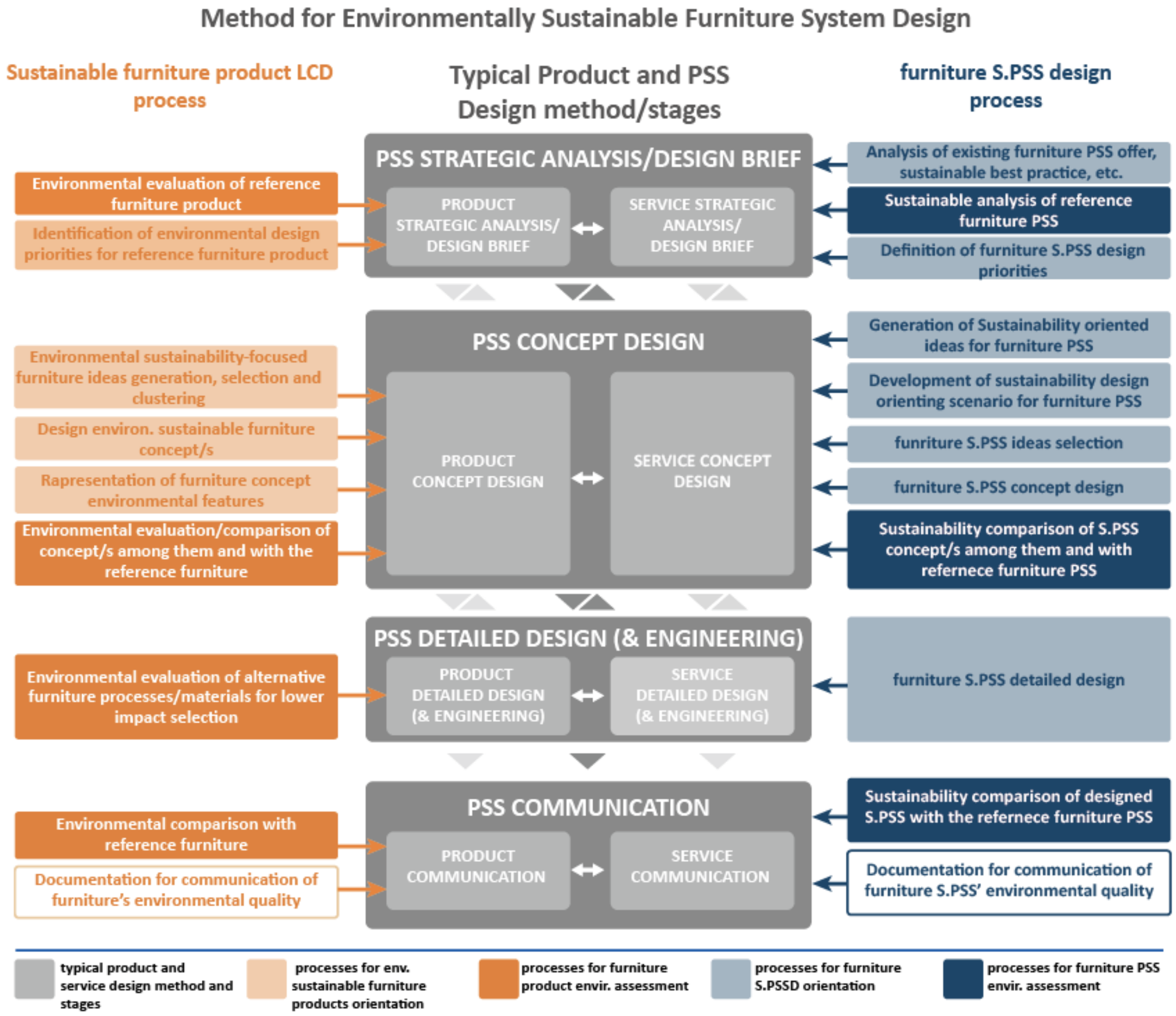


Figure 71 The Method for Environmentally Sustainable Furniture System Design, integrating furniture-specific sustainable product & S.PSS design processes within the typical design method (process).

8.1.1 Method for Sustainable Furniture Product Design

The Method for Sustainable Furniture Product Design described below aims to integrate sustainability into furniture Life Cycle Design using consolidated tools (the ICSxfurniture Toolkit which is described in detail in chapter 8.2). The method has a modular structure, so it can be easily used for specific design requirements or diverse design contexts and even integrated into other design procedures. However, for optimal efficiency and sustainability, it is recommended that designers adopt the method and tools from the very beginning of the design process. A detailed description of the sustainable furniture product design steps, aims, and tools related to each design stage is provided in the following table.

Table 38 The Method for Sustainable Furniture Product Design aims, steps, and tools.

Process	**Aim**	**Stages**	**Tools**
Furniture product strategies analysis/design brief	To identify the environmentally critical areas and the LCD strategies with the greatest potential for reducing the environmental impact of the furniture product (functional unit)	. Environmental evaluation of reference product . Identification of environmental design priorities	• LCA software • Checklist for existing furniture evaluation (ICSxfurniture toolkit) • Multi-strategy Radar (ICSxfurniture toolkit)
Furniture product concept design	To orient the generation of ideas towards environmentally sustainable solutions	. Environmental sustainability-focused ideas generation, selection, and clustering	• Eco-idea boards (ICSxfurniture toolkit) • Multi-strategy Radar (ICSxfurniture toolkit)
	To design promising environmentally sustainable concept/s	. Design environmentally sustainable concept/s . Representation of concept environmental features	• Life cycle exploded diagram
		. Environmental evaluation/comparison of concept/s among them and with the reference product	• LCA tools • Checklist for concept improvement evaluation/LCD strategies pursuit evaluation (ICSxfurniture toolkit)
Furniture Product detailed design (& engineering)	To orient the design of project details toward the most environmentally sustainable solutions	. Environmental evaluation of alternative processes/materials for lower-impact selection	• LCA tools

Communication	To communicate the environmentally sustainable benefits and characteristics of the newly designed furniture product	. Environmental comparison with reference products . Documentation for communication of environmental quality	• LCA tools • Checklist for concept improvement evaluation/LCD strategies pursuit evaluation (ICSxfurniture toolkit)

8.1.2 Method for Sustainable furniture Product-Service System Design (furniture S.PSSD)

The method for furniture S.PSSD is presented below with the goal of integrating and supporting the design process towards win-win environmentally and economically sustainable solutions with consolidated tools (the SDOxfurniture Toolkit which is described in detail in chapter 8.3). Similar to the product part, this method has a modular structure, and it can be easily adapted to specific design requirements, diverse design contexts, and other design procedures. However, to gain the highest efficiency and sustainability, it is recommended to adapt the method with tools at the very beginning of design.

Table 39 The Method for Sustainable Furniture PSSD aims, steps, and tools.

process	**Aim**	**stages**	**tools**
Furniture S.PSS strategies analysis/design brief	To obtain the information necessary to facilitate the generation of sustainable system innovation ideas	. Analysis of sustainable best practice . Sustainable analysis of reference PSS . Definition of S.PSS design priorities	• Innovation diagram x furniture • Environmental analysis Checklist (SDOxFurniture toolkit)
Furniture S.PSS concept design	To make a ‘catalog’ of promising strategic possibilities available or, in other words, a sustainability design-orienting scenario and/ or a set of sustainably promising system ideas	. Generation of Sustainability-oriented ideas for furniture S.PSS . Furniture S.PSS ideas selection	• Idea boards (SDO×furniture toolkit) • Radar diagram (SDO×furniture toolkit)

	To develop one or more system concepts oriented toward sustainability	. Furniture S.PSS concept design . Development of sustainable furniture design orienting scenario	• Innovation diagram x furniture S.PSS
		. Sustainability comparison of furniture S.PSS concept/s among them and with reference to PSS	• Environmental analysis Checklist (SDO×furniture toolkit) • Radar diagram (SDO×furniture toolkit) • LCA tools
Furniture S.PSS detailed design (& engineering)	To develop the most promising system concept into the detailed version necessary for its implementation	. Furniture S.PSS detailed design	• System mapxFurniture S.PSS
Communication	To draw up reports to communicate the general and, above all, sustainable characteristics of the system designed	. Sustainability comparison of designed furniture S.PSS with the reference PSS . Documentation for communication of environmental quality	• Environmental analysis Checklist (SDO×furniture toolkit) • LCA tools • System mapxFurniture S.PSS

8.2 Furniture Product LCD Tools Adaptation/Design and Prototyping

A comprehensive analysis was conducted on 120 tools originating from 29 different institutions and 58 publications (Chapter 2.3). One aim was to identify the potential application of these general tools for furniture, while another aim was to identify gaps in tools for furniture system design. The results revealed that there are tools for complete or simplified Life Cycle Assessment (LCA), dedicated tools for specific environmental performance (such as materials selection), and tools for description. However, there is a lack of Qualitative Evaluation Tools and design tools for both furniture Life Cycle Design (LCD) and furniture S.PSSD.

The development of furniture-specific system design tools drew upon the functionalities of the general ICS toolkit and SDO toolkit for several reasons:

- These tools were developed as part of European Union-funded projects and the Lens Network. They have undergone verification by collaborators from approximately 150 universities.
- These tools integrate functions crucial for qualitative assessment, sustainability design orientation, and improvement comparison. These functionalities are significant in the development of sustainable projects (Vezzoli and Manzini, 2007, p. 210) and can support the entire design process from strategic analysis to concept design, detailed design, and communication.
- Their modular nature allows the integrated tools to be used either sequentially or separately.
- The new knowledge developed within this research, including the Life Cycle Assessment (LCA) data, the developed guidelines, the cases, and the archetypal furniture S.PSS map, can be seamlessly integrated into these tools to support furniture system design.

In conclusion, the prototyping of furniture-specific tools follows the structures and functions of the general ICSxToolkit and the SDOxToolkit. New efforts encompass the specification of knowledge integrated into the tools for furniture (Chapter 5-7), the optimization of functions of general ones, the optimization of the sequence of operation, the optimization of using steps, and the optimization of layouts. The results are detailed in the following chapters.

8.2.1 ICS x Furniture Toolkit

The ICSxFurniture toolkit is designed to provide guidance at the early stages of furniture product development, with the aim of promoting environmentally sustainable solutions. The toolkit is grounded in comprehensive knowledge and practice, specifically, 7

Sustainable Furniture product life cycle design strategies, 23 sub-strategies, 154 guidelines, and 41 best cases. These 7 furniture-specific Product Life Cycle Design strategies are:

- Furniture use extension/intensification (HIGH PRIORITY)
- Reduce material consumption of furniture (HIGH PRIORITY)
- Furniture materials life extension (MIDDLE PRIORITY)
- Reduce toxicity of the furniture system (LOW PRIORITY)
- Reduce energy consumption of the furniture system (LOW PRIORITY)
- Resources conservation/biocompatibility (LOW PRIORITY)
- Design for furniture disassembly

The furniture-specific ICSxFurniture toolkit, as the furniture-specific LCD guidelines was developed as a part of the GIOTTO project, which focused on Circular Economy for enhancing the competitiveness of value chains within the "Made in Italy" sector. This project was funded by the Italian Ministry of Education and Research (MIUR). Within this project, I conducted the preliminary research (chapter 1 and chapter 5), and developed the toolkit.

The ICSxFurniture toolkit is built upon a spreadsheet file that incorporates 4 inter-connected tools enabling seamless navigation among them, see Figure 72, includes:

- Checklist for existing furniture Evaluation (6 checklists, one for each strategy);
- Eco-idea boards (6 boards, one for each strategy);
- Checklist for concept improvement/furniture LCD strategies pursuit evaluation (3 levels of detail: strategy level-simplified, sub-strategy level-normal, guideline level-deep);
- Muti-strategy Radar;

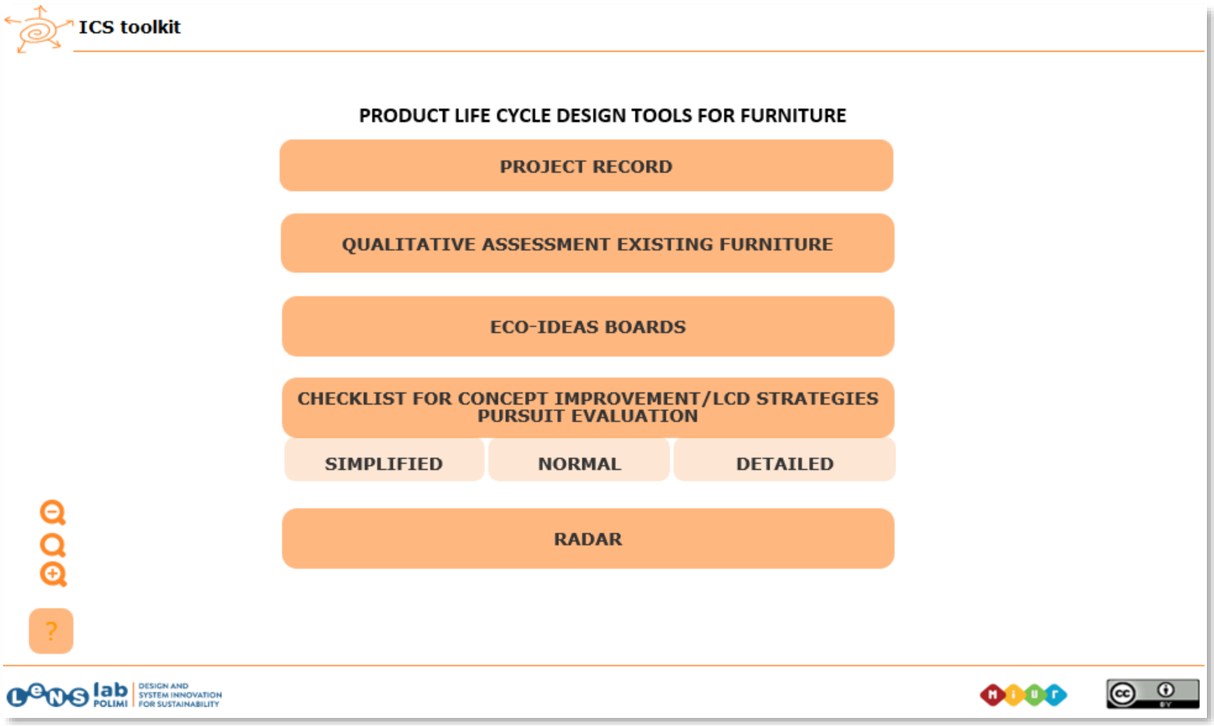


Figure 72 The homepage that navigates among 4 tools

The suite of tools offered by the ICSxFurniture toolkit, though diverse in their specific functionalities, are designed to collectively facilitate the development of sustainable furniture products. Comprising several tools tailored to various design stages, this modular toolkit offers users the flexibility to select and employ tools based on their unique project requirements. The succeeding paragraphs outline each tool in detail, providing insight into their respective aims, components, usage procedures, and integration within the design method.

8.2.2. Checklist for the Existing Furniture Evaluation (ICS x Furniture Toolkit)

Aim

The objective of the tool is to assess the environmental impact of the existing furniture with a qualitative approach. The ultimate goal is to identify the level of priority for each of the six furniture Life Cycle Design strategies, i.e., the degree of environmental improvement potential by employing each strategy.

Components (Figure 73)

1. 6 checklists, one for each furniture LCD strategy;
2. A navigator to move from one checklist to another;
3. A list of environmentally-focused questions associated with furniture for each strategy;
4. A space to record the environmental analysis results for reference furniture;
5. A drop-down menu to select the level of priorities to be assigned to each strategy;
6. The visual representation of assigned priority for each design strategy.

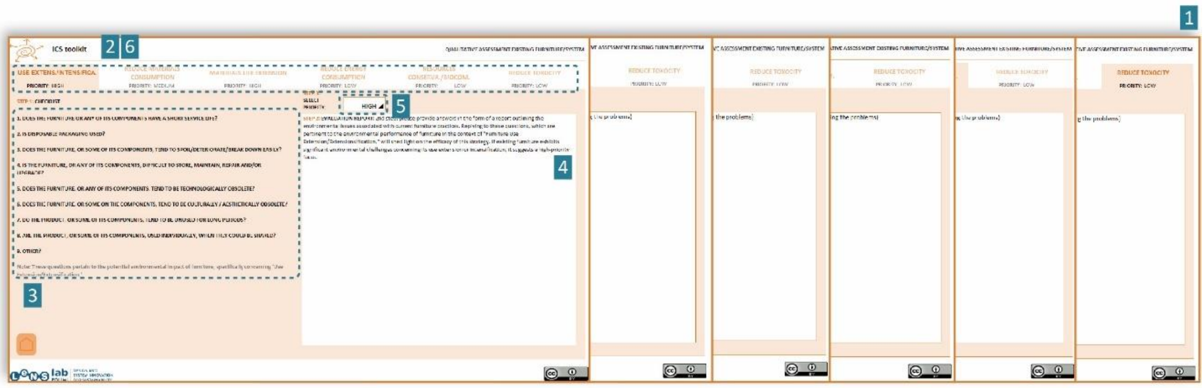


Figure 73 The components for Checklist for the Existing Furniture Evaluation_ICS x Furniture Toolkit

How to use the tool (Figure 74)

1. To access the tool, click on ‘qualitative assessment existing product/system’ on the home page.
2. Start from the first checklist (for the strategy ‘Furniture use extension/intensification”) and read each question in sequence;
3. Answer these questions to evaluate the existing furniture product;
4. Repeat this process for all six strategies to obtain a comprehensive and detailed overview of how environmental impact is allocated;
5. Identify the relative priorities for each strategy with the drop-down list by choosing no, low, medium, or high priority.

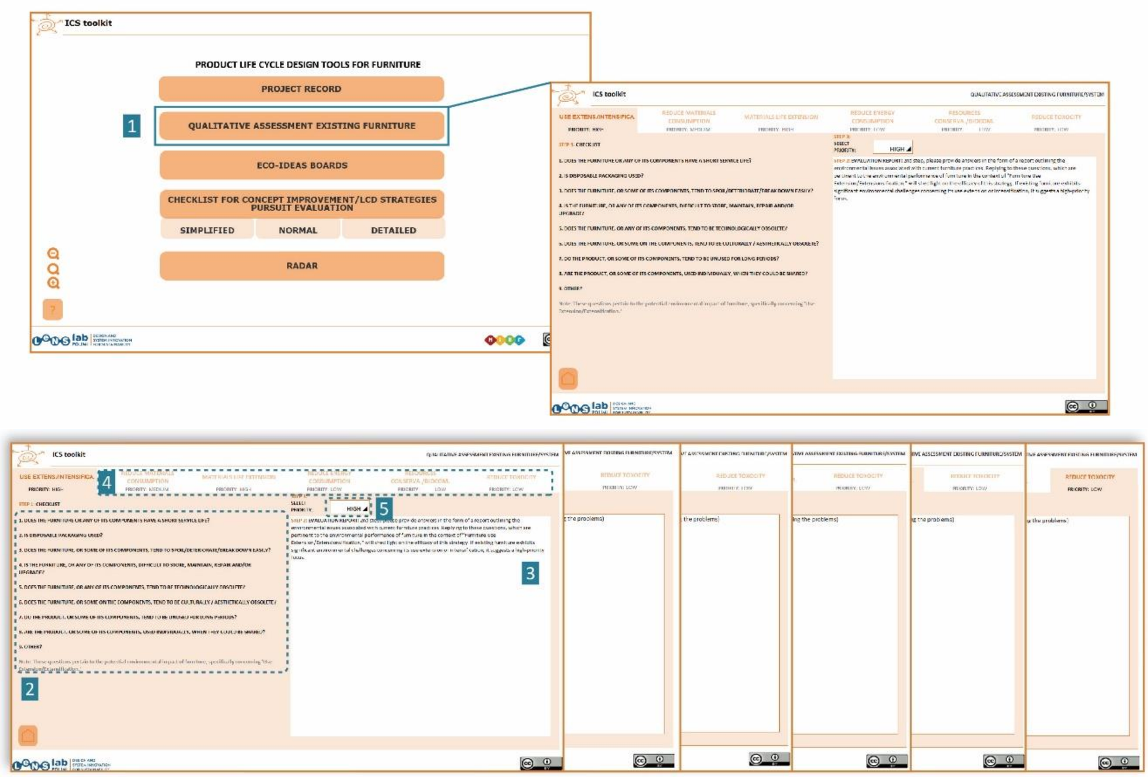


Figure 74 The steps for Checklist for the Existing Furniture Evaluation_ICS x Furniture Toolkit

Tool's integration into the design process

The checklist is supposed to be integrated into the 'furniture product strategic analysis' stage to evaluate the environmental impact of reference furniture and subsequently to prioritize the environmental design strategies.

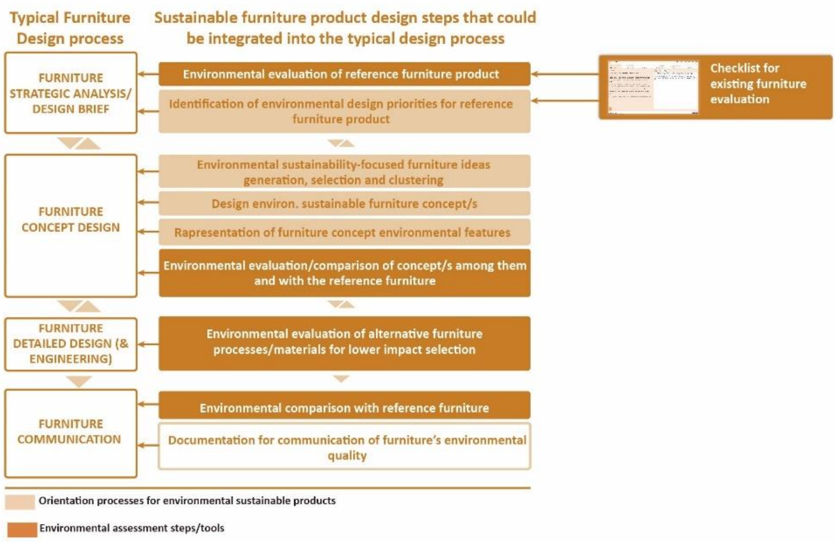


Figure 75 The checklist for the Existing Furniture Evaluation integration into the design process

8.2.3. Eco-idea Boards (ICS x Furniture Toolkit)

Aim

The eco-idea boards aim to facilitate the generation and collection of ideas focused on the environmental sustainability of furniture products. The tool consists of seven boards, each corresponding to a particular LCD strategy. The boards contain indications of previously identified priorities as well as specific guidelines and examples associated with each strategy to stimulate and guide the generation of environmentally sustainable ideas.

Components

1. 11 idea boards for 7 furniture LCD strategies;
2. A navigator to move from one idea board (strategy) to another;
3. A list of design guidelines for each strategy;
4. E-post-its to write down promising new ideas;
5. Best practices as examples for some guidelines;
6. The visualization of priorities for each strategy.

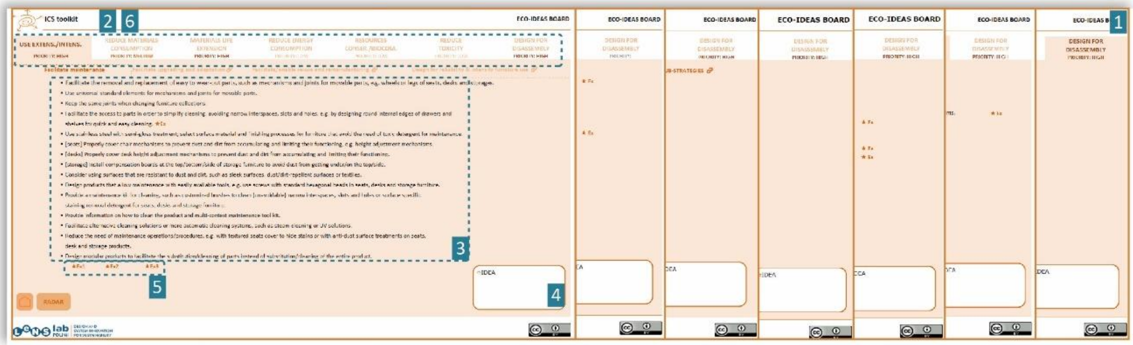


Figure 76 The components for Eco-idea Boards (ICS x Furniture Toolkit)

How to use the tool

1. To access the tool, click on ‘ECO-idea boards’ on the home page;
2. Start from the strategy with ‘high priority’, and read furniture-specific LCD guidelines;
3. Click on ‘EX” to check the best practice from the repository on lens-international.org, to access additional information and have further inspiration;
4. Write down ideas oriented toward environmental sustainability on the digital post-its;

5. Repeat this process for all seven LCD strategies (21 sub-strategies) based on the priority allocated for each strategy.

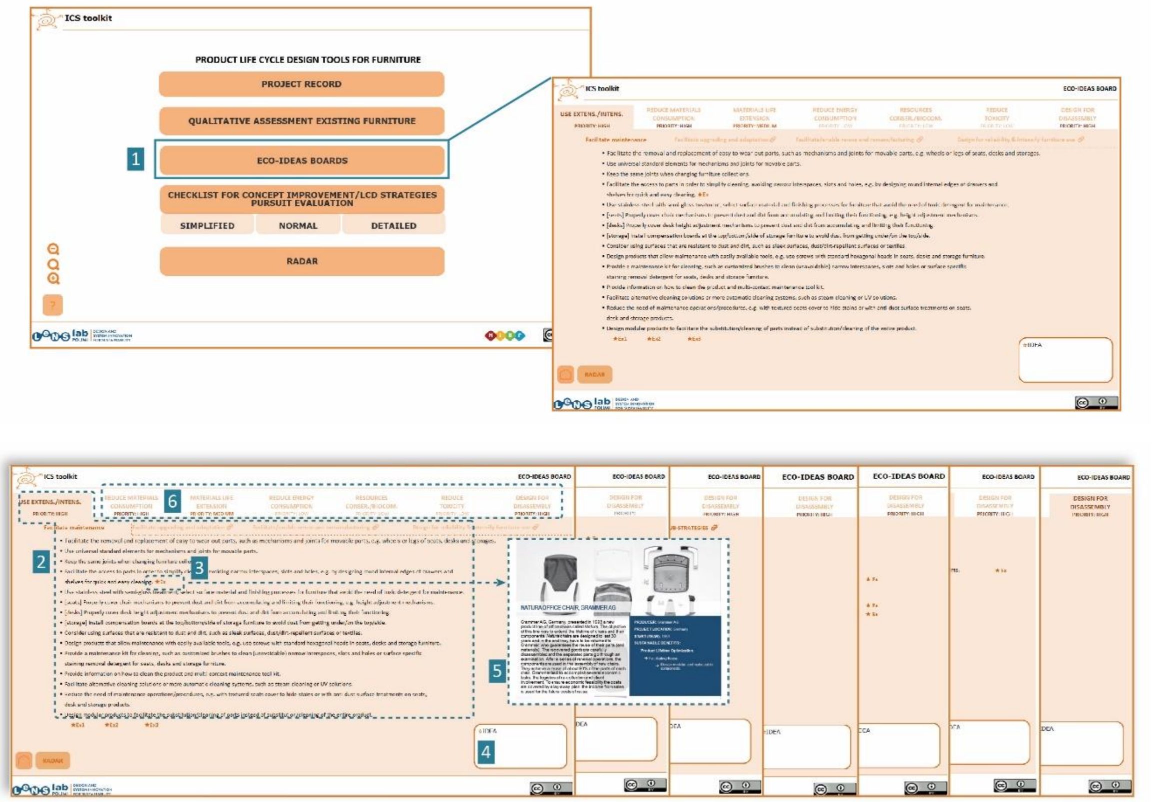


Figure 77 The using steps for Eco-idea Boards (ICS x Furniture Toolkit)

Tool’s integration into the method for sustainable furniture S.PSS design

The checklist is supposed to be applied in the ‘furniture product concept design’ stage to facilitate environmental sustainability-focused ideas generation, selection, and clustering.

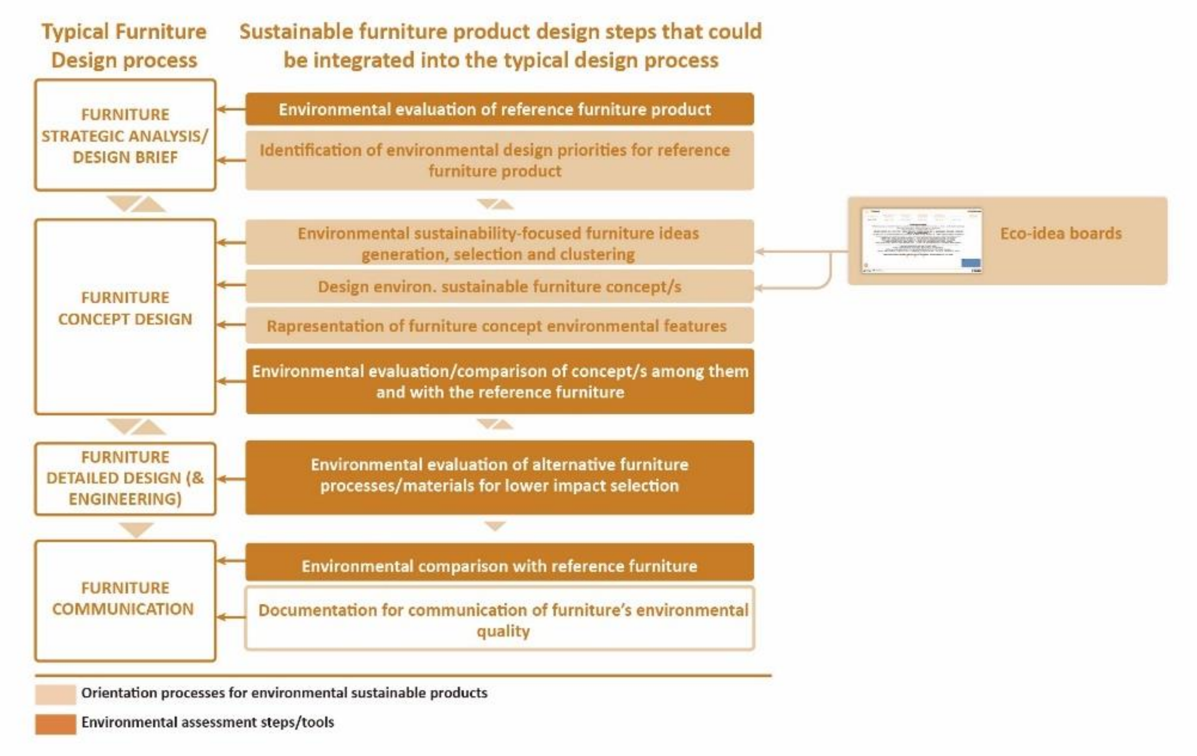


Figure 78 Eco-idea Boards (ICS x Furniture Toolkit) integration into the design process

8.2.4 Checklist For Concept Improvement/LCD Strategies Pursuit Evaluation (ICS x Furniture Toolkit)

Aim

The checklist for concept improvement (simplified/normal) aims to have a qualitative indication of the level of improvement of the new concept in comparison to the existing furniture. The checklist for LCD pursuit evaluation (deep) aims to have a qualitative indication of the level of pursuit of the furniture-specific LCD strategies.

(1) Checklist for furniture product LCD strategies pursuit evaluation (simple)

Components (simple)

1. A drop-down list to assess the level of improvement for each strategy, including options for worse/ no improvement/ incremental improvement/ radical improvement;
2. The identified priority for each strategy;
3. A final score and level of improvement for the pursuit of strategies.

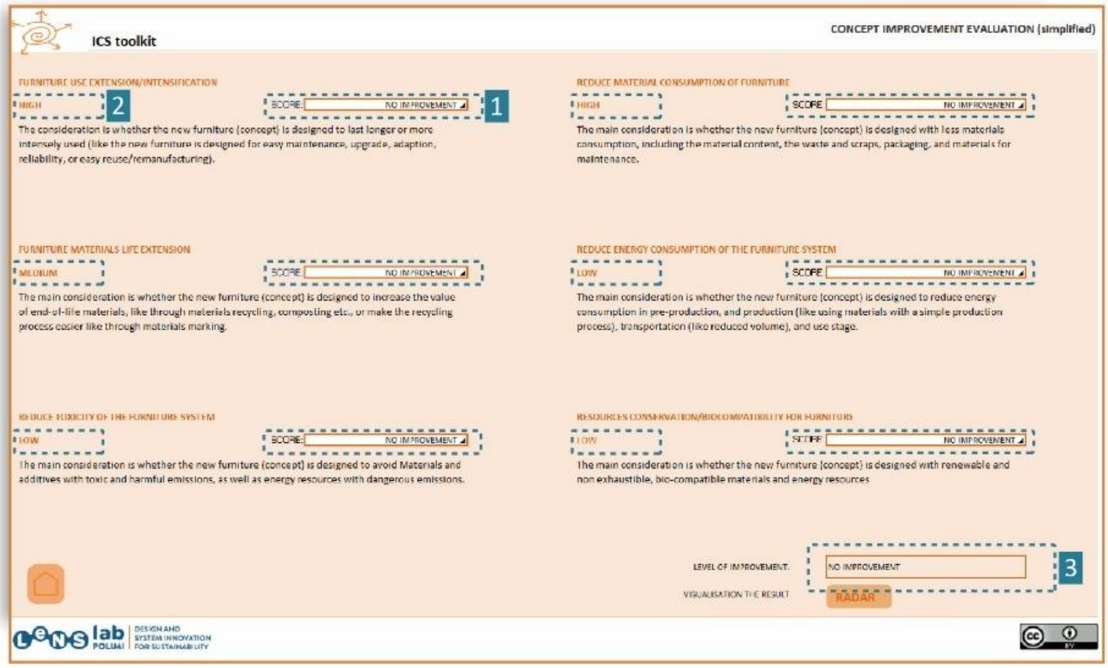


Figure 79 The components for the Checklist for furniture product LCD strategies pursuit evaluation (simple)

How to use the tool

1. To access the tool, click ‘life cycle design strategies pursuit evaluation_ simplified’ on the home page;
2. On a “simplified” mode, the level of pursuit is evaluated per each of the six LCD strategies through the above-mentioned scale;
3. The evaluation is automatically weighted with the priorities given for each LCD strategy, providing an overall evaluation of improvement, which is summarized into an overall total score.

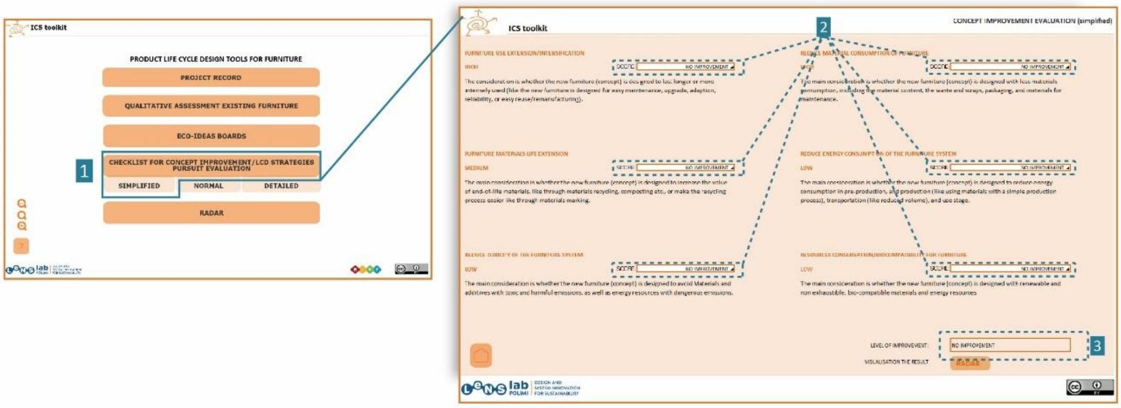


Figure 80 The steps for the Checklist for furniture product LCD strategies pursuit evaluation (simple)

(2) Checklist for furniture product LCD strategies pursuit evaluation (normal)

Components (normal)

1. A drop-down list to assess the level of improvement achieved for each sub-strategy, including options for worse/ no improvement/ incremental improvement/ radical improvement;
2. The identified priority for each strategy;
3. A score and level of improvement for the pursuit of sub-strategies;
4. A final score and level of improvement for the pursuit of strategies.

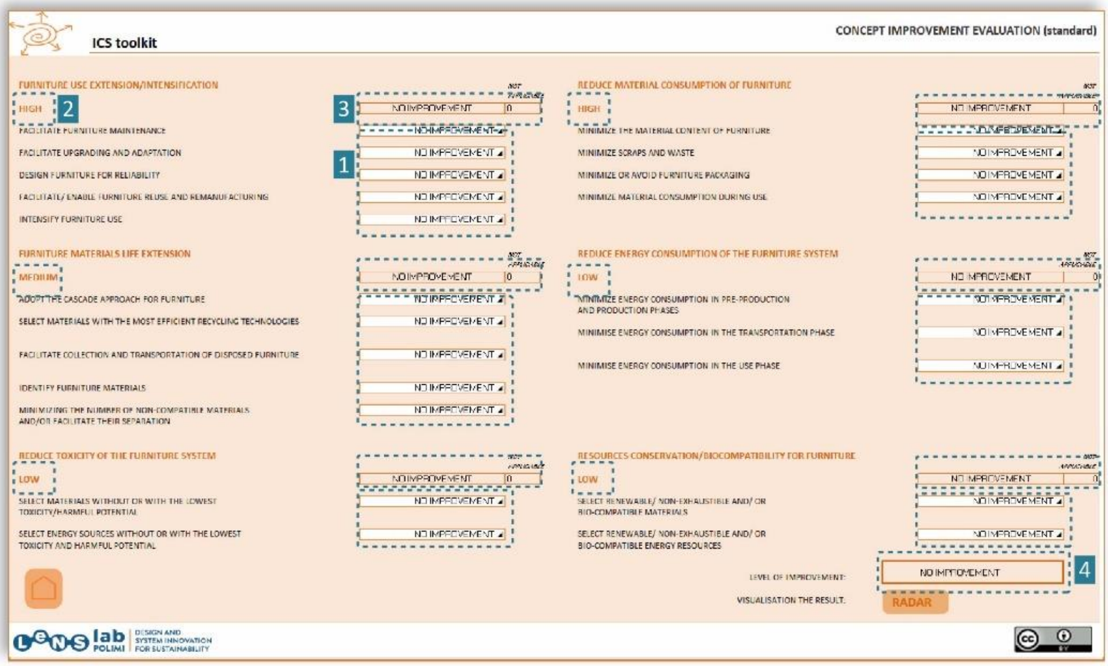


Figure 81 The components for the Checklist for furniture product LCD strategies pursuit evaluation (normal)

How to use the tool

1. To access the tool, click ‘life cycle design strategies pursuit evaluation_normal’ on the home page;
2. The “normal” mode allows the evaluation of the pursuit of strategies through the assessment of each sub-strategy's improvement;
3. Results are then summed up to determine the level of improvement for each strategy;
4. Finally, the score is weighted with each LCD priority and is summarized into an overall total score.

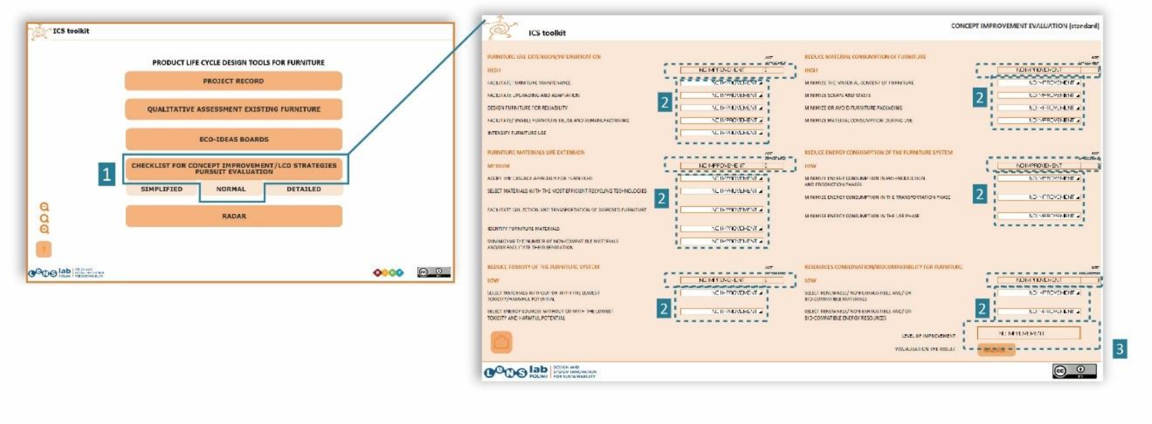


Figure 82 The steps for the Checklist for furniture product LCD strategies pursuit evaluation (normal)

(3) Checklist for furniture product LCD strategies pursuit evaluation (deep)

Components (deep)

1. A checklist for the pursuit evaluation of each guideline for each sub-strategy;
2. A count number of achieved guidelines for each sub-strategy;
3. An automatically calculated percentage of achievement for each sub-strategy and then the overall strategy;
4. The identified priority for each strategy;
5. A final score and level of improvement for the pursuit of strategies.

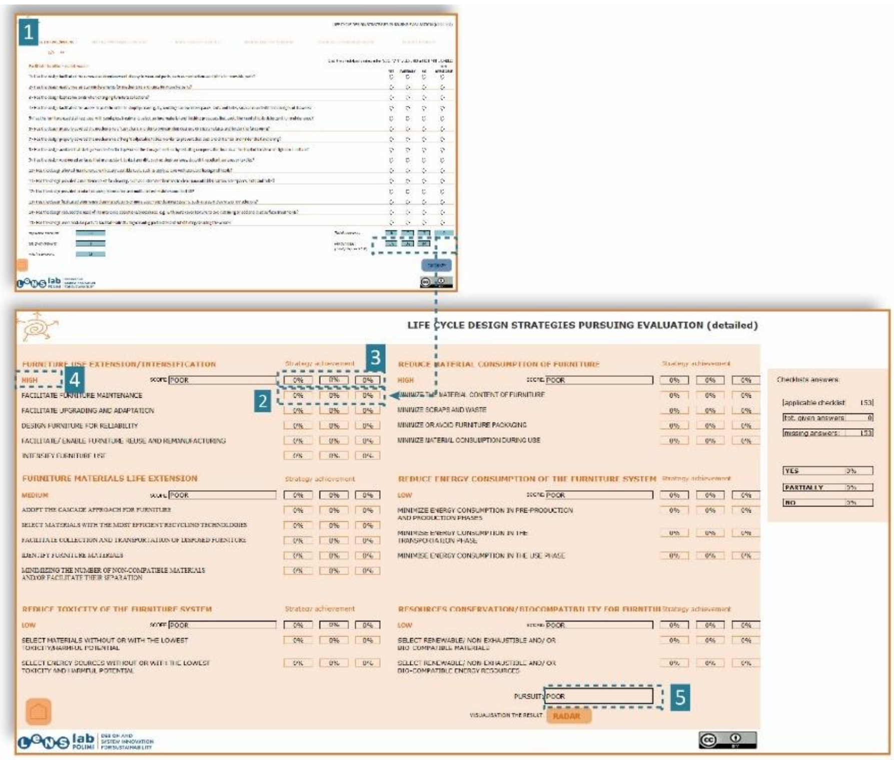


Figure 83 The components for the Checklist for furniture product LCD strategies pursuit evaluation (deep)

How to use the tool

1. To access the tool, click on ‘life cycle design strategies pursuit evaluation_deep’ on the home page;
2. The “deep” mode analysis allows for the assessment of the pursuit level of guidelines for each sub-strategy of every strategy. The checklist provides pre-determined options (“yes”, “partially”, no”, “not applicable”) that are automatically converted into percentages for each sub-strategy;
3. The percentages for each sub-strategy are aggregated to determine the pursuit level of the strategy as either radical, incremental, none, or worsen;
4. Repeat this process for each guideline of each sub-strategy of all seven strategies;
5. Finally, the level of pursuit of each strategy is weighted in relation to its priority. This weighted pursuit level is summarized into an overall total score on the summary board, providing a new concept's overall improvement level.

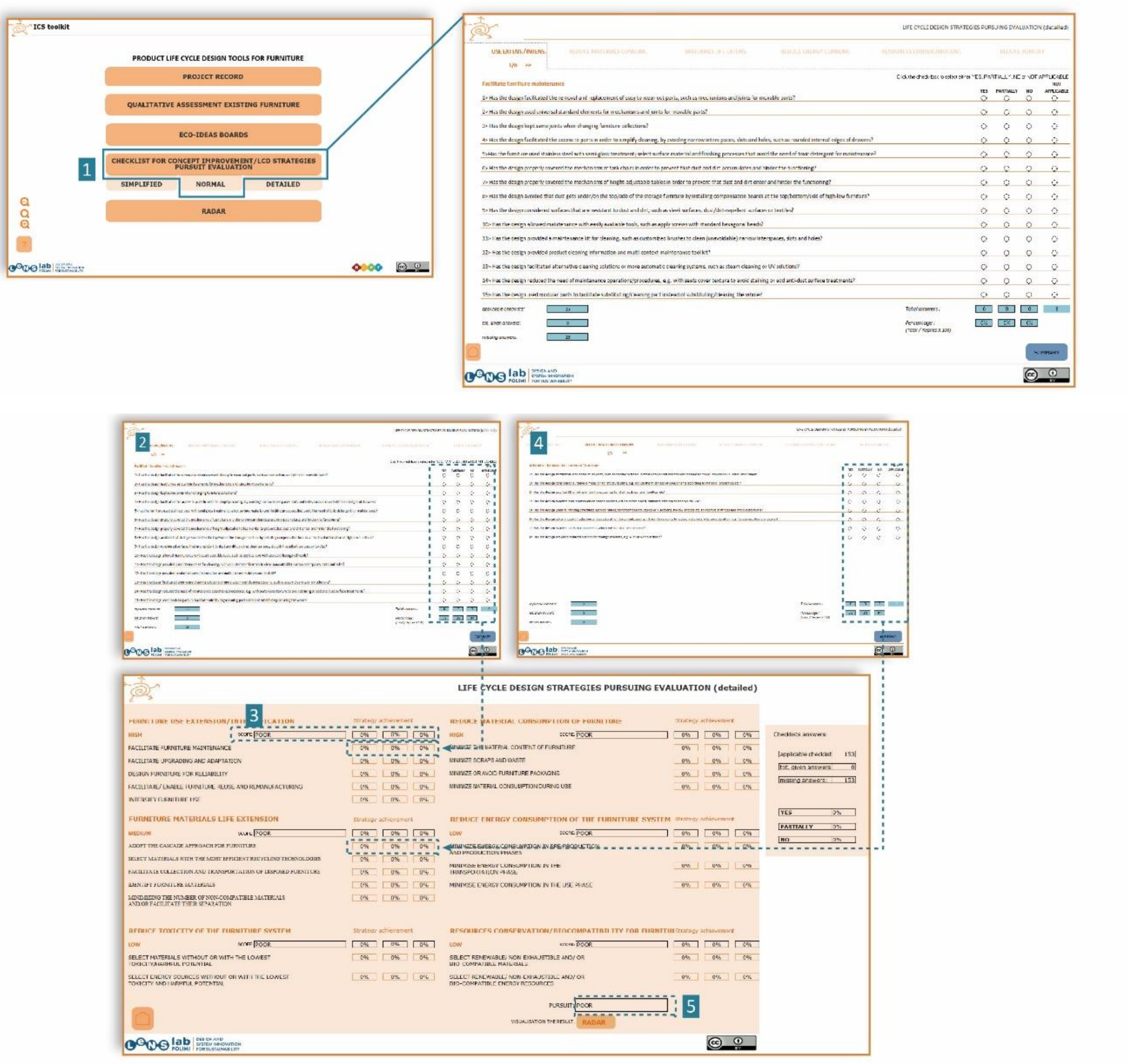


Figure 84 The steps for the Checklist for furniture product LCD strategies pursuit evaluation (deep)

Tool’s integration into the method for sustainable furniture product design

The checklist for LCD strategies pursuit evaluation can be integrated into the ‘furniture product concept design’ stage for the environmental sustainability evaluation of the furniture product concept as a comparison to a standard product. During the ‘furniture product communication’ stage, the outcome of this evaluation/comparison could be effectively used as input for the communication contents.

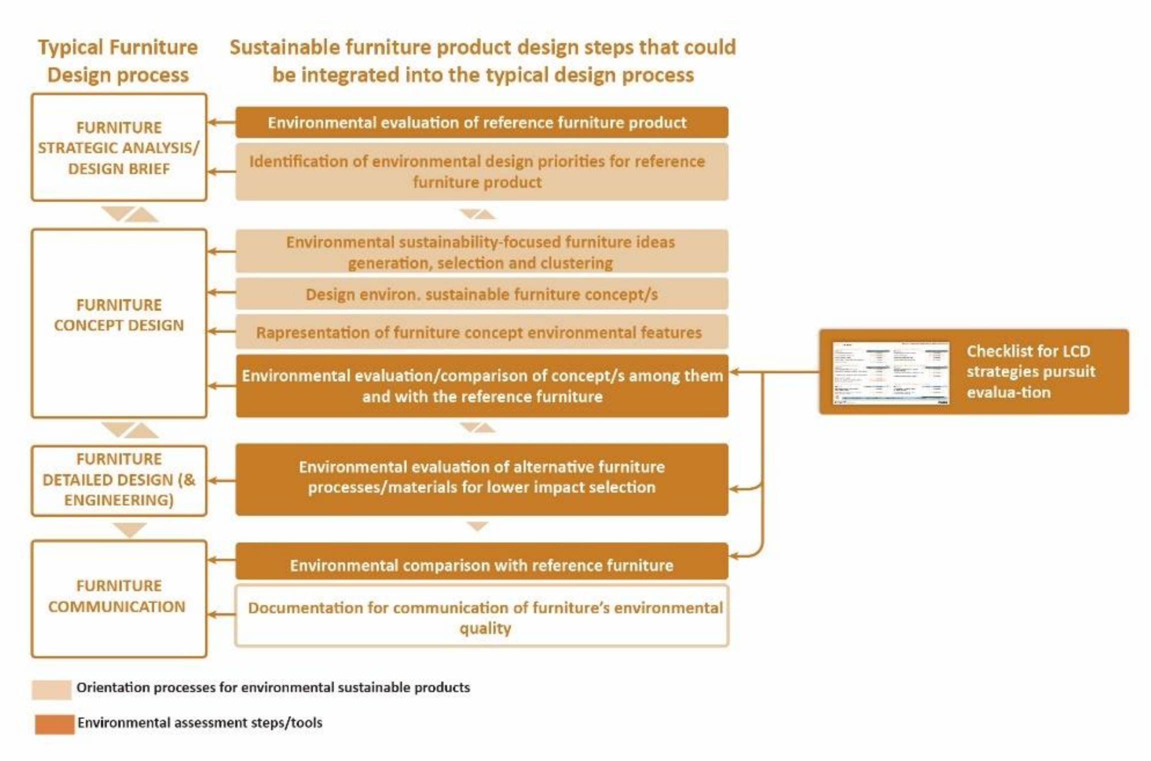


Figure 85 Checklist for concept improvement evaluation/furniture product LCD strategies pursuit evaluation integration into the design process

8.2.5 Multi-strategy Radar (ICS x Furniture Toolkit)

Aim

The radar is a visual tool that can be used to summarize evaluations and ideas elaborated with idea boards. Specifically, radar could be used to visualize the allocation of intervention priorities for each LCD strategy, the potential improvement determined by the concept (whether it is radical, incremental, none, or worsened), and the main characteristics that contribute to such improvements in the furniture concept. In addition, the radar can also serve as a useful tool for collecting the most promising eco-ideas generated during the ideation phase.

Components

1. a radar map to visualize the potential improvement of the furniture product concept over the existing furniture product for each of 6 strategies;
2. a space for each strategy to recap the promising ideas for the new concept;
3. text to remind the users of the level of priorities and improvement for each strategy.

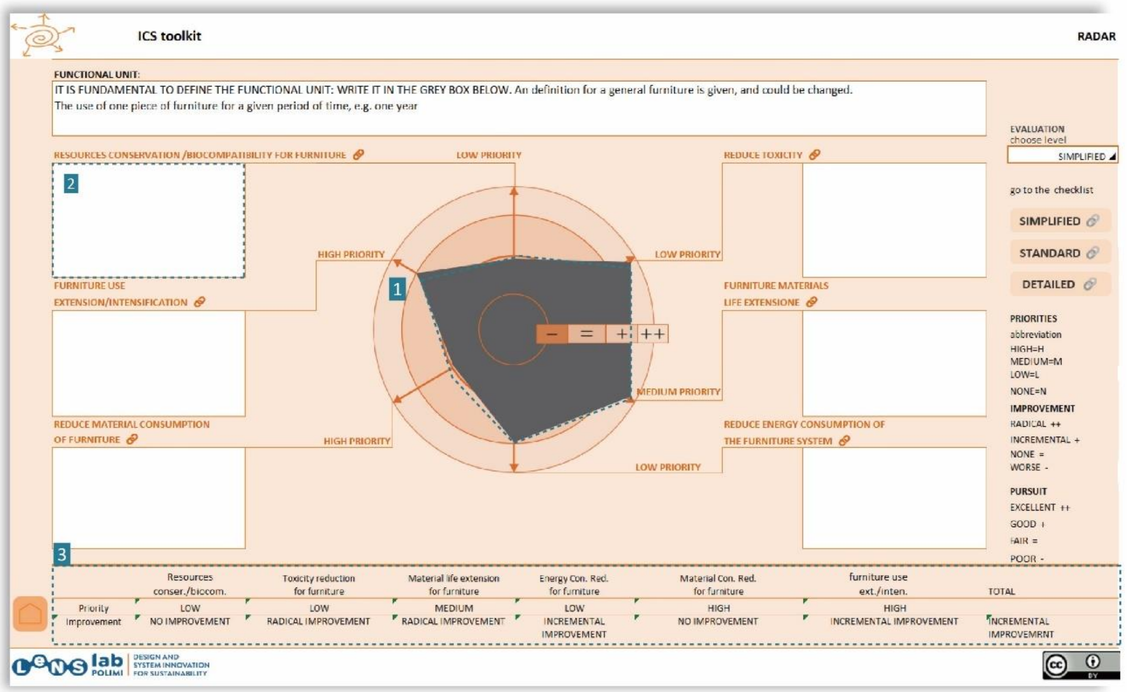


Figure 86 The components for the radar map

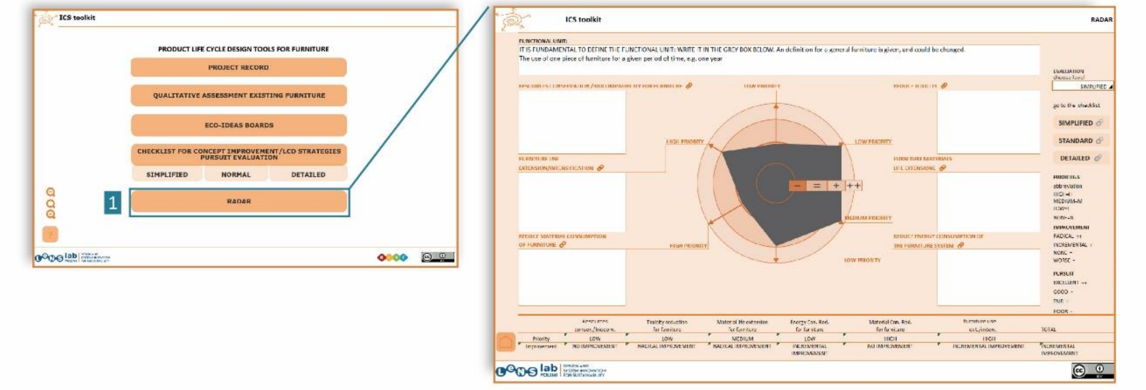
How to use the tool

The multi-strategy radar is a tool that provides a visual representation of six furniture Life Cycle Design (LCD) strategies. It utilizes a diagram based on a set of concentric circles with radial arrows emanating from the center.

1. To access the tool, click on ‘Radar’ on the home page;
2. After using the tool ‘Checklist for existing furniture Evaluation’ and ‘Checklist for furniture product LCD strategies pursuit evaluation’, priorities (for each strategy) and

the potential improvements of the concept in relation to the initial product (for each strategy) will be automatically visible on each strategy button;

3. The priority automatically appears on strategy arrows;
4. The hexagonal shape vertexes move on automatically radial coordinates as soon as a "Checklist for LCD strategies pursuit evaluation" has been carried out, with options for a simplified, normal, or deep assessment. This visualizes clear and immediate feedback between the identified environmental priorities and the potential benefits achievable through a given concept;
5. Select and visualize the most promising eco-ideas generated from the previous stage. Users can transfer the "digital post-its" produced within eco-idea boards for each strategy through a simple copy-paste action and place them near the arrow corresponding to the specific strategy from which the eco-ideas were extracted;
6. Summarize the most valuable environmental characteristics that would allow the improvement.



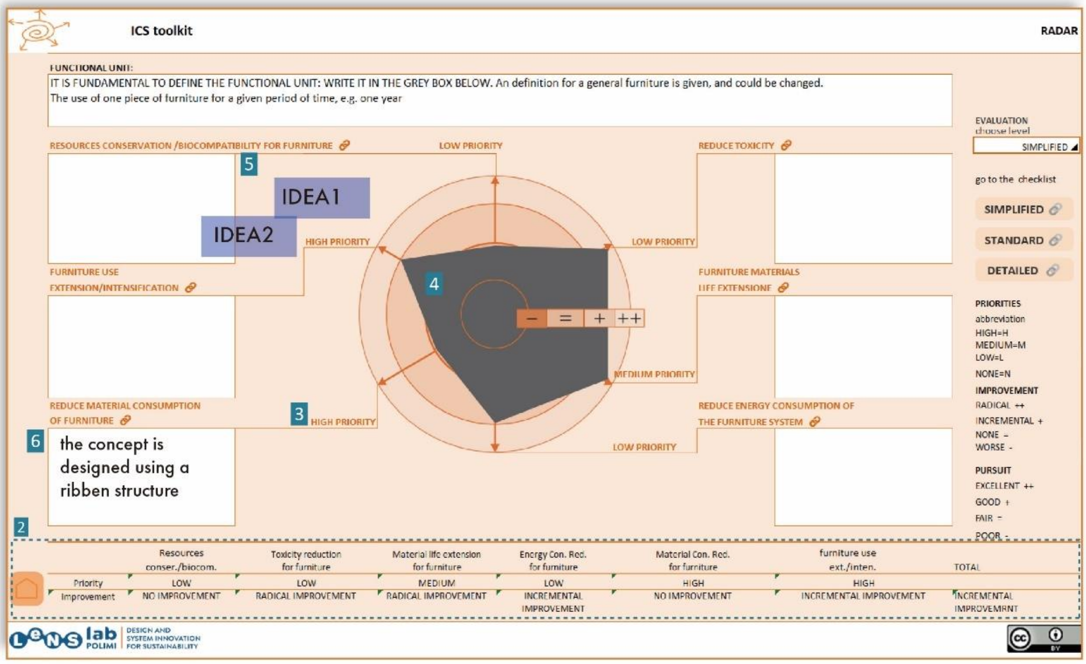


Figure 87 The steps for the radar map

Tool’s integration into the method for sustainable furniture product design

Due to its multiple ways of interaction with other tools, the multi-strategy radar can be integrated within different stages of the design process. During the strategic analysis phase, it can be used to report identified environmental priorities for each strategy; it can be used during the furniture product concept design stage, in combination with eco-idea boards to transfer and clearly visualize the best ideas, as well as a visual synthesis of the overall potential environmental benefits of the concept; during the furniture product communication stage, the tool can be used to show the results for environmental comparison with reference products.

Figure 88 The radar map integration into the design process

8.2.6 ICSxFurniture toolkit availability

As previously mentioned, the ICSxFurniture toolkit encompasses all the tools outlined above and is accessible through an open-access and open-source spreadsheet file, available to download for free at LeNS Lab polimi [27] / Learning resources / Furniture system design for sustainability tools. Indeed, the toolkit is a resource to spread, implement, and improve the practice of furniture Life Cycle Design, e.g., by introducing strategies and guidelines related to furniture-specific domains. A video presentation is linked to the source of the tool.

[27] https://www.lenslab.polimi.it/

8.3 Furniture S.PSSD Tools Adaptation/Design and Prototyping

This section outlines several tools that can support the various stages of the methods presented for designing furniture environmentally Sustainable Product-Service Systems (S.PSS).

In particular, the following paragraph provides a detailed description of tools developed specifically for the furniture. These tools (or toolkits) are described in the following chapters:

SDOxFurniture toolkit, which consists of :

- Environmental Analysis Checklist;
- Idea boards;
- Environmental Comparison Checklist
- Radar diagram;
- Innovation Diagram x Furniture S.PSS;
- System map x Furniture S.PSS.

Each tool is described using the following structure:

- The aim;
- The components of the tool (what it consists of);
- Tool's integration into the Method for Furniture S.PSS Design;
- How to use the tool in the design process;
- Availability and resources required to use the tool.

8.3.1 SDOxFurniture Toolkit

The SDOxFurniture toolkit is designed to facilitate the development of furniture S.PSS solutions in the system design process. To achieve this, the toolkit draws upon a comprehensive understanding of the Furniture System's environmental impacts, as well as 6 furniture S.PSS design strategies and 37 guidelines, and 44 best practice cases. These 6 strategies provide a framework for incorporating sustainability principles into furniture PSSD. Specifically, the furniture S.PSS design strategies include:

- Furniture System life optimization
- Transportation/distribution reduction in the furniture system
- Minimize resource consumption in the furniture system
- Furniture system waste minimization/valorization
- Resources conservation/biocompatibility in the furniture system
- Furniture system toxicity reduction

By leveraging these strategies, the SDOxFurniture toolkit empowers designers to create furniture S.PSSs that are not only functionally pleasing but also environmentally responsible. The toolkit is composed of a spreadsheet file that seamlessly integrates a variety of tools, providing users with the ability to easily navigate between them. These tools include:

- Environmental Analysis Checklist (6 checklists, one for each strategy)
- Idea boards to generate sustainability-focused ideas (6 boards, one for each strategy)
- Environmental improvement Checklist (6 checklists, one for each strategy)
- Radar diagram to visualize the improvement of new solutions

These tools have different functions, but with the same aim of supporting designers in designing furniture S.PSS. Specifically, the SDOxFurniture toolkit is used to:

- Qualitatively analyzing the existing furniture system's environmental impact and setting sustainability design priorities (with the checklist tool);
- Generation of sustainable ideas with design-orienting guidelines and related best practices (with the idea board and case cards);
- Checking (checklist tool) and visualizing (radar diagram) the potential sustainability improvements in relation to the existing furniture system.

The SDOxFurniture toolkit offers support for various design steps with a range of tools. This modular toolkit empowers users with the flexibility to select and utilize multiple tools depending on the unique requirements and circumstances of each design project.

8.3.2 Environmental Analysis Checklist (SDOxFurniture toolkit)

Aim

The tool serves the following purposes in a qualitative way:

- To analyze the environmental impact of the current (reference) furniture system;
- To prioritize furniture S.PSS design strategies based on their effectiveness in reducing the furniture system's environmental impact;

Components

1. 6 checklists, one for each furniture S.PSS design strategy;
2. A navigator for users to move between checklists;
3. A list of questions related to the environmental impact of each design strategy;
4. A report-writing space to record the environmental analysis results for the reference system;
5. A drop-down menu to select the level of priority for each strategy;
6. Visual representations of the design strategies' priorities

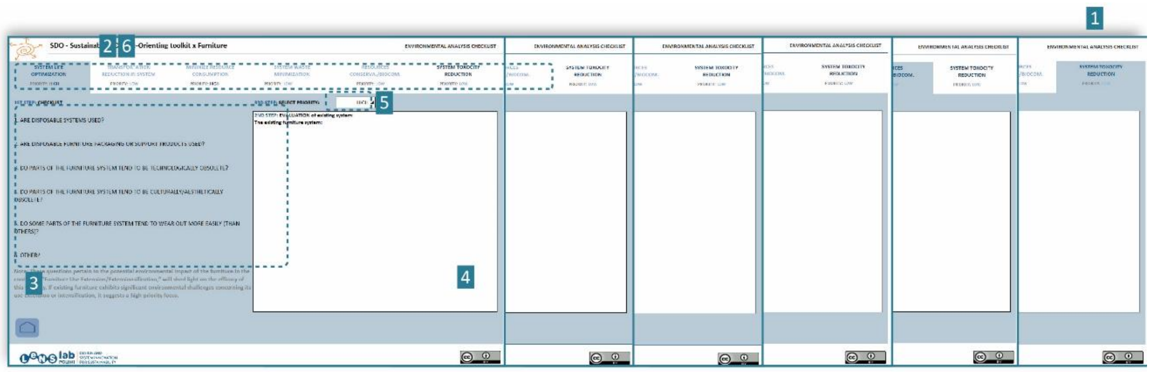


Figure 89 The components for the Environmental Analysis Checklist_SDOxFurniture toolkit

How to use the tool

1. To access the tool, click on the 'Environmental Analysis Checklist' on the home page;
2. Start from the first checklist (for the strategy ' Furniture System Life Optimisation") and read each question in a sequential order;
3. Respond to each question for the strategy;
4. Make the evaluation of all 6 strategies to assess the current state of the furniture system;

5. Define the relative priorities for each strategy using the drop-down menu by selecting: ‘no (priority)’, ‘low(priority)’, ‘medium (priority)’, or ‘high (priority)’.

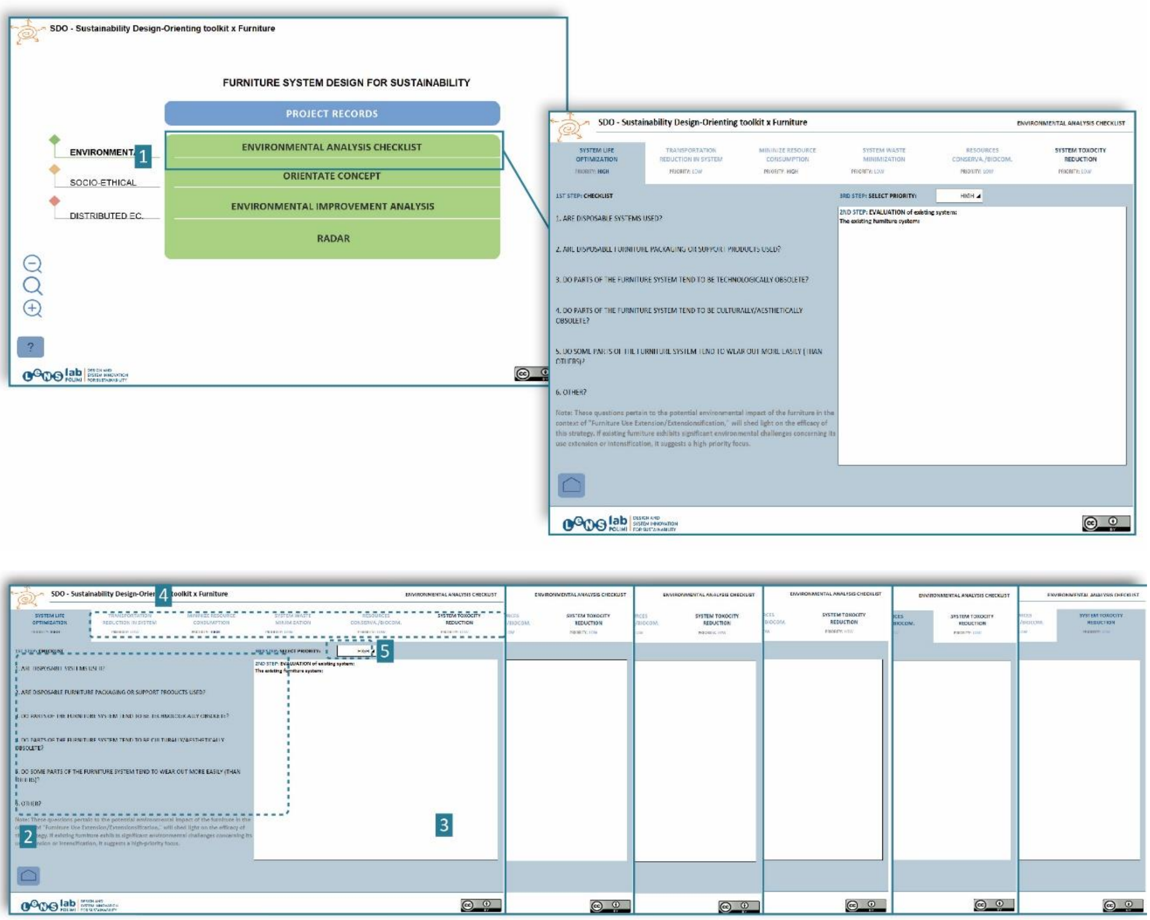


Figure 90 The steps for using the Environmental Analysis Checklist_SDOxFurniture toolkit

Tool’s integration into the sustainable furniture system design process

The tool can be integrated within multiple design stages: during the furniture S.PSS strategic analysis stage, the tool could be used for ‘sustainable analysis of reference PSS’, and “definition of S.PSS design priorities’; during the furniture concept design stage and the furniture S.PSS communication stages, the tool can be used for sustainability comparison of S.PSS concept with reference furniture PSS.

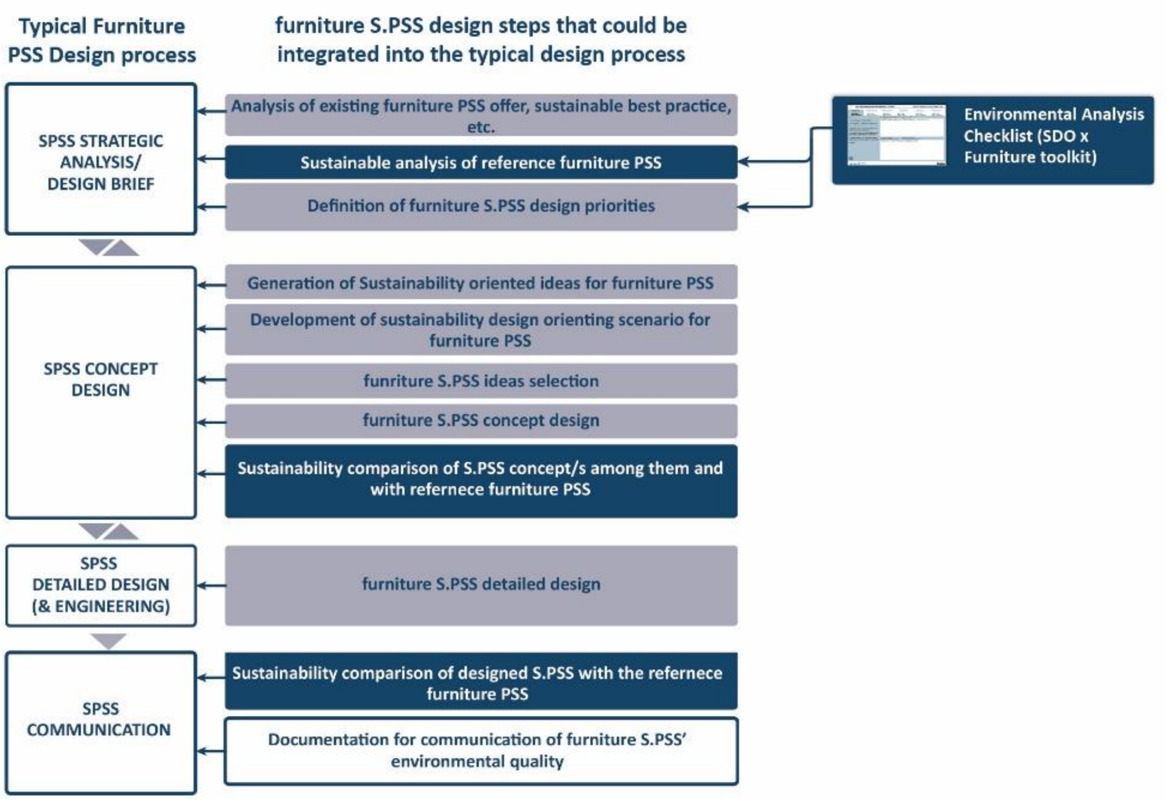


Figure 91 The Environmental Analysis Checklist (SDOxFurniture toolkit) integration into the design process

8.3.3 Idea Boards (SDOxFurniture toolkit)

Aim

The tool aims to foster the generation of furniture S.PSSD ideas using 6 idea boards. These idea boards provide design strategies, guidelines, and best practices for sustainability. These strategies support to reduce the environmental impact of furniture systems and include the following:

- furniture system life optimization;
- reduce the transportation/distribution in the furniture system;
- minimize resource consumption in the furniture system;
- minimization/valorization of waste from the furniture system;
- resource conservation/biocompatibility in the furniture system;
- reduce the toxicity in the furniture system.

Components

1. 6 idea boards, each corresponding to a furniture S.PSSD strategy;
2. A navigator to switch between idea boards;
3. A list of design guidelines for each strategy;
4. E-post-its to record new ideas;
5. Best practices as examples of guidelines;
6. A visual representation of the priority level for each strategy.

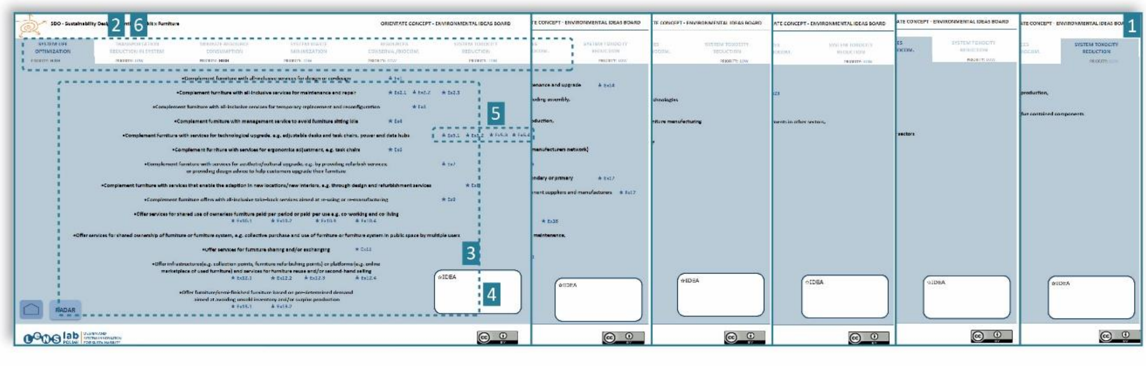
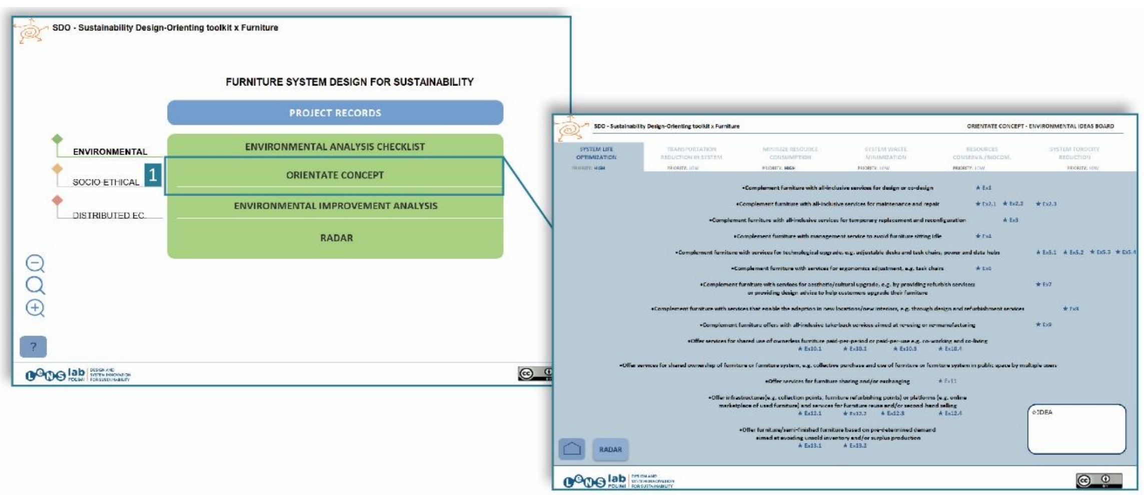


Figure 92 The components for Idea Boards (SDOxFurniture toolkit)

How to use the tool

1. To access the tool, click on ‘Orientate concept’ on the home page;
2. Begin with the strategy identified as ‘high priority, and Read each furniture-specific design guidelines in sequence;
3. Click on the ‘EX’ mark next to certain guidelines to access additional information and gain further inspiration from these best practices;
4. Use the digital post-its to record any emerging system ideas;
5. Navigate to the next strategy and repeat the same process until ideas are generated for each strategy.



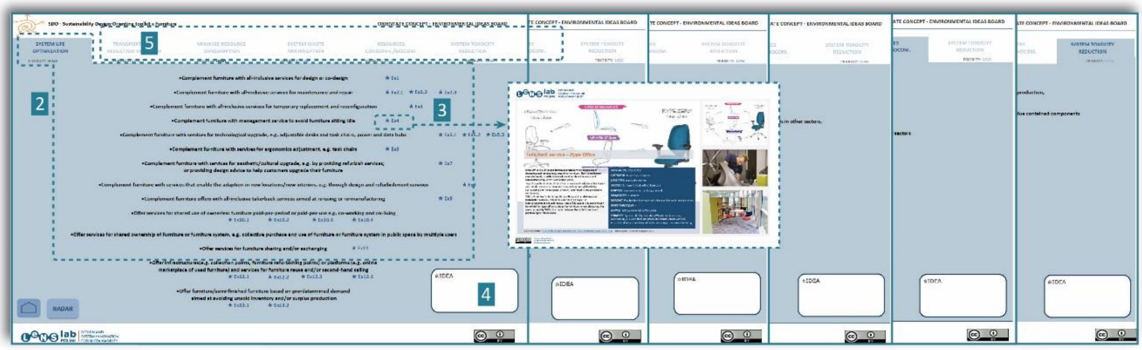


Figure 93 The steps for using Idea Boards (SDOxFurniture toolkit)

Tool’s integration into the method for sustainable furniture S.PSS design

The tool can be integrated into the ‘Furniture S.PSS concept design’ stage to ‘generate sustainability-oriented ideas for PSS’.

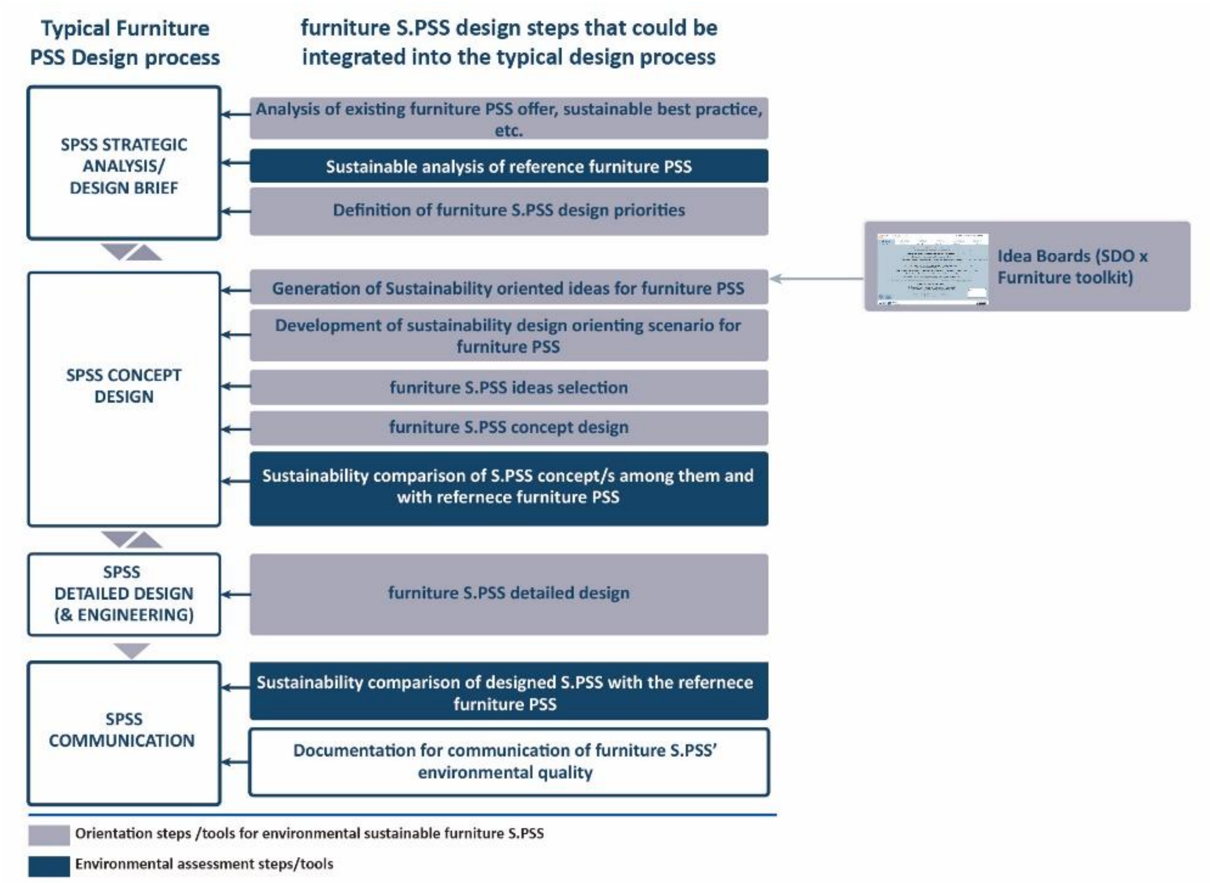


Figure 94 Idea Boards (SDOxFurniture toolkit) integration into the design process

8.3.4 Environmental improvement Checklist (SDOxFurniture toolkit)

Aim

The tool serves the following purposes in a qualitative way:

- To analyze the environmental impact of the new furniture concept and compare it to the existing system.

Components

1. 6 checklists, one for each furniture S.PSS design strategy;
2. A navigator for users to move between checklists;
3. A list of questions related to the environmental impact of each design strategy;
4. A report-writing space to record the environmental analysis results for the new system concept;
5. The environmental evaluation result of existing furniture;
6. A drop-down menu to choose the level of improvement for the new system concept compared to the reference system;
7. Visual representations of the design strategies' priorities and the level of improvement for the new concept compared to the reference furniture system.

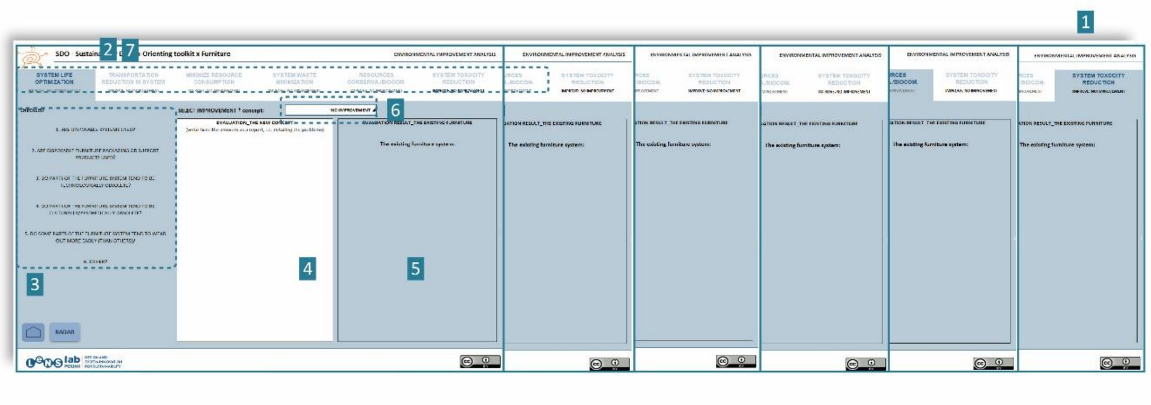


Figure 95 The components for Environmental improvement Checklist (SDOxFurniture toolkit)

How to use the tool

1. After designing a new concept, click on the ‘Environmental Analysis Checklist’ on the home page to access the tool;
2. Start from the first checklist (for the strategy “Furniture System Life Optimisation”) and read each question in a sequential order;
3. Respond to each question for the strategy for the new concept;

4. Define the relative improvement by comparing the new concept with the reference furniture system, with the drop-down menu by choosing ‘no improvement’, ‘worse’, ‘incremental improvement’, and ‘radical improvement’.
5. Continue with the other strategies until finished.

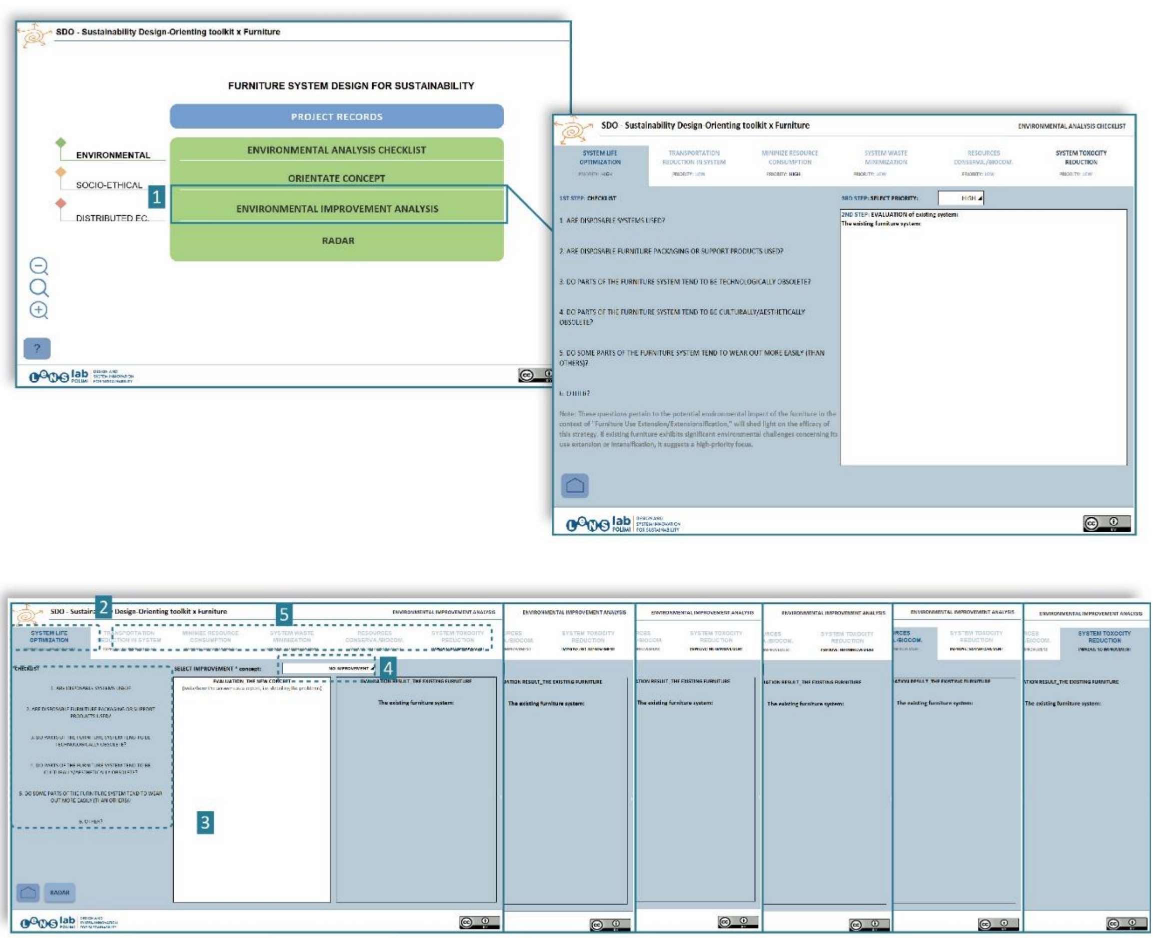


Figure 96 The steps for using the Environmental improvement Checklist (SDOxFurniture toolkit)

Tool’s integration into the sustainable furniture S.PSS design

The tool can be integrated within multiple stages of the design process: during the furniture S.PSS strategic analysis stage, the tool could be used for ‘sustainable analysis of reference PSS’, and “definition of S.PSS design priorities’; during the furniture concept design stage and the furniture S.PSS communication stages, the tool can be used for sustainability comparison of S.PSS concept with reference furniture PSS.

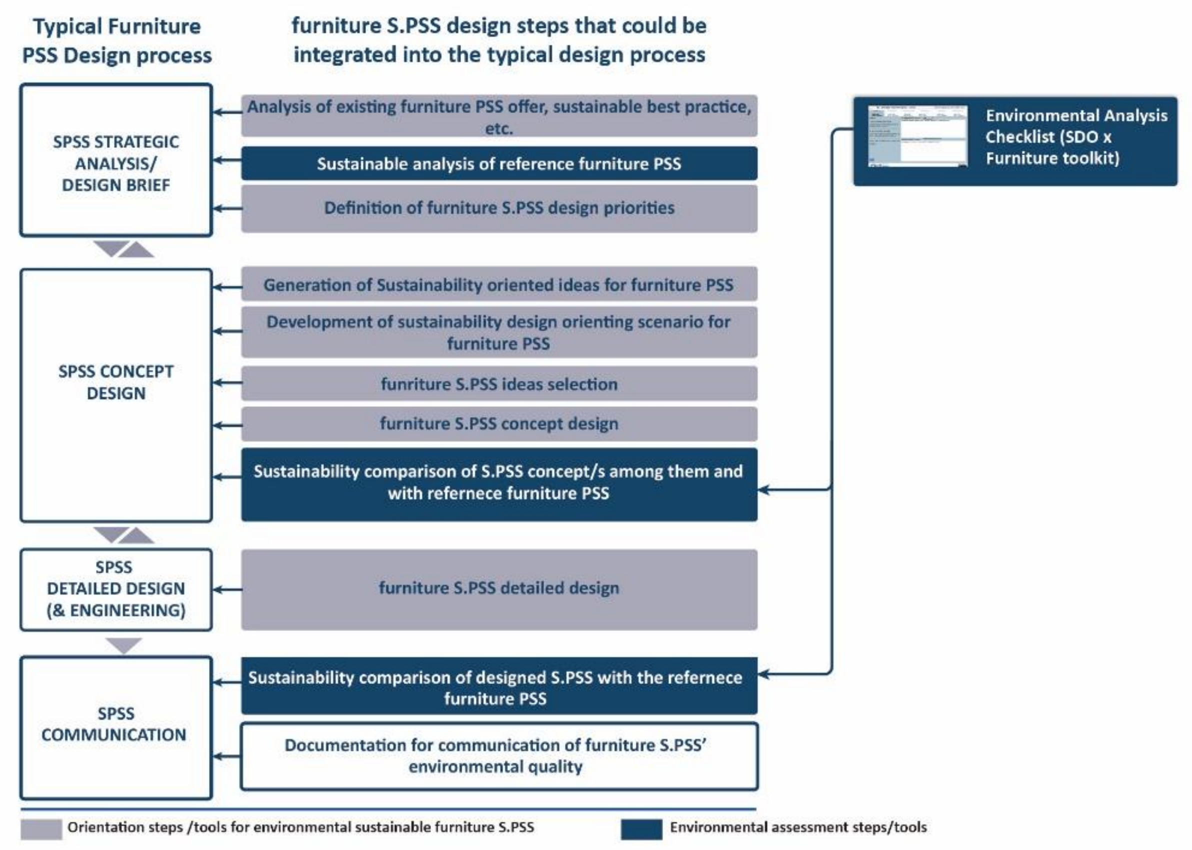


Figure 97 The Environmental improvement Checklist (SDOxFurniture toolkit) integration into the design process

8.3.5 Radar diagram (SDOxFurniture toolkit)

Aim

- The radar diagram aims to visualize the potential improvement of the furniture S.PSS concept over the existing furniture system;
- to recap the promising ideas in terms of each strategy for the new concept;
- to record the level of priorities for each strategy.

Components

1. A radar map to demonstrate the potential improvement of the new system concept over the existing system for each of the six strategies being evaluated;
2. A frame for each strategy to outline and summarize the most promising ideas for the new concept;
3. Text to remind of the priority level and potential improvement for each strategy.

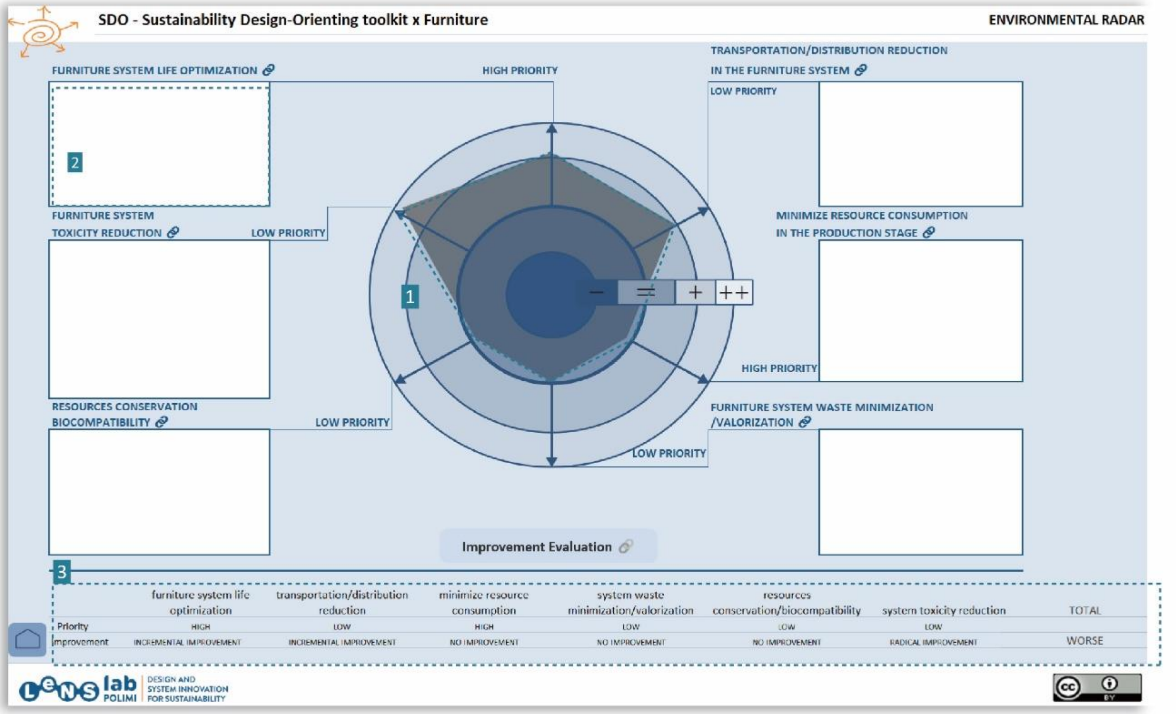


Figure 98 The components for the Radar diagram (SDOxFurniture toolkit)

How to use the tool

1. Access the tool by clicking ‘Radar’ on the home page;
2. After using the tool ‘Environmental Analysis Checklist’, existing system priorities (for each strategy) and the potential improvements of the concept in relation to the initial system (for each strategy) will be automatically visible on their respective buttons;
3. The potential improvements of the concept in relation to the initial system (for each strategy) will be visually represented on the radar map;
4. each strategy’s priority for the existing system is automatically shown on the arrow based on the result of the ‘environmental analysis checklist’;
5. Summarize the promising ideas that led to the improvements in the text boxes.

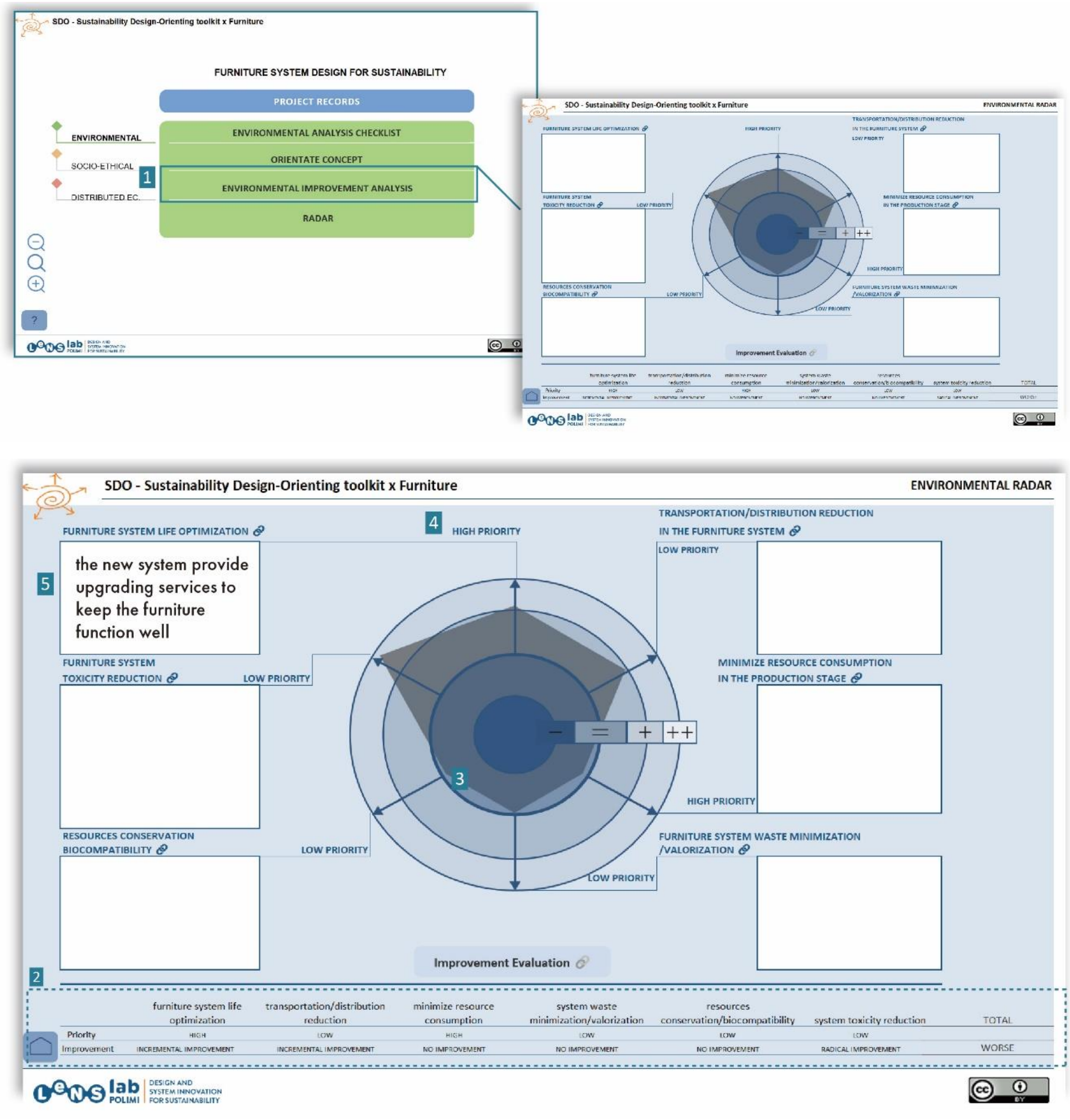


Figure 99 The steps for using the Radar diagram (SDOxFurniture toolkit)

Tool’s integration into the method for sustainable furniture S.PSS design

The tool can be integrated into the ‘Furniture S.PSS concept design’ stage of the design process to ‘select S.PSS ideas’ and ‘visualize the sustainability improvement of S.PSS concept/s in comparison with reference furniture PSS’; can be integrated into the ‘Furniture S.PSS communication’ stage, to visualize the sustainability improvement of the final concept.

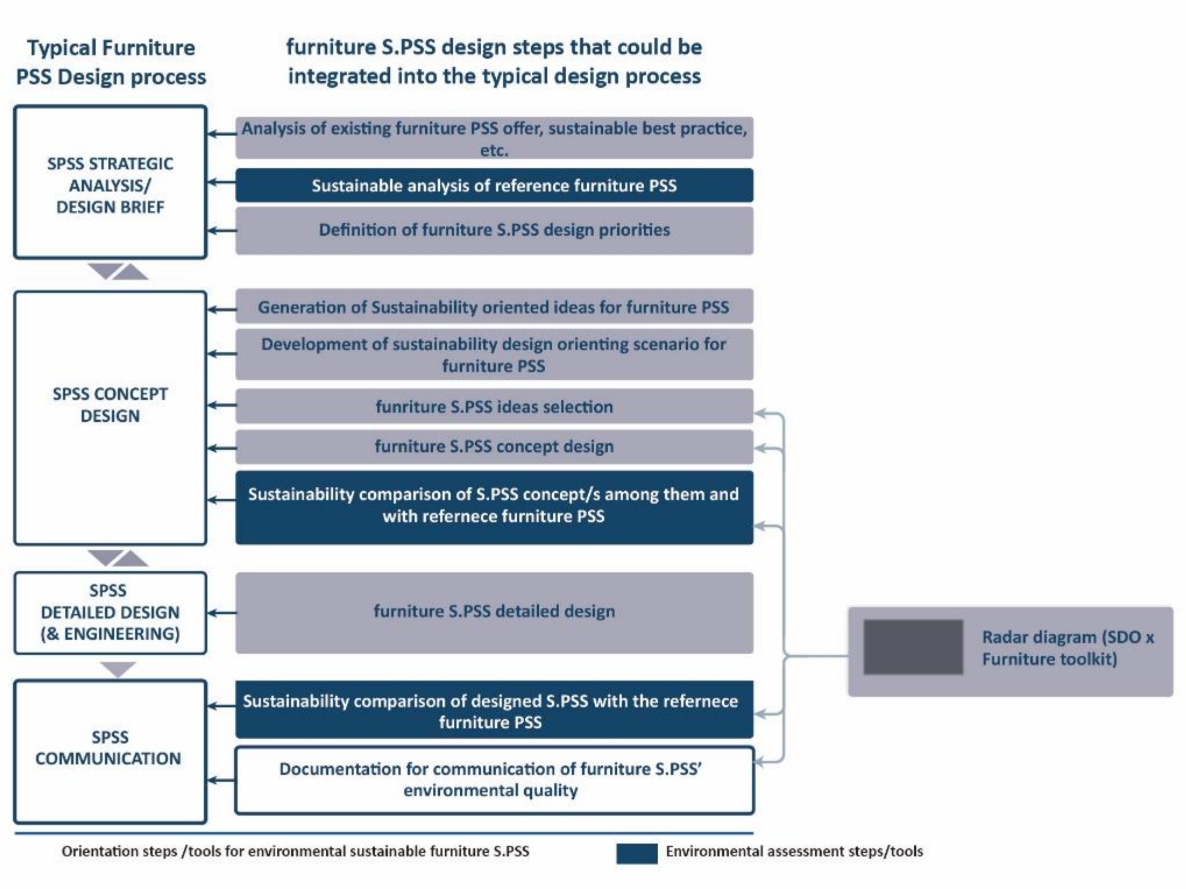


Figure 100 The Radar diagram (SDOxFurniture toolkit) integration into the design process

8.3.6 Innovation DiagramxFurniture

Aim

The objective of the tool is to position and characterize the existing furniture system as well as competitors' offers; additionally, it is used to identify and select promising sustainable ideas for the furniture system. Ultimately, the tool is designed to facilitate the development of a new concept profile.

Components

1. A home page with navigation and tutorial;
2. Polarity diagrams (for new concept design, existing offer/competitor analysis);
3. Characterization of the offer/system with 7 key elements;
4. Repository of labels for 7 key elements;

5. A concept description form.

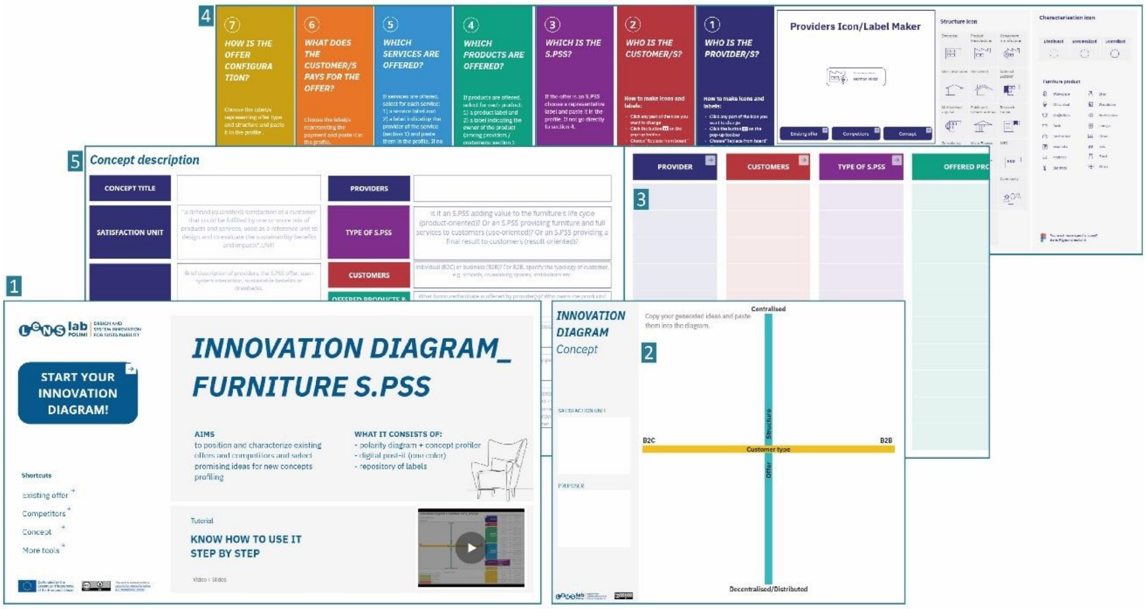


Figure 101 The components for the Innovation DiagramxFurniture

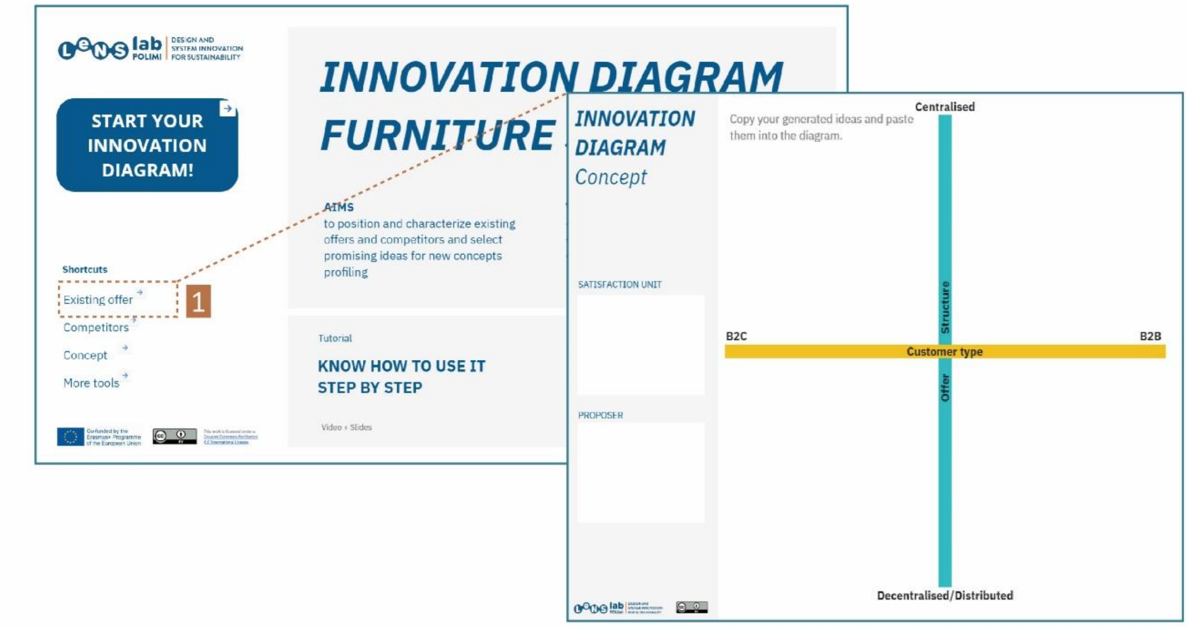
How to use the tool – analyzing existing offers and/or competitors' offers

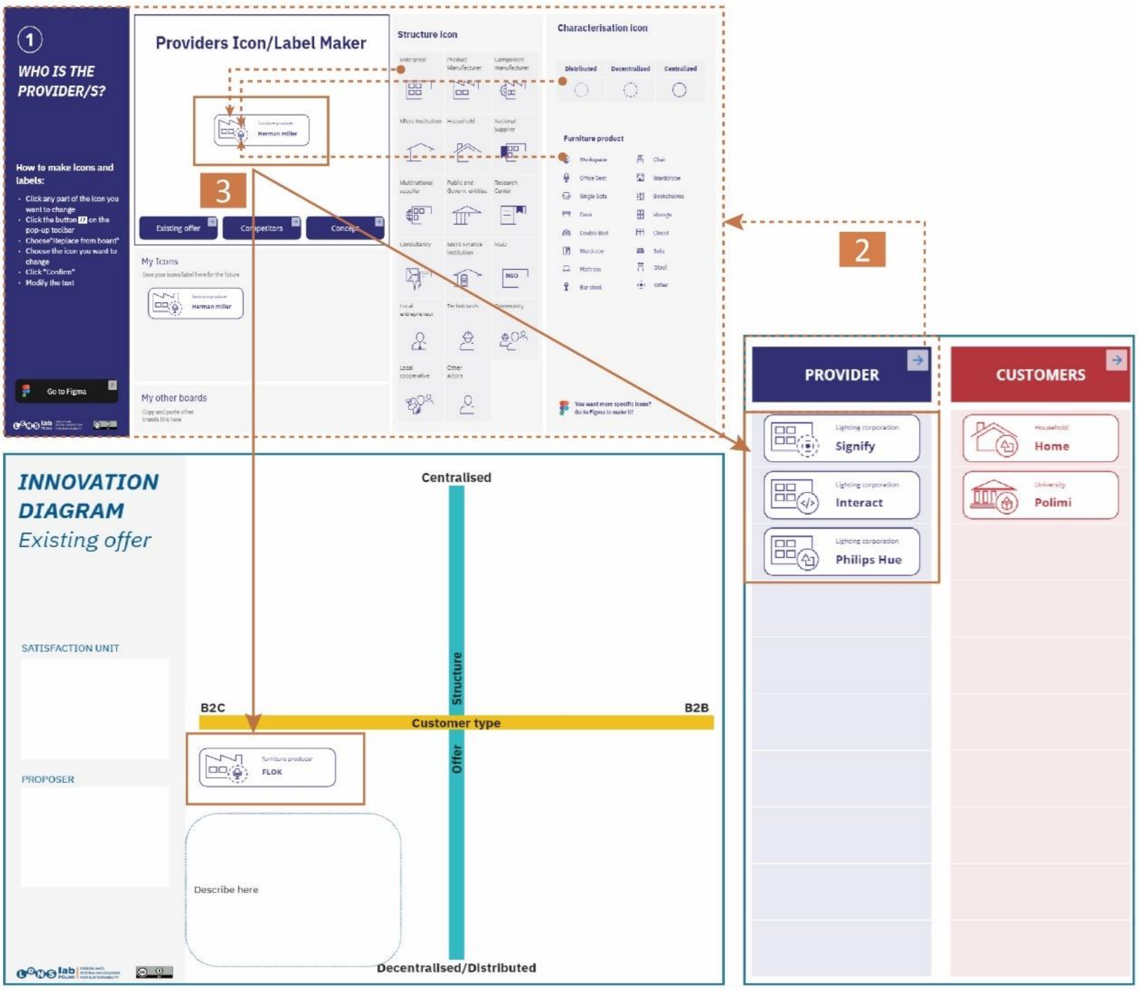
1. Open the tool and access the "existing offer" board;
2. Build the "provider" icon for the existing furniture S.PSS offers. Click the link on "PROVIDER" to access the repository for the provider. Build the provider by choosing the right representative for the structure icon, characterization icon, and furniture product icon. Write down the provider's name and a descriptive text on the right of the icon.
3. Next, paste the whole "provider" label on the 'existing offer' polarity diagram in the correct position considering the two polarities and paste the icon on the characterization table on the right-hand side.
   Characterize the existing offer by specifying all the following elements:

4. Type of customer/s. Click the link on the "CUSTOMER" to access the repository for the customer. Build the customer by choosing the right representative for the structure icon, characterization icon, and furniture product icon. Write down the provider's name and type it on the right of the icon;
5. Type of PSS and customer type. Select the S.PSS type of the existing offer (if any): PRODUCT-ORIENTED, CARE-ORIENTED, RESULT-ORIENTED, and paste it in the S.PSS type section. Remember that not all offers are already S.PSS. At the same

time, select the right business type (B2B or B2C). Paste the whole label on the existing offer_type of S.PSS.

6. Offered products and owner. Select the offered product icons and paste them into the products section. Select who retains the product OWNERSHIP (provider or customer) and place the built label in the product owner section.
7. Offered services and providers. Select the offered service icons and paste them into the service section. Select who provides the service and paste the icon in the service provider section.
8. What is paid. Select the icon describing what is paid by the customer/s and place the label in the payment section.
9. Offer configuration. Select the Distributed economy type icon of the offer and paste it into the Distributed economy type space. Select its structure icon and place it in the section.
10. To comprehensively assess the context, it is essential to analyze the existing offer as well as the competitors' offers. This can be achieved by employing a similar process for the existing offer characterization, working on the "Competitors" polarity diagram.


START YOUR INNOVATION DIAGRAM!
INNOVATION DIAGRAM FURNITURE
AIMS
to position and characterize existing offers and competitors and select promising ideas for new concepts profiling
Shortcuts
Existing offer
Competitors
Concept
More tools
1
Tutorial
KNOW HOW TO USE IT STEP BY STEP
Video + Slides
INNOVATION DIAGRAM
Concept
Copy your generated ideas and paste them into the diagram.
SATISFACTION UNIT
PROPOSER
Centralised
B2C
B2B
Customer type
Structure
Offer
Decentralised/Distributed


WHO IS THE PROVIDER/S?
How to make icons and labels:
Providers Icon/Label Maker
Structure icon
Characterisation icon
3
Existing offer
Competitors
Concept
My Icons
My other boards
Furniture product
Go to Figma
2
PROVIDER
CUSTOMERS
Signify
Interact
Philips Hue
Home
Polimi
INNOVATION DIAGRAM
Existing offer
SATISFACTION UNIT
PROPOSER
Centralised
B2C
B2B
Customer type
Structure
Offer
FLOK
Describe here
Decentralised/Distributed

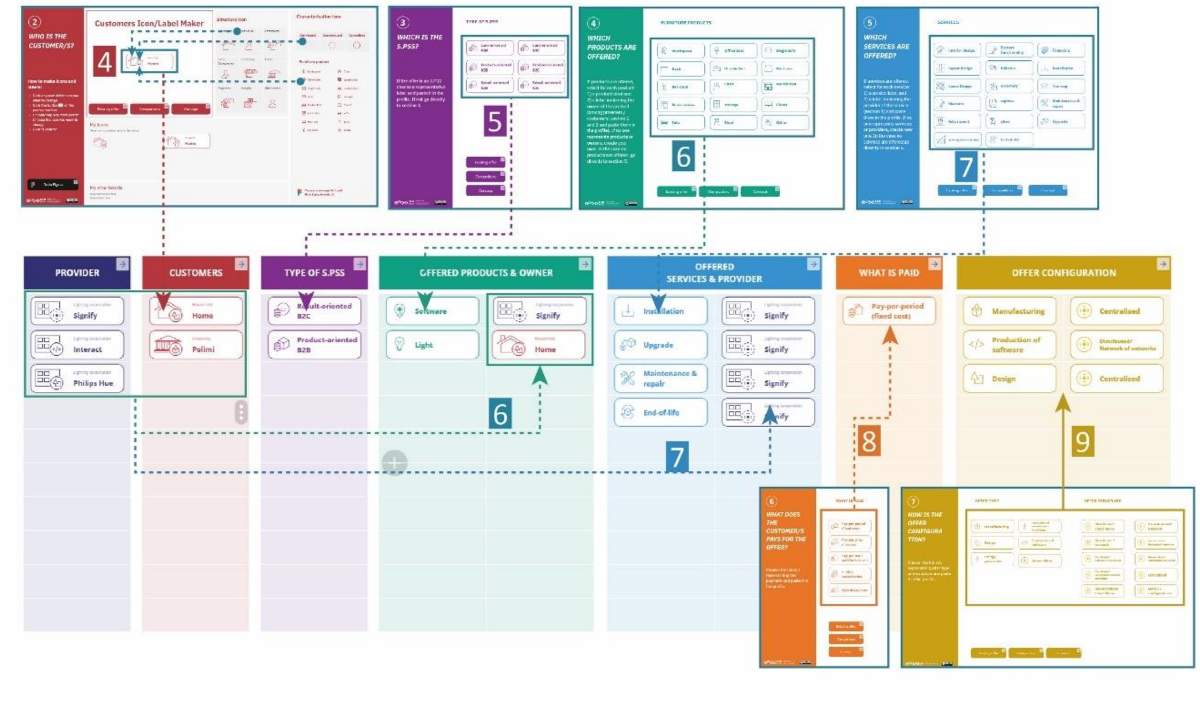


Figure 102 The steps for using the Innovation DiagramxFurniture_ analyzing existing offers and/or competitors' offers

How to use the tool – concept design

The Innovation DiagramxFurniture S.PSS tool can be effectively used for concept design when combined with other tools such as Idea Boards (SDOxFurniture toolkit). The following steps can be taken to utilize the tool for concept design:

1. Access the concept page by clicking "concept";
2. Fille in the satisfaction unit for the project and proposer of the project;
3. Select and position promising ideas designed with Idea Boards (SDOxfurniture toolkit or from other tools) on the 'concept' page;
4. Generate new ideas by spotting the empty areas in the diagram;
5. Identify and cluster ideas that can be combined to draft the system concept and Draft the preliminary system concept by writing a brief text of a maximum of 200 characters;
6. Profile the furniture S.PSS draft concept in its offer (provider, customer, etc.) by copying and pasting characterizing icons from the offer label.
7. Profile the furniture S.PSS draft concept with the concept description form.

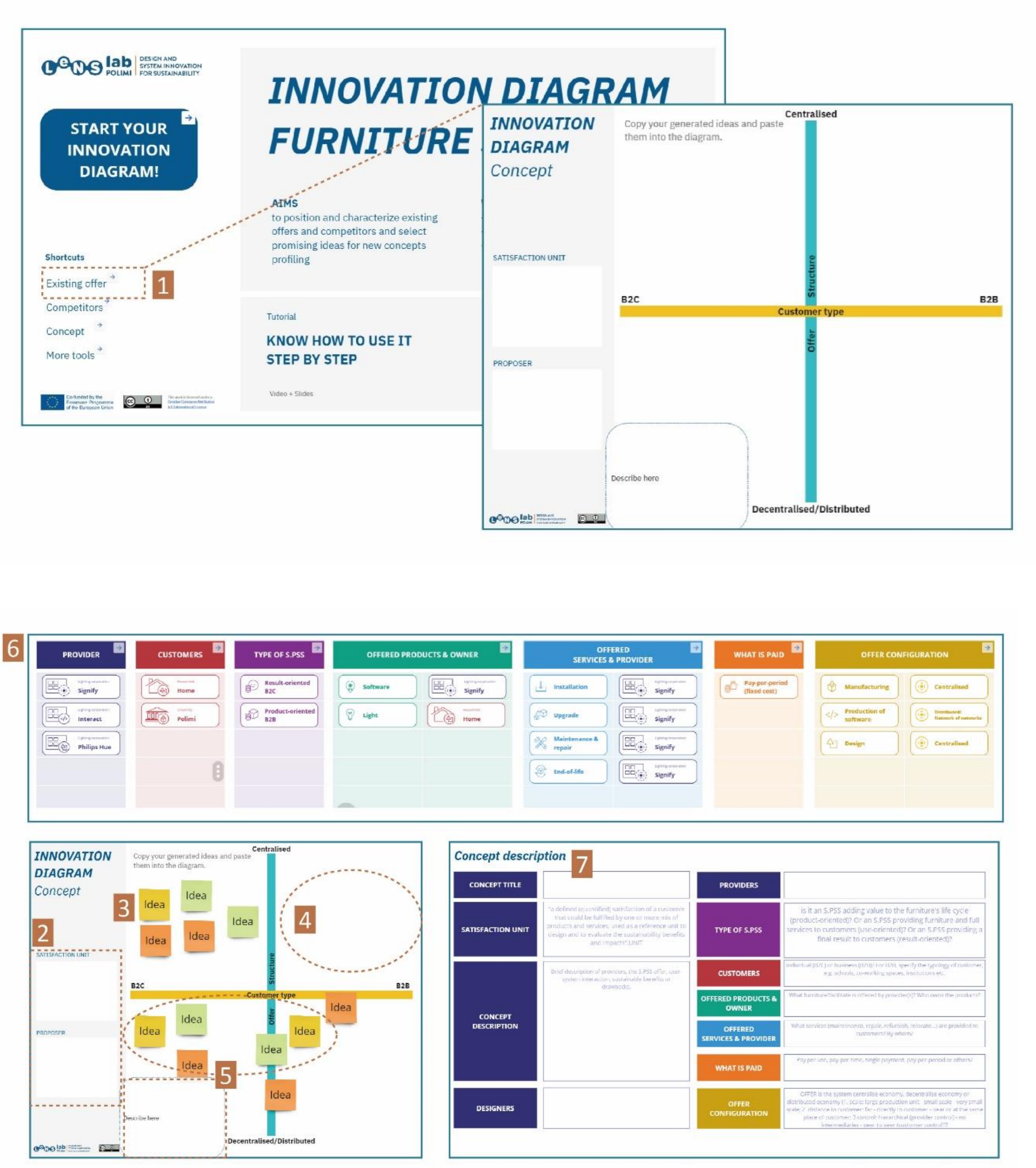


Figure 103 The steps for using the Innovation DiagramxFurniture_for concept design

Tool’s integration into the method for sustainable furniture S.PSS design

The tool can be integrated into the ‘Furniture S.PSS strategic analysis’ stage to ‘analysis existing offer, sustainable best practice’; integrated into the ‘Furniture S.PSS concept design’ stage to ‘generate sustainability-oriented ideas for PSS’, ‘ select S.PSS ideas, and ‘design S.PSS concepts’.

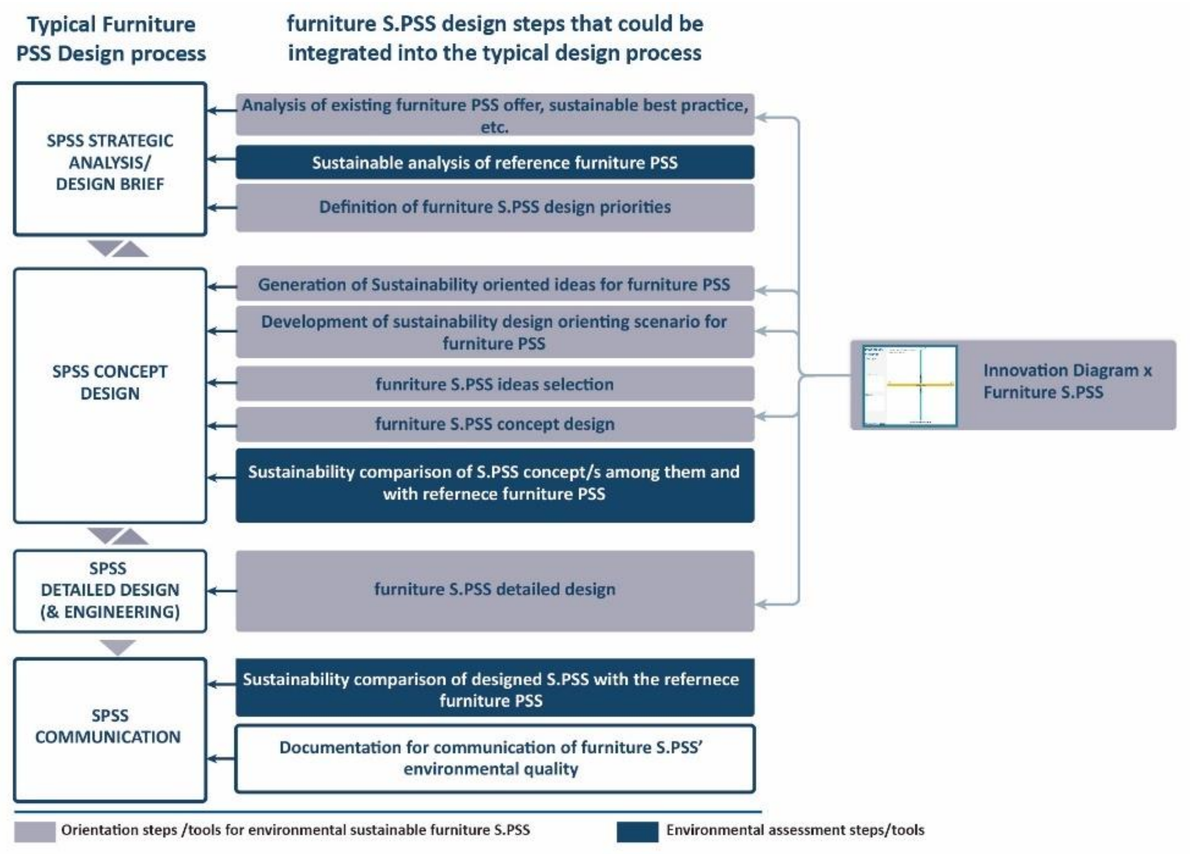


Figure 104 The Innovation DiagramxFurniture integration into the design process

8.3.7 System MapxFurniture S.PSS

Aim

The purpose of the System map is to support the co-design, visualization, and configuration of the system structure, indicating the actors involved and their interactions in the system.

Components

The System map is a graphical representation of:

1. A home page with navigation and tutorial. A system map building board;
2. Stakeholder maker with Repository of providers, consumers, furniture products and characterization, and tutorial;

3. Flow makers with a repository of interaction legend (physical, financial, informational, and labor performance), payment, furniture products, services, ownership and partnership, and tutorial

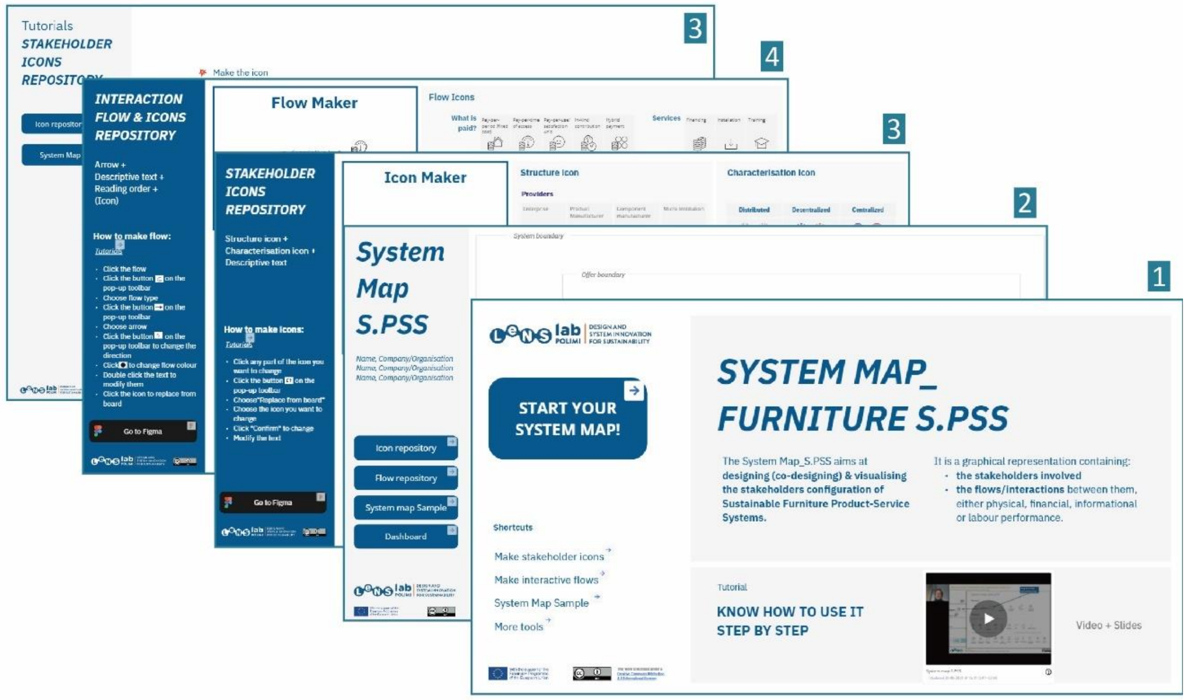


Figure 105 The components for the System MapxFurniture S.PSS

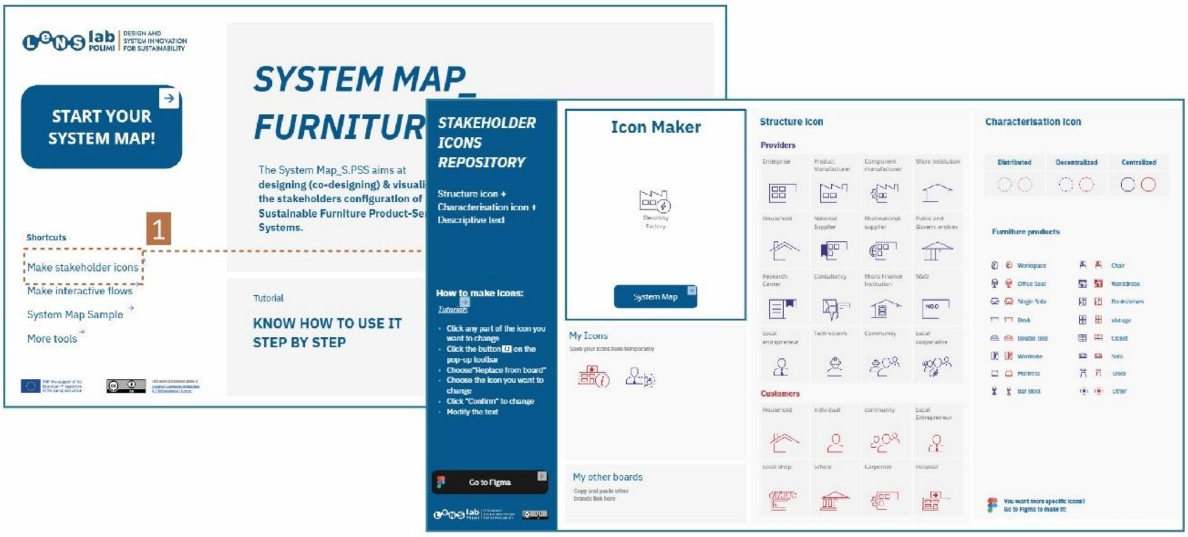
How to use the tool

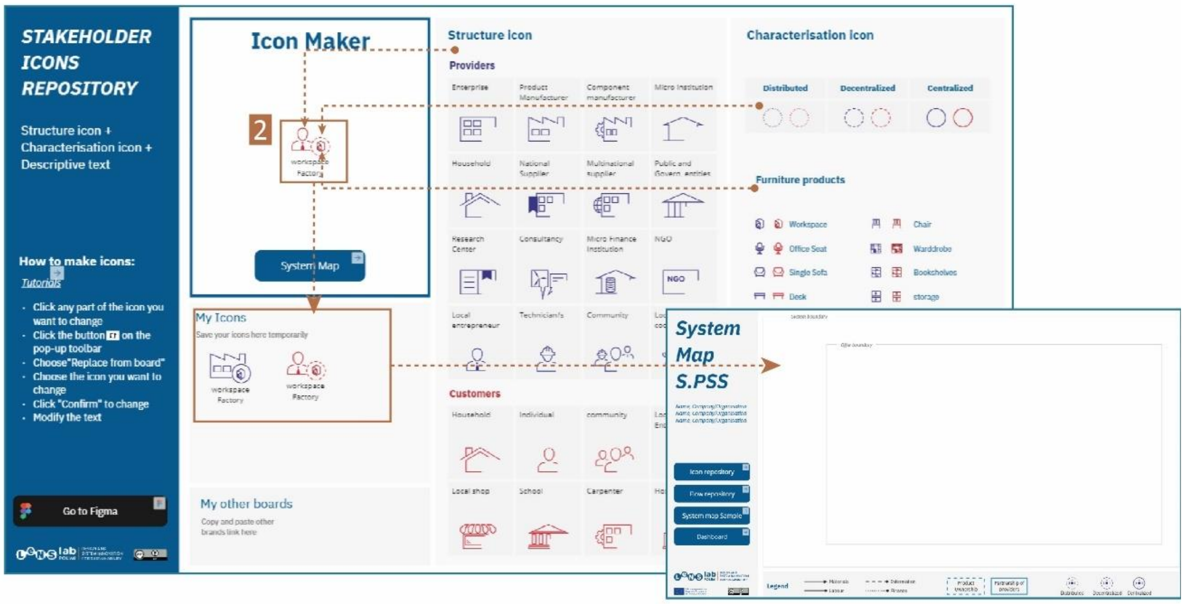
The System Map enables comprehensive visualization of the system structure. On the system map building page, the boundaries are set up, including an offer boundary where the main stakeholders must be positioned and a system boundary for the secondary ones.

1. Enter the STAKEHOLDER ICONS REPOSITORY through the homepage;
2. The first step is to work on the STAKEHOLDER ICONS REPOSITORY to build all stakeholders involved in the system. With the “Icon maker”, users can build the provider by choosing the right representative for the structure icon, characterization icon, and furniture product icon. Write down the provider’s name and a descriptive text on the right of the icon. Save the stakeholder's labels in the “my icons” until finishing. And paste them on the system map board.

   Another element that distinguishes stakeholders is the color: dark violet is used for providers, while magenta is used for customers.

3. Later, define interaction flows on the “INTERACTION FLOW & ICONS REPOSITORY”, using arrows, descriptions, and icons on the board. Interaction flows can be material flow, information flow, financial flow, and labor flow. Remember that the numbering of interaction flows follows the order of activities happening. Within Flow Maker, to create interaction flows, click the flow and change the linear based on the type of flow. Then, click interaction characterization icons and replace them with the proper ones. Copy the Flow to either “my flows” or to the system map.
4. Finally, use dashed squares to indicate ownership of a system or a furniture product and squares around actors to indicate partnership. Both dashed squares and squares are available at the bottom of the system map.





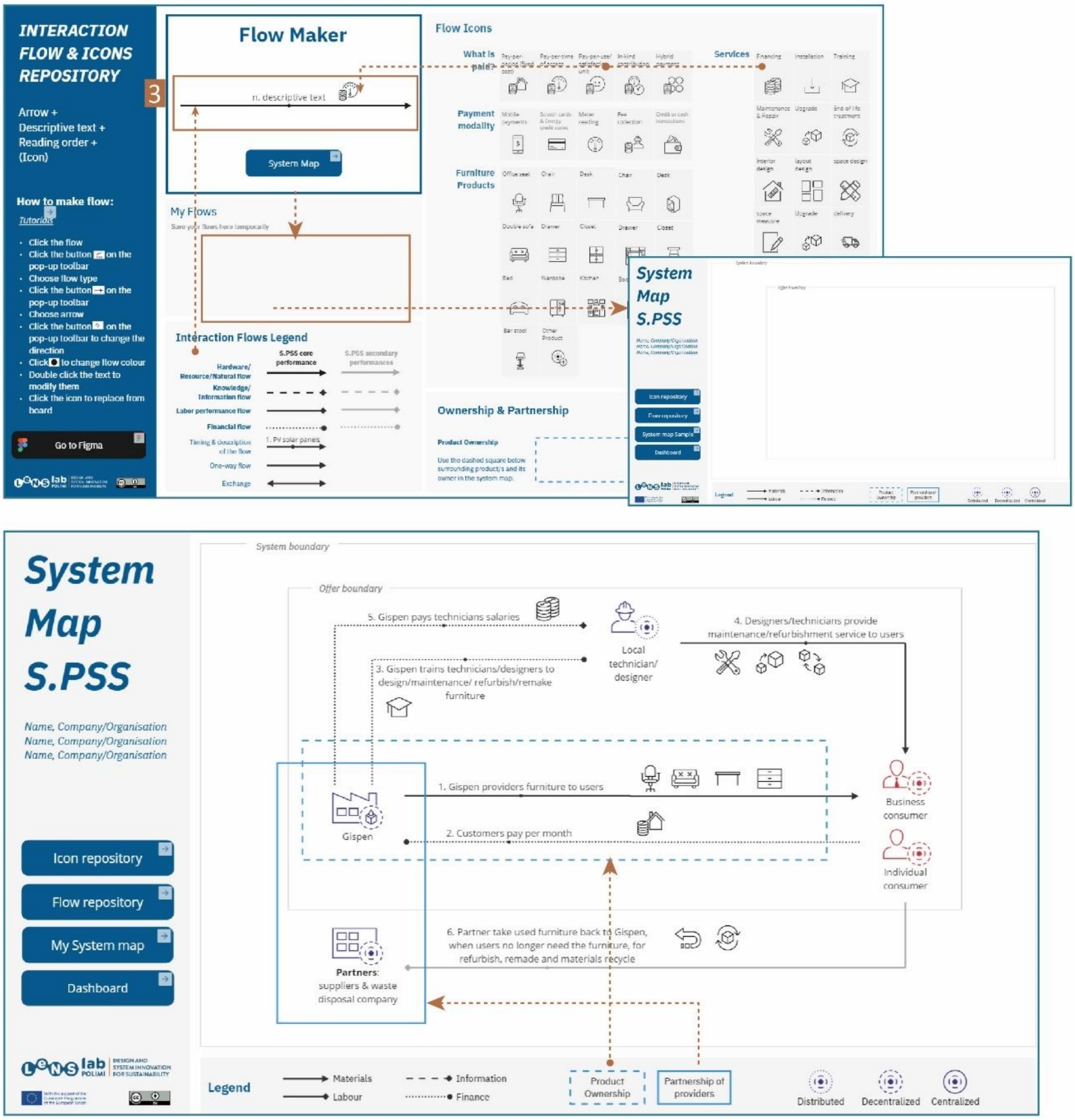


Figure 106 The steps for using the System MapxFurniture S.PSS

Tool's integration into the method for sustainable furniture S.PSS design

Strategic analysis of existing furniture PSS offer/sustainable best practice can be used to visualize stakeholders' interactions within the existing (reference) offer.

Concept Design can be used to visualize stakeholders' interactions within the concept.

Detailed design can be used to further detail and visualize stakeholders' interactions within the detailed concept.

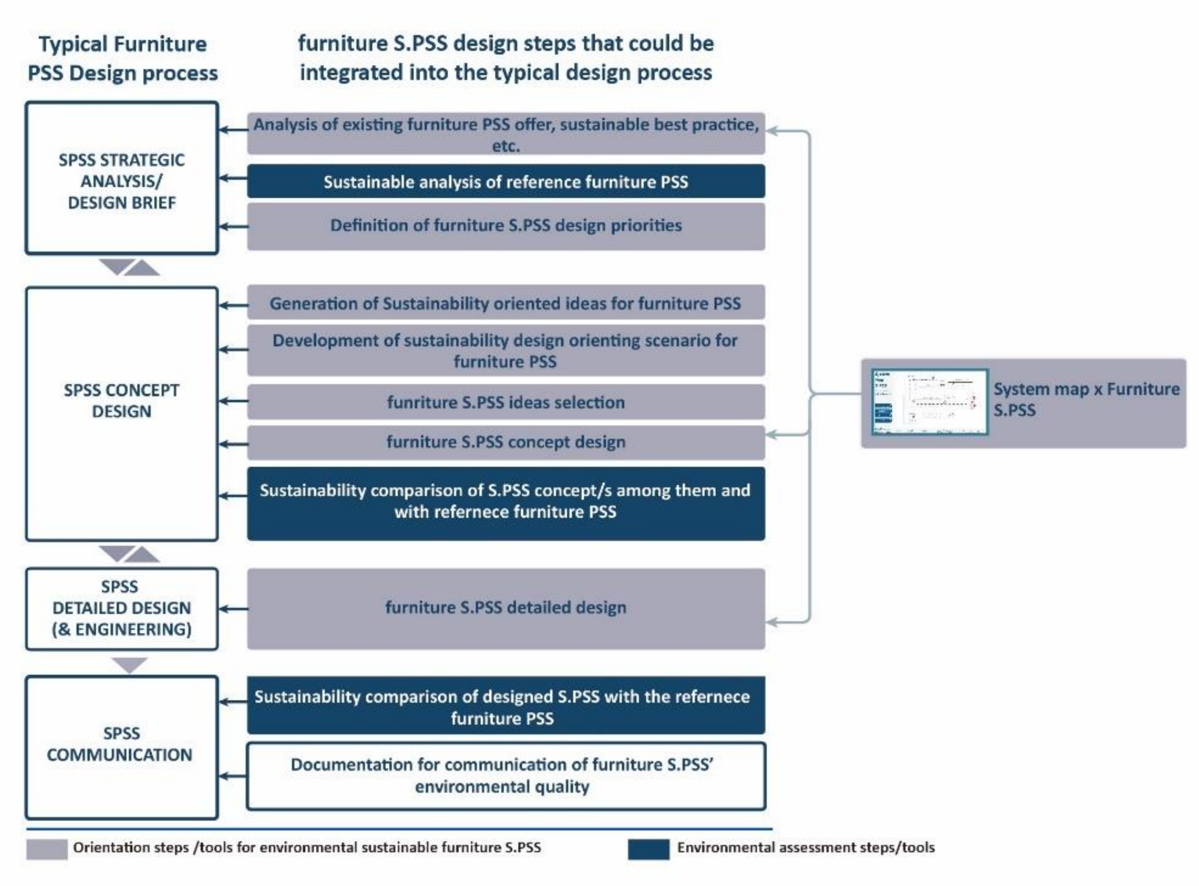


Figure 107 The System MapxFurniture S.PSS integration into the design process

8.3.8 Furniture S.PSSD tools availability

All tools described before for the development of furniture S.PSSD, including the SDOxFurniture toolkit, which encompasses all the tools outlined above are accessible through open access and open-source in the form of either spreadsheet, available to download for free at LeNS Lab polimi [28] / Learning resources / Furniture system design for sustainability tools. Indeed, these tools are resources to spread, implement, and improve the practice of furniture S.PSSD, e.g., by introducing strategies and guidelines related to furniture-specific domains. A video presentation is linked to the source of the tool.

[28] https://www.lenslab.polimi.it/

8.4 Who are these design tools for?

The method and tools aim to support potential furniture researchers, teachers, students, designers, design studios, furniture companies, NGOs, or interested organizations in the practical application of environmentally sustainable furniture system design, which includes designing a combination of furniture products and furniture Sustainable Product-Service Systems.

For designers who are working on sustainable furniture system design projects, whether they are designing furniture products or S.PSS, the method and tools provide guidance and support throughout the entire design process, from strategic analysis to communication, and can be integrated into the general design process to enhance sustainability.

For education purposes, the method and tools can guide students in their design exercise. Firstly, these approaches can help students understand the sustainable furniture product/S.PSS development process. Second, the knowledge and cases integrated with these tools can help students gain a deeper understanding of sustainable furniture products/S.PSS.

This study thoroughly documents each tool's objectives, components, and instructions on how to use these tools, as well as how they can be integrated into the general furniture design process. The ultimate aim is to provide researchers, designers, and students with organized and efficient guidance on how to design sustainable furniture products and S.PSS.

Chapter 9 Sustainable furniture system design tools iterative evaluation/improvement

9.1 Introduction

Chapter 8 described the tools developed for environmentally sustainable furniture product Life Cycle Design and Product-Service System design by integrating the knowledge base developed in the preliminary research stage. This chapter describes the process of tool testing/evaluation and refinement.

9.1.1 Sampling

The strategy adopted was purposive sampling, in which participants were chosen and invited because they are the final users or have the experience as final users. Purposive samples are used when particular people, events, or settings are chosen because they are known to provide important information that could not be gained from other sampling designs (Maxwell, 2008).

All developed tools/toolkits (ICSxFurniture toolkit, SDOxFurniture toolkit, Innovation DiagramxFurniture S.PSS, Concept SheetxFurniture S.PSS, and System MapxFurniture S.PSS) underwent an iterative process of testing and refinement (see Figure 108) involving 70 furniture designers and experts in furniture design and/or design for sustainability. The ICSxFurniture tool was developed and first tested within the GIOTTO project. Then, a workshop involving 30 furniture designers within a course on "design for sustainable furniture" offered by a specializing master by the POLI Design (Politecnico Di Milano) was conducted in February 2022. Subsequently, after updating and refining, these tools were evaluated by 40 participants, including furniture designers from design studio, experts, researchers, and professors from LeNS Network, to get further insights to improve them. This was an iterative process with 4 rounds of evaluation, including an interview with furniture designers, a post-doc, and a teacher with a background in furniture design; interviews with experts on design for sustainability from LeNS Network; a focus group within the DESIS China_Hunan University; and an online questionnaire sent to LeNS members.

Specifically, the ICSxfurniture toolkit underwent 6 rounds of iteration and a final evaluation; the SDOxFurniture toolkit, innovation diagramxFurniture underwent 4 rounds of iteration and a final evaluation. Concept SheetxFurniture underwent 3 rounds of iteration, see Figure 108.

9.1.2 Aim

Within all these activities, the study considers it necessary to evaluate 3 aspects of toolkits or tools. The first one is the application/usability evaluation which aims to identify whether the support can be used for the task for which it is intended and whether it does address the factors that are directly influenced in the way they are supposed to be addressed, i.e., the focus is on usability and applicability (Blessing & Chakrabarti, 2009). In this study, the iterative and evaluation try to identify whether the users can use them smoothly.

The second type of evaluation is the Success/usefulness Evaluation, which aims to identify whether the support has the expected impact, taking into account that unexpected side effects may occur. The focus is on usefulness (Blessing & Chakrabarti, 2009). In this study, the iteration and evaluation activities try to investigate whether these tools help to reduce the environmental impact of furniture systems.

The third one is the comprehensibility evaluation which aims to identify whether the support is easily understandable, considering that some knowledge is integrated. In this study, the iteration and evaluation activities try to investigate whether these tools and integrated knowledge are easily understandable. The following sections introduce in detail the iterative evaluation and refinement process.

Figure 108 The iteration and evaluation process of all tools

9.2 Evaluation within the GIOTTO Project

After 6 rounds of internal (LeNSlab Polimi members) checks and improvement, the first evaluation was conducted within the GIOTTO project. The ICSxFurniture toolkit was sent to all project partners for feedback and comments.

9.2.1 Sampling

The GIOTTO partners including: 1) COSMOB: Centro Tecnologico specializzato per il settore legno – arredo, 2) Cluster Arredo: Società consortile preposta allo sviluppo del Cluster di iferimento del Friuli Venezia Giulia, con l'obiettivo di fornire servizi alle aziende del comparto e, in qualità di Polo di innovazione. 3) UNIVERITA' DI CAMERINO (UNICAM): L'Unità di Disegno Industriale della Scuola di Architettura e Design UNICAM.

Results

For comprehensibility, partners suggested that the tool integrated rich knowledge and know-how. This is good for disseminating knowledge, but it is difficult for users to understand this knowledge.

For usability, the toolkit was developed with Excel. The benefit is that the application supports calculations. However, the use of objects in Excel is not quite user-friendly because the visualization changes from Windows computer to Apple Mac, which makes the tool hard to use. The navigation among eco-idea boards and checklists is not clearly indicated.

The partners gave insights into the toolkit: 10 new cases were integrated into the toolkit, which is beneficial for idea generation.

Design considerations

To improve comprehensibility, a tool guide (PPT version) was made to introduce in detail the toolkit and tools inside, including each tool's aim, function, use steps, and integration into the design process. To avoid the visualization change, I avoided the use of objects in Excel and typed information inside cells. The navigation bar was updated to clearly indicate the navigation among them.

9.3 Iterative testing and refinement with furniture designers and experts

Firstly, a workshop involving furniture designers within a course on "design for sustainable furniture" offered by a specializing master by the POLI Design (Politecnico Di Milano) was conducted in February 2022. Subsequently, after updating and refining, these tools were evaluated by 40 participants, including furniture designers from design studio, experts, researchers, and professors from LeNS Network to get further insights to improve them. This was an iterative process with 4 rounds of evaluation, including interviews with furniture designers, post-doc and teachers with the background of furniture design; interviews with experts on design for sustainability from LeNS Network; a focus group within the DESIS China_Hunan University; and an online questionnaire sent to LeNS members.

9.3.1 Workshop within a specializing master– ICSxFurniture toolkit

The ICSxFurniture toolkit_1 was then empirically tested with 30 international furniture designers, i.e., graduated persons attending a specializing master of "Furniture Design" offered by POLI Design (Politecnico Di Milano). This tool testing was carried out within the course "sustainable furniture design", organized in February 2022. The course included theoretical sessions and practical activities about sustainable furniture products and Product-service system design. The focus of the course was on designing sustainable furniture systems applying furniture LCD and S.PSSD approaches. After an introduction to the concepts of LCD and S.PSSD, designers were given a brief to design a sustainable workstation for home working and then a sustainable furniture Product-service system to deliver the workstation to final users. The workshop aimed at applying the tool from a Usability and Comprehensibility point of view and at assessing its Success/Usefulness as design support. This section describes the activities undertaken by designers and summarizes the feedback collected, which was then considered for the tool's further development.

9.3.1.1 Description of Activities

Furniture designers were first introduced to relevant knowledge on sustainable furniture LCD and S.PSSD and the ICSxFurniture toolkit. In the second phase, students were asked to use the ICSxFurniture toolkit to design a new workstation for home working within 3 days.

On the first day, I introduced the strategic analysis results of the existing workstation and gave students the LCD strategies priorities to be followed as one result of the checklist for existing furniture evaluation. Then, they were asked to use the ECO-idea boards to generate as many promising new design ideas as possible, see table below and Figure 109. In the next step, these young furniture designers were asked to discuss their ideas and, choose the most promising ones and put them on the radar map next to the relevant design strategies, see Figure 110.

Table 40 New ideas generated by furniture designers in the workshop

group	Result of using the ECO-idea boards
1	32 new ideas
2	16 new ideas
3	20 new ideas

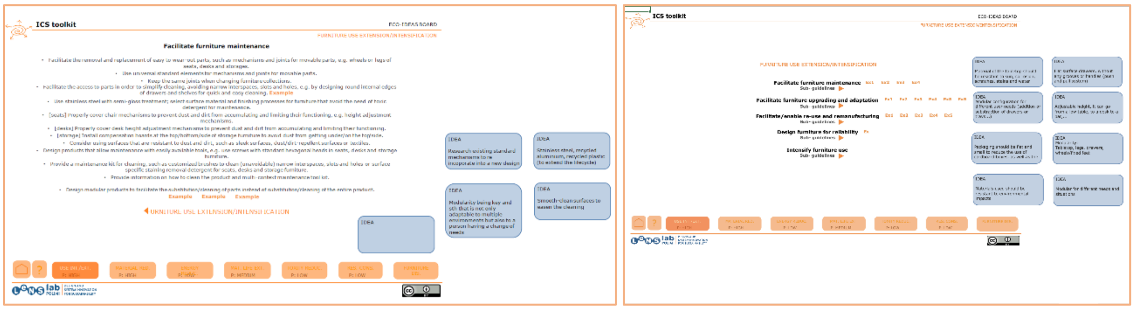


Figure 109 The new ideas generated during the workshop using the Eco-idea tool

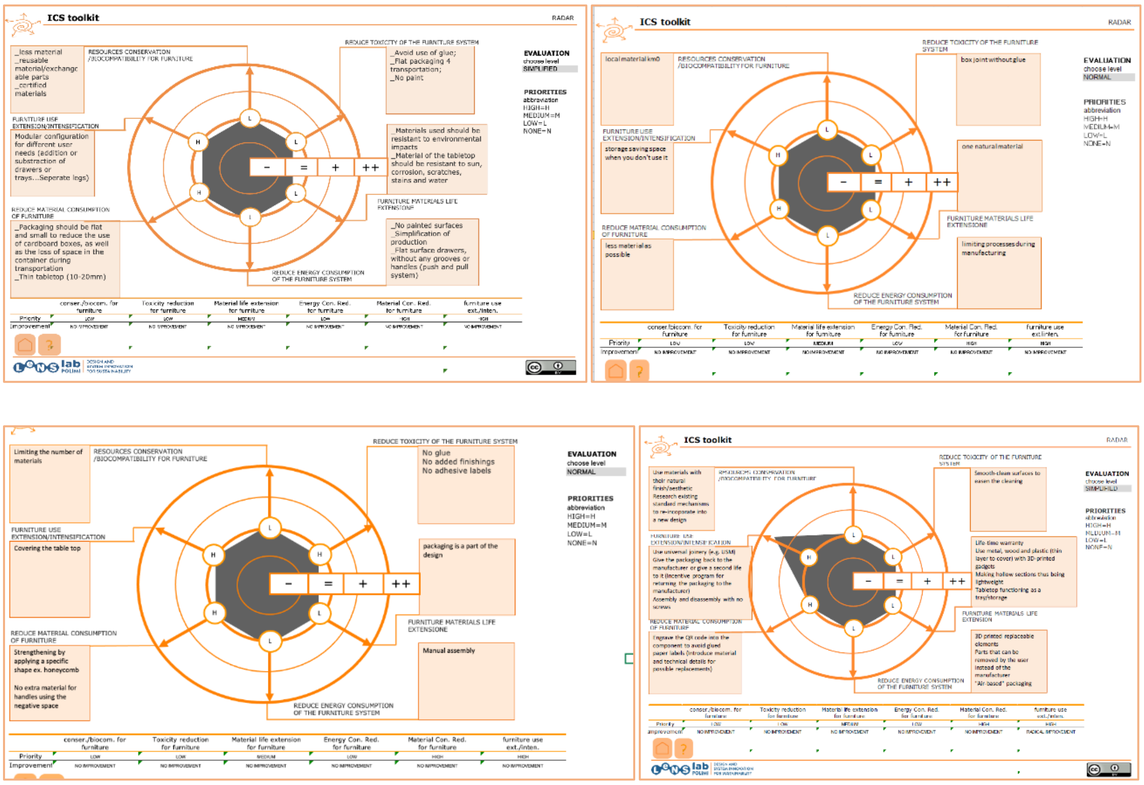


Figure 110 The most promising ideas chosen by users during the workshop using the radar map tool

On the second day, these designers designed new concepts based on the promising ideas generated and clustered on the first day. It is free to use sketches or 3D modeling software to show their concepts. Then, each group presented their concepts in terms of an overview presentation, images, and sustainable design characteristics. From the presentation, even though not all work is finalized due to limited time, all groups have grasped and worked on some key points of furniture LCD.

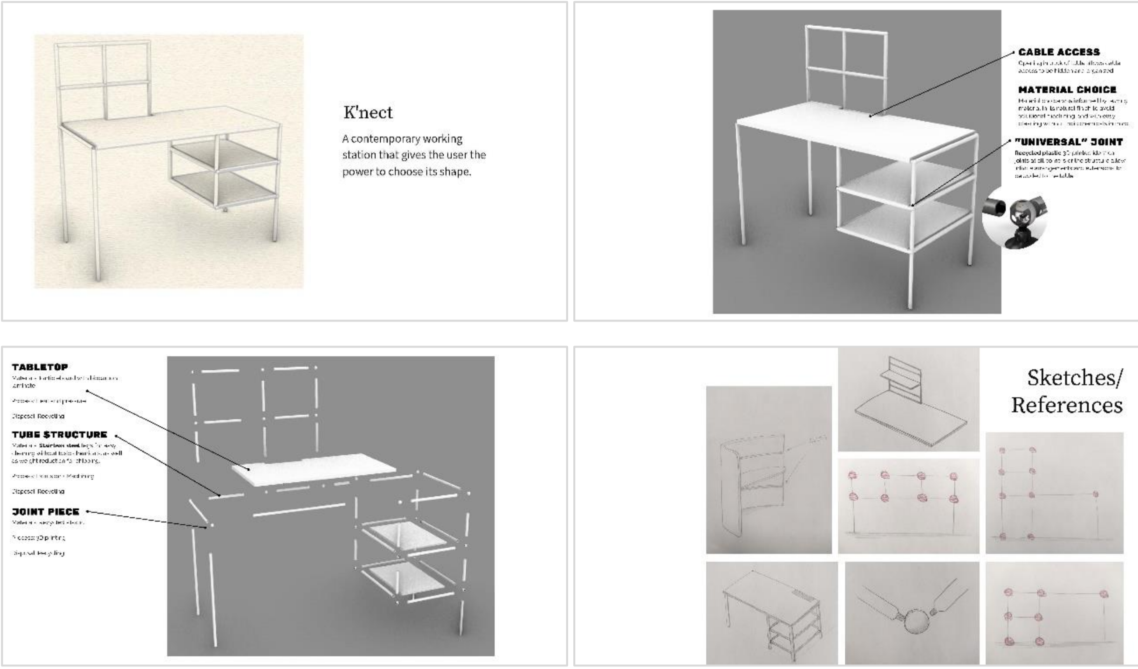


Figure 111 The concept of Group 1.

Note: The concept is characterized by a universal joint that supports easy assembling and disassembling for repair and upgrade. By integrating a QR code, transparent information like the source of materials and the recycling method are displayed.

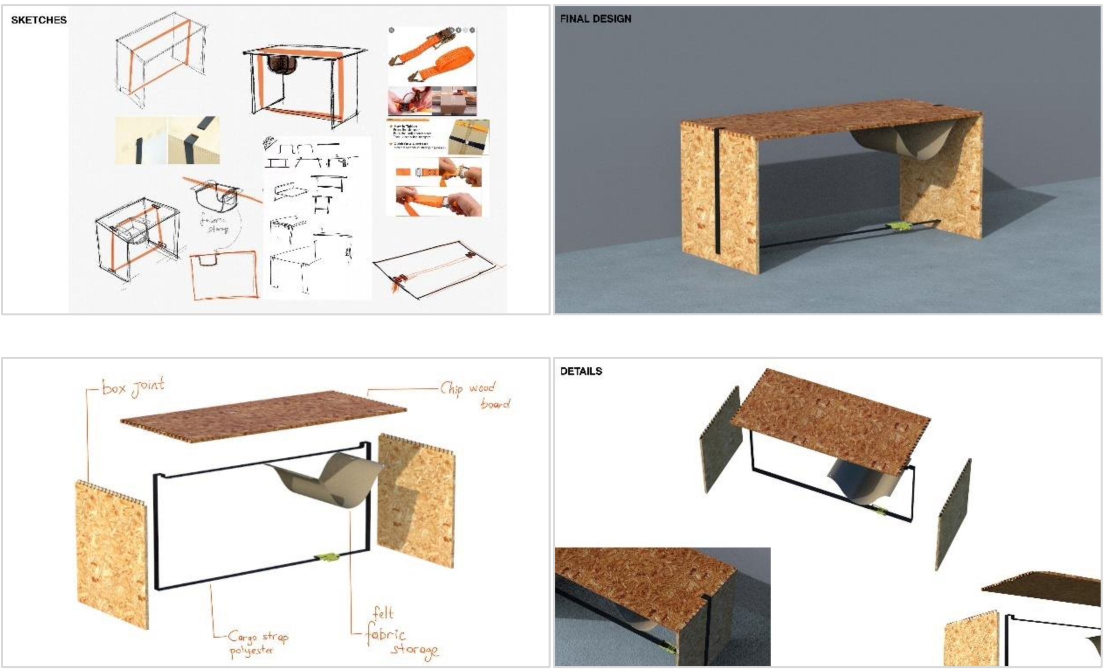


Figure 112 The concept of group 4.

Note: The concept is characterized by reduced material content and simplified structure.

9.3.1.2 Evaluation results

At the end of the exercise, these young designers were given questionnaires to rate the comprehensibility, usability, and success of the ICSxFurniture toolkit with 5 tools. The qualitative data collected is presented in Table 41, while the qualitative responses are discussed below.

Table 41 Questionnaires' results from the workshop at Poli Design

rating: 1= very unsatisfied; 2=unsatisfied; 3= moderately satisfied; 4=satisfied; 5= very satisfied						
tool	1	2	3	4	5	4+5
Comprehensibility: Do you clearly understand the aim of the tool?						
eco-idea boards	0%	0%	27%	40%	33%	73%
multi-strategy radar	13%	7%	7%	53%	20%	73%
checklist for existing furniture evaluation	0%	13%	13%	20%	53%	73%
ESPI form	7%	7%	20%	27%	40%	67%
checklist for LCD strategies pursuit evaluation	0%	7%	27%	27%	40%	67%
Usability: is it easy to understand how to use the tool						
eco-idea boards	0%	0%	27%	27%	47%	73%
multi-strategy radar	0%	7%	20%	33%	40%	73%
checklist for existing furniture evaluation	0%	0%	27%	27%	47%	73%
ESPI form	0%	7%	27%	27%	40%	67%
checklist for LCD strategies pursuit evaluation	0%	0%	33%	60%	7%	67%
Success/Usefulness: do you think the tool is helpful to achieve its aim?						
eco-idea boards	0%	13%	7%	20%	60%	80%
multi-strategy radar	0%	7%	33%	47%	13%	60%
checklist for existing furniture evaluation	0%	13%	53%	20%	13%	33%
ESPI form	0%	0%	21%	43%	36%	79%
checklist for LCD strategies pursuit evaluation	0%	0%	27%	53%	20%	73%

Regarding comprehensibility, most participants (67% -73%) rated as very comprehensible or completely comprehensible with the toolkit.

About the usability, most participants (67% -73%) rated as more than very satisfied with the toolkit. Some participants agree that Excel is the most appropriate platform to develop and achieve the aims of the toolkit, while others suggested the possibility of using other platforms to develop the toolkit, such as an application, Miro, website, and even printable versions. These comments reflect the necessity of easier use and organization, co-working requirements, and better visualization. In addition to this, the navigation between different tools might be confusing. To better understand how to use the tool, some users suggest a description of how to use the tool on each tool's page.

Most participants highly rated the success of the toolkit, with 80% being more than very satisfied with the eco-idea boards. This can also be confirmed by the richness of the new ideas generated after using the tool. 60% rated more than very useful with the multi-strategy radar, 79% with the ESPI form, and 73% with the checklist for LCD strategies pursuit evaluation.

However, only 33% rated more than very successful with the checklist for existing furniture evaluation. The tool is used to define the furniture LCD strategies priorities by making a qualitative evaluation of the environmental problems and improvement potential of the existing furniture. The main consideration is there is not existing furniture to be evaluated but a new design to be developed. In this case, it is impossible for the users to define design priorities by evaluating the environmental problems of the existing furniture.

As a general comment, 93.3% of students would like to use Eco-idea boards in future projects, 66.7% of students would like to use the Checklist for Existing furniture Evaluation, 53.3% would like to use the Checklist for Furniture LCD Strategies Pursuit Evaluation, 40% would like to use ESPI form and Radar.

9.3.1.3 Design considerations

The workshop provided important insights into the ICSxFurniture toolkit's applications and design features. Drawing conclusions from the feedback collected, it can be stated that the tool required some improvements from the function point of view to improve its usability and comprehensibility. Some efforts have been made to address the following aspects:

- A tool guide video presentation has been made for users to understand the function of each tool and how to use each tool.
- Since the eco-idea boards and the checklist for existing furniture evaluation contain different pages, I redeveloped the title for better navigation to avoid missing some strategies.
- Color differentiation was used to guide the operation of tools.

9.3.2 Interviews and Focus group with furniture designers and experts

After the workshop within the specializing master, all toolkits/tools were evaluated by participants, including furniture designers from design studios, experts, researchers, and professors from LeNS Network, to get further insights for improvement. This was an iterative process with 4 rounds of evaluation, including an interview with furniture designers, Post-docs, and teachers with a background in furniture design; interviews with experts from LeNS Network; a focus group in DESIS China_Hunan University. All 19 designers and experts in furniture design and/or design for sustainability gave feedback to improve the tool till the final version presented in this thesis.

9.3.2.1 Sampling

As said, a total of 19 experts were involved in the iterative evaluations, including:

- A furniture designer from SMOOTH studio (the comments were coded and referred to as 3D*[29]);

[29] The first number refers to the round of evaluation, the letter refers to the role of participants within that round, and the last number refers to the sequence of the comments. For example, 3D1 refers to the third-round evaluation (3) with designers (D) and the first (1) comment made by the designer. Ex refers to Experts in the field of design for sustainability, F refers to furniture designers, D refers to designers.

- A postdoc researcher with furniture design experience from Shanghai Jiaotong University (3D*);
- A furniture design teacher from Zhengzhou University of Light Industry (3D*);
- 4 experts belonging to the LeNS network were involved in the study, including a professor and three researchers in the field of design for sustainability and/or furniture design (5Ex*, 7Ex*);
- A professor and 11 researchers in the field of design for sustainability and with experience in furniture design from DESIS China_Hunan University (6F*).

9.3.2.2 Description of process

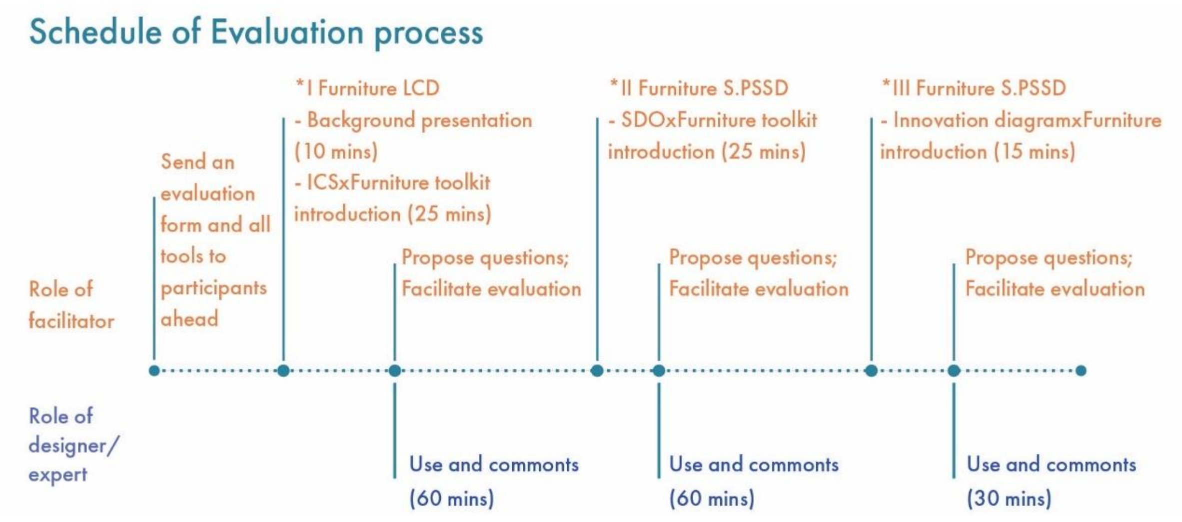


Figure 113 The process of the interviews

Within each evaluation activity, the PhD candidate acted as the facilitator. Before each evaluation activity, the facilitator sends participants an evaluation form and all tools to be evaluated during the interview/focus group. The evaluation started with a background presentation of the aim, the materials used for the interview, the essential knowledge integrated into these tools or toolkits, each tool’s aim and function, and its integration into the design process. The presentation lasted 10 minutes.

Then, the facilitator presented the toolkits and tools to be discussed and evaluated for their aim, function, composition, use process, and integration into the design process. After each introduction, the facilitator facilitates the application with a project of designing a furniture product (a sofa with the ICSxFurniture toolkit) and, subsequently, a product-service system (the sofa's S.PSS with the SDOxFurniture toolkit, innovation diagramxFurniture S.PSS), discussion of these toolkits and the tool with the participants. Each interview/focus group lasts around 4 hours. See the process of the interview in Figure 113.

The discussion and evaluation focus also on the Comprehensibility, Usability, and Success/Usefulness of each tool or toolkit.

9.3.2.3 Iterative evaluation results and design considerations

ICSxFurniture toolkit

Most designers/experts considered the toolkits and integrated tools to be successful in terms of achieving the aims. The overall experience of using is good (7Ex9). Some participants indicated that "the tools are inspirative, give many new opportunities, and would like to use it in future projects (3D3)". The logic of tools application steps and sequences is clear. The articulation between these tools is smooth (3D2). The toolkit is logical and expert for its aim (7Ex28).

At the same time, they expressed some expectations for the toolkit. The development based on the Excel platform may not be as smooth as online platforms (7Ex9, 7Ex3, 7Ex4). Specifically, many people talked about collaboration functions (7Ex7, 7Ex6, 5Ex39, 6F17). However, although I have tried many platforms recommended by these designers, such as board mix, fabire, feishu, Tencent form (6F16), and Miro, and sought suggestions from computer programmers, there is not a platform that could support functions like formula calculation, table creation, collaboration and open access coding and updating which is now synthesized in the Excel. I hope in the near future, the collaboration function and drawing function of Excel will be improved, or the formula calculation function will be integrated into

Miro for further improvement of the existing toolkit. Specifically, for each tool, the suggestions and comments were coded, and the tool design was improved as follows.

Homepage

There is a homepage of the ICSxFurniture toolkit, which is used to navigate among different tools and necessary resources. One element is the ‘furniture-specific LCD strategies’, which are used to show the basic knowledge integrated with the toolkit. Some participants suggested simplifying the interface (5E7, 5E8). The participant also suggested “to cancel the LCD strategies, and change it to Learning resources, video class, etc. the basic knowledge about the tool for practical users (5Ex8).”

For these suggestions, I deleted the elements and visualized the information about design strategies in each tool using pop-up notes. On the other hand, I added open-access learning resources (a tool guide video presentation, a handbook of sustainable furniture system design, and a strategic analysis of the furniture system is attached on the "guide" page (E17), see Figure 114.

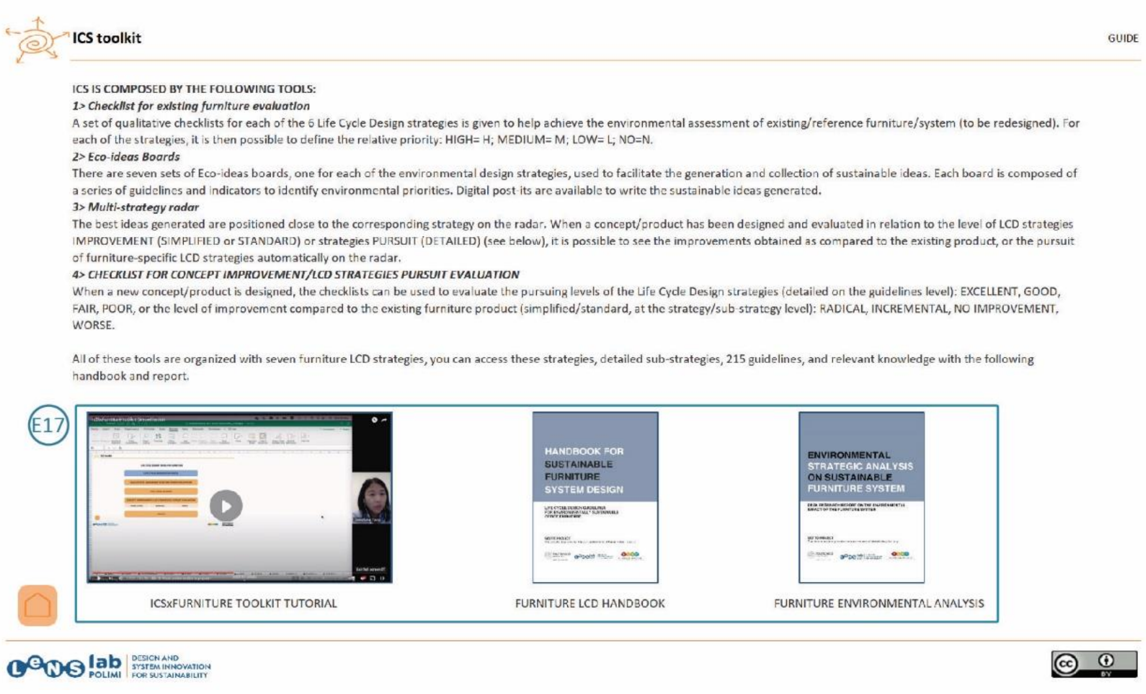


Figure 114 The updated “guide” page

Checklist for existing furniture evaluation:

There is a sequence of using these tools. Some participants expressed difficulties in using the first tool to define design strategies and priorities by defining the environmental problems of existing furniture (system). Some participants considered it difficult to define each strategy's priority by answering the environmental impact of existing furniture (6F2, 7Ex20, 3D10). Some people suggested simplifying the evaluation process, such as by "selecting 'yes' or 'no', and defining the priorities automatically based on the numbers of 'yes' or 'no'" (4D7, 3D11) by providing fixed priority for some categories (6F3), provide some general information (5Ex9). The steps of using the tool are not clear enough. Some participants expressed this by saying, "It may take me some time to understand where to start (despite its clear objectives)" (4D9). Some participants even found a technical bug in the priority's definition and the subsequent step of idea generation, which indicated the understanding of the toolkit (4D8). Some participants consider it necessary to highlight the drop-down list to inform the function/operation (7Ex18).

For these issues, I first made a technical check and debug of the priority definition. I added a pop-up note on the logic of questions with design strategies priorities definition (D6). I added indications on the steps to be followed (D5). I added a translation to indicate the drop-down list for users to choose from (Q1). See Figure 115.

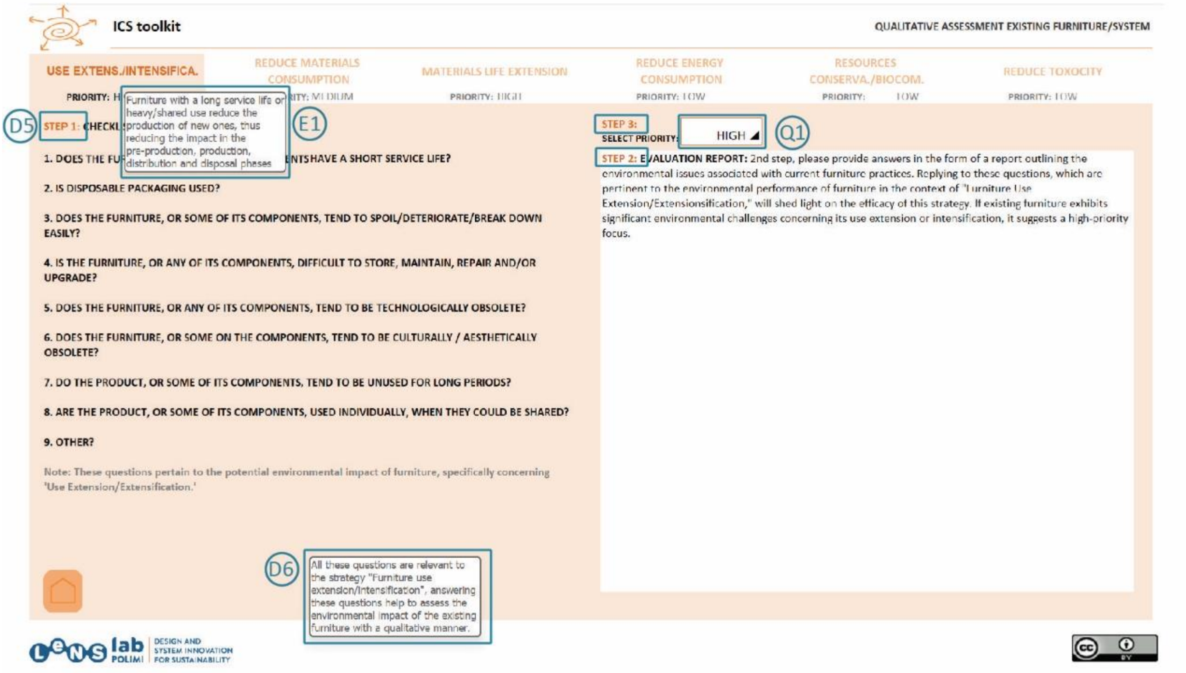


Figure 115 The improvements of the ‘checklist for existing furniture evaluation’ made after the interview.

ECO-IDEA boards

For the ECO-idea board, 154 furniture-specific LCD guidelines were developed and integrated into the tool for promising idea inspiration. In this study and within this tool, design guidelines are specific, detailed, and actionable principles for generating ideas during the design process. Different opinions appear on the integration of so many guidelines. Some participants appreciate the integration of these guidelines and stated, “eco-ideas boards are very helpful for inspiration and useful to generate ideas “(3D16), while others believe these guidelines may be a frame and limit designers’ thoughts, which is not helpful for innovation (4D13). Another issue is the navigation among strategies is clear, while the navigation from one sub-strategy to another is not. This may cause the lack of some sub-strategies inspirations. This is expressed as “the meaning of ‘1/4 >’ is confusing” (3D15). The last issue was about the process of choosing the most promising design ideas from the eco-idea board and visualizing them on the radar map next to the relevant strategy. Some participants considered the process too complex. The ECO-idea board integrates furniture-specific LCD guidelines, which is helpful in facilitating promising ideas generation. However, too much information hinders the visualization of knowledge. Some participants suggested optimizing the visualization of guidelines (5E26, 5Ex32, 5Ex4, 7Ex16, 7Ex11, 7Ex13, 7Ex12, 6F4). Some participants suggested keeping the possibility of using the tool offline (5E40, 5E41). The ECO-idea boards show the design priority for each strategy by inserting a 'HIGH', 'LOW, 'MIDDLE', or 'NONE'. Some participants confirmed the importance of this operation and suggested highlighting the information (5E02). It is suggested to paste all selected promising ideas on the radar map by the tool. However, some people believe there are too many steps and they are not necessary (3D29, 3D30, 3D31). Some have questions about how to select the most promising ideas (5Ex33, 5Ex5) and collect ideas (5Ex1). Some suggested having one example for each guideline (5Ex3) and suggested better visualizing the best case (6F5). Some suggested other platforms, such as Figma (6F8). Some still suggest the possibility of using sketches to express ideas (6F9) and collaboration (7Ex15). For the ECO-idea boards, some design guidelines are equipped with best practices to further inspire the brainstorming process. Some participants thought the mark of EX was not clear enough (6F5).

I consider comprehensive guidelines help designers brainstorm for the following reasons: 1) furniture LCD is not widespread among furniture designers, and most of them lack enough knowledge when proposing new ideas, which can also be confirmed in the semi-structured interview (chapter 5.3.3). These furniture designers sometimes need these guidelines to open their minds to not only materials innovation, which is the most used method now, but also to many new possibilities such as life extension. 2) this tool focuses mainly on the environmental sustainability aspects and is a modular tool that is integrated into the sustainable concept design (ideas generation) phase. It is not the only tool that should be used for all aspects of innovation, such as aesthetics. Designers could also use other tools for innovation in other aspects.

This tool adopts three levels of design guidelines. The first level is ‘Design strategy’ which represents broad visions that guide the design directions. The second level is the ‘design sub-strategy’ which is a more detailed design direction or an abstract of design instructions. The third level is ‘design guideline’, which is more specific, detailed, and actionable instructions for generating ideas during the design process. To make the hierarchical structure clear, I made the following improvements: 1) I replaced the ‘1/4’ title with the names of sub-strategies but emphasized the activated one with a dark brown color (D7); 2) I made a pop-up note to each level of design guideline and guide the next step when there are sub-strategies to be followed (D7).

To deal with the visualization problem, I redesigned the layout of the page by 1) aligning guidelines to the left (E2), 2) increasing the line space (E3), and 3) changing the eco-idea page set to A3 size so users could have a choice of using printable eco-idea, 4) highlighting the different level of priorities with different color and font size to guide the information (E5). The study used a star mark to highlight the cases (F2); at the same time, the title of the case would pop up if the user put their mouse on the icon (F3). I added a navigation icon to the radar to reduce the steps of pasting promising ideas (D8). See Figure 116 for the update.

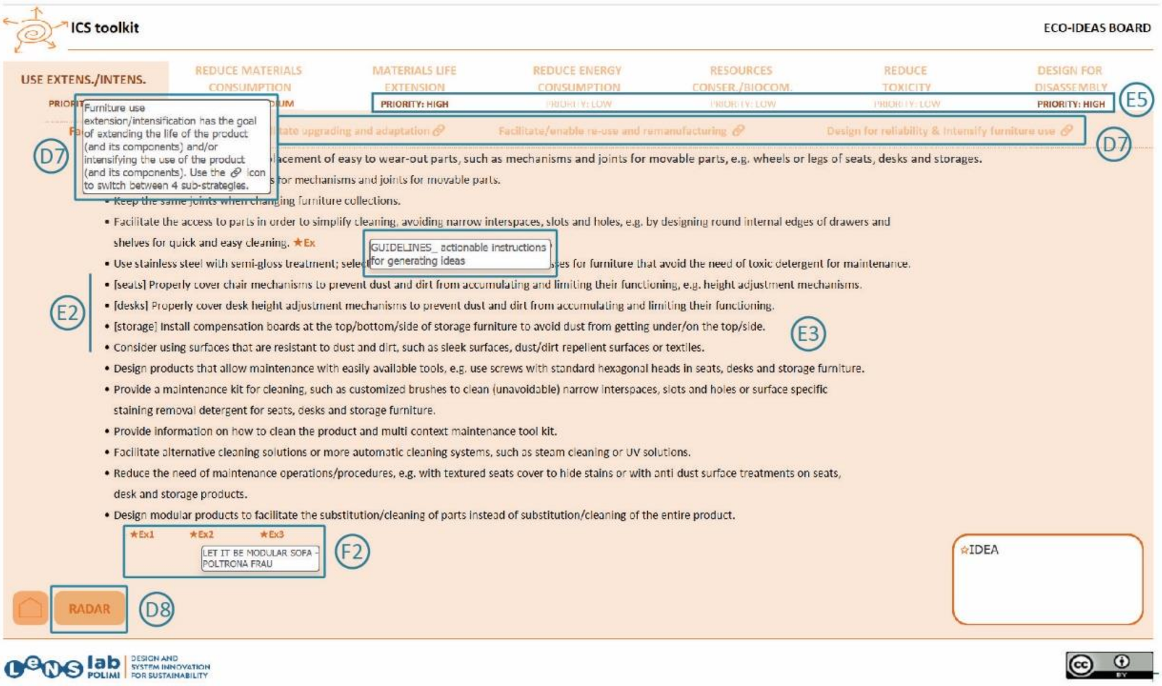


Figure 116 The improvements made for the ‘ECO-idea boards’ after the interview

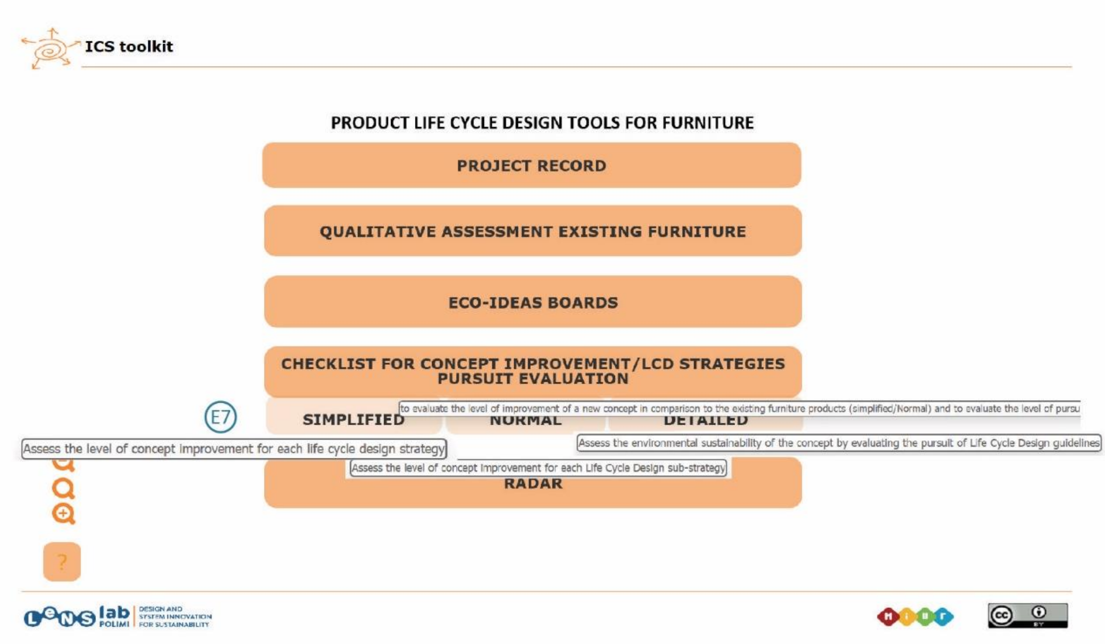
Concept improvement/LCD strategies pursuit evaluation

This tool has three levels of detail: specifically simplified, which compares the concept with existing furniture on the LCD strategy level; normal, which compares the concept with existing furniture on the LCD sub-strategy level; and deep, which evaluates the pursuit of LCD on the guideline level. Participants appreciate the choice of different levels of innovation (5Ex7). However, some participants thought it would be good to tell the differences between these three choices (5E37).

The normal level was thought to be quite clear and easy to use. However, some participants have some questions about the simple level and deep level evaluation. For the simple level evaluation, some participants considered it confusing to show both strategies and sub-strategies but made the evaluation only on the strategy level (3D17). It is suggested to ‘hide these sub-strategies and explain strategies with a short paragraph of words’ (3D17,3D18, 3D19).

For the deep-level evaluation, the method of choosing answers (by inputting '1' under the right answer) is not user-friendly. Some participants suggested using a drop-down list instead of inputting '1' (3D22). It is suggested to visualize the result after evaluation (3D25).

To deal with these issues, I first made the following improvements: E7) used pop-up notes to indicate the differences among these three levels of detail and the approximate time for the tool. For the simplified version, I explained strategies with a short paragraph of words (D9). For the answers to each question, some participants were confused by the choices of 'no' and 'not applicable'. For the detailed version, I technologically improved the way of making choices using a check box rather than input '1'. About the confusion of 'no' and 'not appliable', I give a pop-up box for all choices and their meaning. For each detail level, I put a link to the radar for faster visualization of the result.



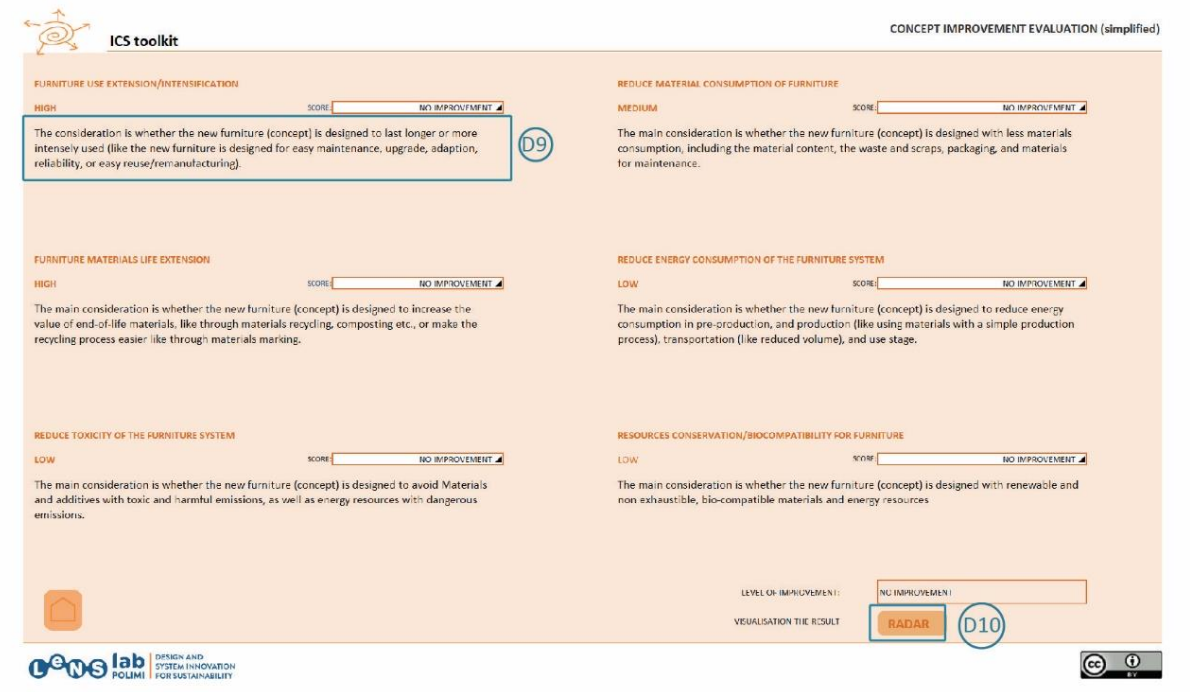


Figure 117 The improvements made to the 'checklist for the pursuit of furniture LCD strategies_simplified' after the interview

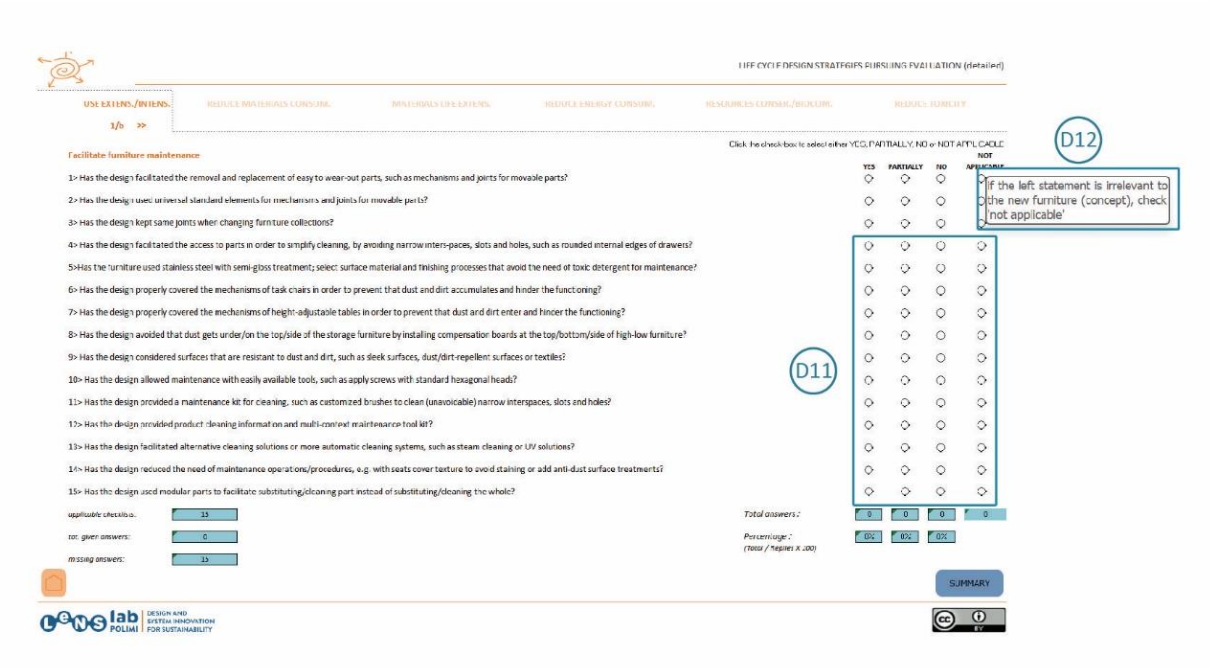


Figure 118 The improvements made to the 'checklist for the pursuit of furniture LCD strategies_deep' after the interview

Radar map

The radar map can be used to show the priority of each LCD strategy, and each strategy can be linked to the ECO-idea board for design iteration. For these functions, some participants proposed that the visualization of priority is not quite clear (6F11), and the hyperlink function from radar to eco-idea boards is not visible (6F12, 3D26), as well as the hyperlink to each checklist for new concept evaluation is not visible (3D27).

Some participants thought the guide was not clear enough. Firstly, the tool could be used to visualize the improvement of a new concept in comparison to the existing one. For this function, some participants suggested emphasizing the comparison by instructing the existing concept and the new concept (5E10). Another participant suggested giving instructions on the existing furniture (5E38). The instructions for improvement levels were not clear enough (5E24, 7Ex21, 7Ex22). The radar map could be used to visualize three levels of comparison (simplified, standard, and detailed). One participant suggested the ‘choose level" should be emphasized (5E25). Finally, the radar can be used to visualize the most promising ideas generated from the tool_ECO idea boards, so the radar is linked to each board by clicking the name of the strategies. For this function, one participant suggested visualizing the navigation function (5E35).

For the radar map, the navigation among tools to support a smooth design process is not that convenient. To deal with this, the tool added hyperlinks to each ECO-idea board and to each checklist for the pursuit of furniture LCD strategies. In addition, some notes to explain in detail all elements were added. See all improvements in Figure 119.

To deal with these issues, I made the following improvements: E8) I added a hexagon in orange color to represent the existing furniture for easier comparison; E9) the circle that one the no improvement level is thicker than others; E10) to make the guide of different levels of improvement clearer, each circle that represents different levels of improvement are filled with colors, the more improvements (radical improvement), the lighter colors (the less environmental impact); E11) the font of ‘choosing level’ is enlarged; E12) a graphical arrow is inserted in the test of each LCD strategy to indicate it is linked to the ECO-idea boards.

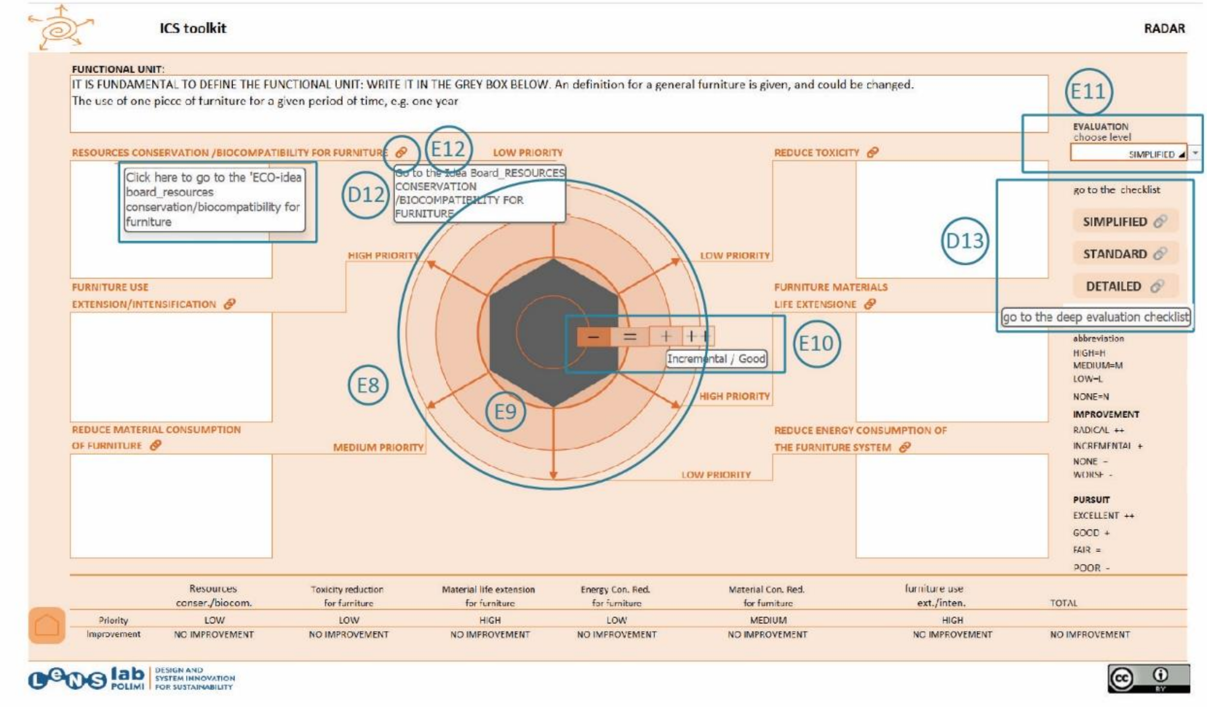


Figure 119 The improvements made to the ‘RADAR map’ after the interview

SDOxFurniture toolkit

The SDOxFurniture toolkit has a similar structure and design logic to the ICSxFurniture toolkit. The main difference lies in the knowledge integrated. The aforementioned comprehensibility and usability issues on the ICSxFurniture toolkit were all checked and improved for the SDOxFurniture toolkit. Besides, considering integrated knowledge, some participants suggested new cases for some guidelines. For example, the IKEA secondhand furniture selling case is linked to the guideline_ Offer infrastructures (e.g., collection points, furniture refurbishing points) or platforms (e.g., an online marketplace of used furniture) and services for furniture reuse and/or second-hand selling (4D14).

SDOxFurniture toolkit

Project record

The first step is to record the basic information of a system using the project record. To fill this form, some background knowledge should be communicated, such as the definition of satisfaction unit and how to describe a system. One participant suggested giving some examples or a taxonomy of the satisfaction unit (5Ex12). To make it clear, I give a definition of a satisfaction unit and some key elements to be included to define a system's satisfaction unit (E13). In addition, key elements of a system are presented to support the description of the existing system (E14).

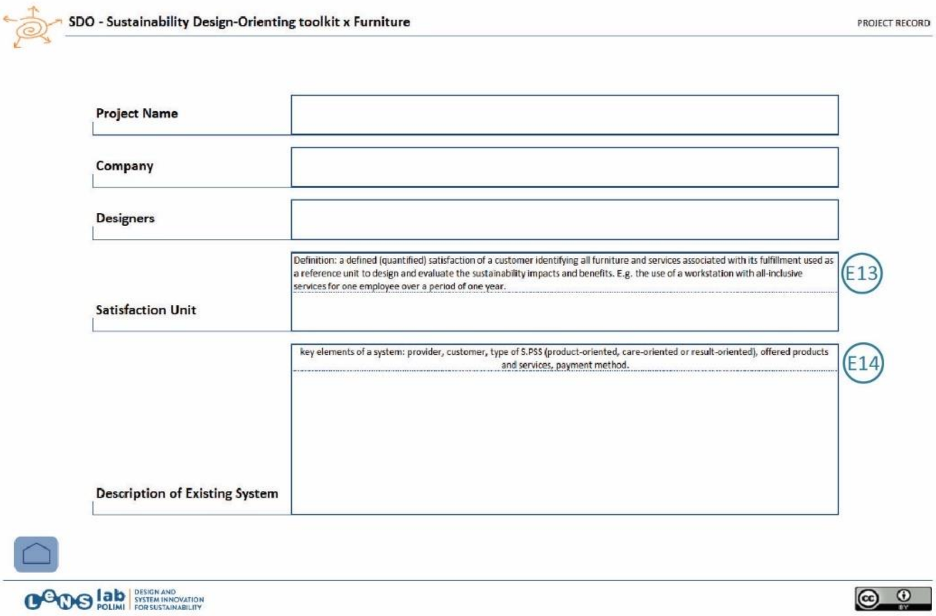


Figure 120 The improvements made to the 'Project record' after the interview

Environmental analysis checklist

The tool is used to analyze the environmental impact of the current (reference) furniture system to prioritize furniture S.PSS design strategies and to analyze the environmental impact of the new furniture concept and compare it with the existing furniture system. It integrates two functions and can be used in two design processes. The circulation process is not quite clear, according to a participant (5E45). To make the design process more fluent, I redesigned the tool and separated the tool into two, one for priority definition and one for improvement evaluation. At the same time, by using the formula function, the environmental impact of existing furniture is automatically transferred to the second tool for easy comparison (E15).

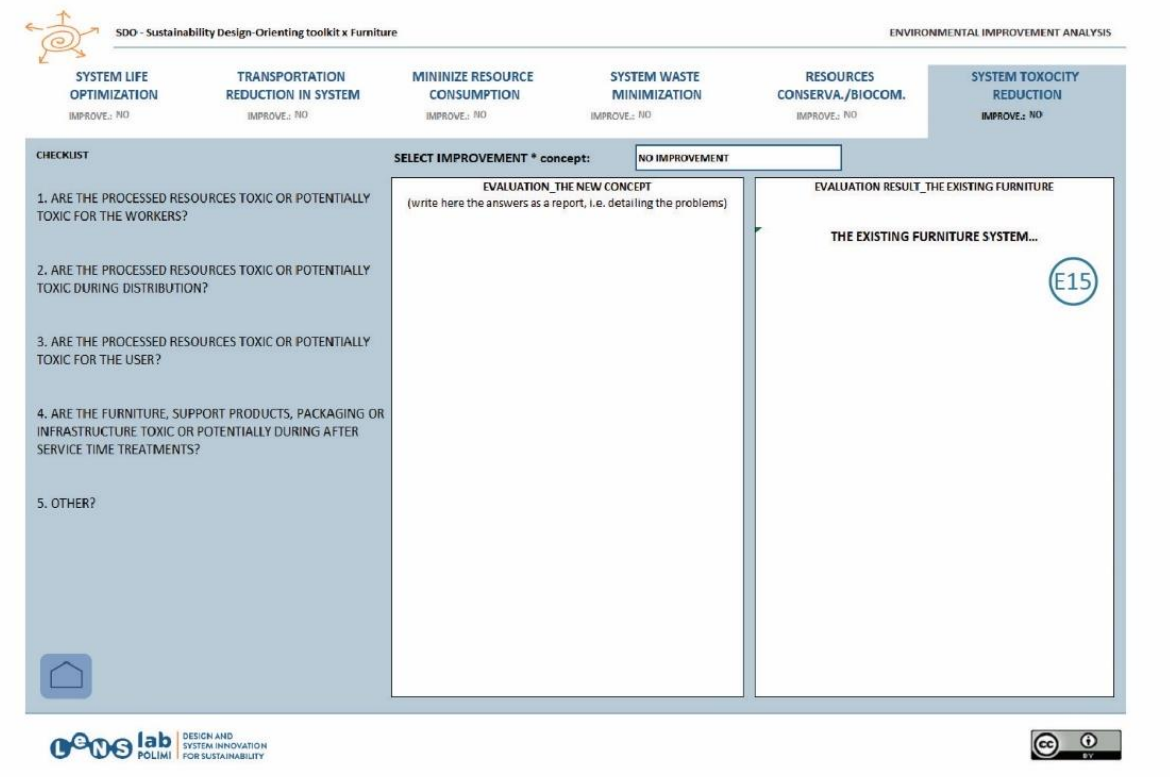


Figure 121 The improvements made to the ‘Environmental analysis checklist’ after the interview

IDEA boards

This tool has the same structure as the ECO-idea board (ICSxFurniture toolkit). The tool aims to foster the generation of furniture S.PSSD ideas. Participants think this is clearer than the ECO-idea boards (5E45). One reason is that the line space is larger, and the font is bolder. These good practices were adopted for the ECO-idea boards. Some guidelines are lined with examples for deeper understanding. Participants repeatedly talked about the collaboration functions and the voting process for the best ideas (5Ex15, 6F19, 7Ex39). The integration of cases makes the tool heavy, and the layout and navigation are not clear (5E14).

To address these challenges, the optimal cases were initially transferred to the Miro board for accessibility (E16). Regarding collaboration functions, various platforms were explored, but none supported formulae, calculations, collaboration, or voting functions. Addressing these functionalities remains a consideration for future work.

Innovation DiagramxFurniture S.PSS, System MapxFurniture S.PSS, and Concept SheetxFurniture S.PSS

The tool can be used to identify and select promising sustainable furniture system ideas (which can be generated from the IDEA board) and design new concepts. Since the functions of the IDEA board and the innovation diagram are sequentially connected, and the current design and cognition are quite different, it is not helpful for easy use. Some participants suggested integrating the IDEA board with the innovation diagram (5E21, 5E22, 5E41). In this case, the SDOxFuriture toolkit is used for environmental evaluation, and the IDEA board and the InnovationxDiagram Funiture would be used for ideas generation and concept design.

Some participants considered it necessary to put steps for using the tool (5Ex29) and tutorials on how to use the tool (5Ex30). The Category axis is a new concept with little knowledge and explanation on them (6F20). It is recommended to give the definition of decentralized, distributed, and centralized (6F21, 7Ex28). It is also recommended to give a detailed introduction of different elements within a system, such as the offer configuration (7Ex25). The jumping from page to page is not user-friendly (7Ex29, 7Ex30). Also, participants suggested moving the tool to miro (7Ex26, 7Ex32, 7Ex33).

These tools have been redeveloped on the Miro platform based on the old version by a master student supervised by the PhD candidate. All these mentioned issues are resolved.

All tools

Considering the usability and success of these tools. Some participants showed interest in integrating these tools in the daily management activities in furniture design (It would be great to integrate these interesting and useful checklists into the software (daily management or quality control) for the users' convenience (4D5)). Some believe it would be simpler to integrate all tools into one (4D1, 5Ex44, 7Ex24, 7Ex1, 5E22, 5E41, 5Ex21). On the other hand, the collaboration function is mentioned repeatedly by users. In addition, users suggested clarifying the role of these tools in the design process, which gives a clearer logic of application. At the same time, this study would leave this work into future studies since, within this work, I would like to keep the modular structure of these tools, which means that designers could choose to work on the product part or the S.PSS part or even using only some of these tools.

9.3.2.4 Future consideration

Since design is a co-creation process, designers expressed expectations of the collaboration characteristics (5E39, 5E01). Considering the calculation and visualization functions integrated into the current toolkit, this function will be further explored in future studies.

The last step of using the ECO-idea board (ICSxFurniture toolkit) and idea board (SDOxFurniture toolkit) is to choose the most promising ideas. Some participants suggested integrating a voting mechanism to select the most promising ideas (5E5, 5E33, 5E15). To optimize the voting mechanism, additional steps would be added, which, on the other hand, makes the process more complex. However, this could be resolved if the tool development platform could be changed to a co-working platform, like the MIRO. This will be further explored in future studies. Some participants suggested adding an example for each guideline (5E3), which is also an aim of this study. However, this study developed 154 guidelines. It is a huge work to collect so many cases. This tool is developed as an open-access toolkit, and I have delivered the toolkit to all LeNS members so researchers and practitioners who are working on sustainable furniture system design could add new cases. In the future, I will also further develop this toolkit.

9.3.3 Online questionnaire

Simultaneously, online questionnaires were distributed to the LeNS Network members who were interested but not available to participate in the focus group or interviews. Each questionnaire included a video presentation of the tool and a link for downloading it freely. A total of 21 LeNS members responded to the questionnaire, providing highly positive feedback across both comprehensibility, usability, and usefulness/success for all of the tools. All members are from the field of Design for Sustainability, with cross-disciplinary knowledge of Product-Service system design, product design, or furniture design.

9.3.3.1 Questionnaire design

These tools integrate a lot of knowledge not only on sustainable evaluation but also on sustainable design. They are complex tools that support the design of sustainable furniture systems. To make the evaluation process more fluent, I designed one questionnaire for each tool/toolkit. For each questionnaire, I put a link to the tool/toolkit for users to work on the tool/toolkit. In addition, a video presentation of the tool, including the aim, function, components, use steps, and integration into the design process, was detailed introduced. A short demo about how to use the tool in a project was given.

For each tool/toolkit, there are three choice questions evaluation and three short answers questions. See below for the questionnaires.

- Questionnaire 1_ICSxFurniture toolkit evaluation: https://forms.gle/oKs7Lb4Ub5YZWLGC9
- Questionnaire 2_SDOxFurniture toolkit evaluation: https://forms.gle/JgYRFVkfSkUHm2eF9
- Questionnaire 3_Innovation diagram tool evaluation: https://forms.gle/ujVZ7sNaGpCVfPnA7

9.3.3.2 Results

ICSxFurniture toolkit

Compared with the first round of evaluation (Table 41), all assessed 3 dimensions have seen satisfaction improvement for comprehensibility, usability, and success. For all three dimensions, success/usefulness has the highest rating, followed by usability and comprehensibility.

Table 42 Questionnaire results from 21 LeNs members_ICSxFurniture toolkit

rating: 1= very unsatisfied; 2=unsatisfied; 3= moderately satisfied; 4=satisfied; 5= very satisfied						
tool	1	2	3	4	5	4+5
Comprehensibility: Are the ICSxFurniture toolkit (and integrated tools) easily understandable (for the function and aim)?						
Checklist for existing furniture evaluation	0%	0%	24%	62%	14%	76%
ECO-Idea Board	0%	0%	24%	57%	19%	76%
Checklist for furniture product LCD strategies pursuit evaluation	0%	0%	29%	52%	19%	71%
Multi-strategic Radar	5%	0%	24%	43%	29%	72%
Usability: Are the ICSxFurniture toolkit (and integrated tools) easily used?						
Checklist for existing furniture evaluation	0%	0%	24%	48%	29%	76%
ECO-Idea Board	0%	5%	24%	52%	19%	71%
Checklist for furniture product LCD strategies pursuit evaluation	0%	5%	14%	52%	29%	81%
Multi-strategic Radar	0%	0%	10%	62%	29%	90%
Success/Usefulness: To what extent do you think the ICSxFurniture toolkit is useful to fulfill its aims?						
Checklist for existing furniture evaluation	0%	0%	24%	38%	38%	76%
ECO-Idea Board	0%	0%	24%	29%	48%	76%
Checklist for furniture product LCD strategies pursuit evaluation	0%	0%	10%	57%	33%	90%
Multi-strategic Radar	0%	0%	14%	24%	62%	86%

Regarding the four tools included in the ICSxFurniture toolkit, a majority of participants (ranging from 71% to 76%) found them to be easily comprehensible. Notably, the checklist for existing furniture evaluation and the eco-idea board received higher comprehensibility ratings compared to the other two tools. Specifically, the Checklist for existing furniture evaluation received a 76% rating, the ECO-Idea Board received 76%, the Checklist for furniture product LCD strategies pursuit evaluation received 71%, and the Multi-strategic Radar received 72%.

However, when it comes to usability and effectiveness, the other two tools, namely the Checklist for furniture product LCD strategies pursuit evaluation and the Multi-strategic Radar, garnered higher ratings. The Multi-strategic Radar received an impressive 90% rating for ease of use (easy and very easy). The Checklist for furniture product LCD strategies pursuit evaluation achieved an 81% rating in this regard. Meanwhile, the ECO-Idea Board obtained a 71% usability rating, and the Checklist for existing furniture evaluation scored 76%. It's worth noting that the ECO-Idea Board received the lowest usability rating, mainly due to concerns about its lack of collaborative features.

In terms of perceived success and usefulness, the Checklist for furniture product LCD strategies pursuit evaluation received the highest satisfaction rating at 90% (satisfied and very satisfied), followed by the Multi-strategic Radar at 86%, the ECO-Idea Board at 76%, and the Checklist for existing furniture evaluation, also at 76%.

This data collectively indicates that, despite initial comprehension challenges, users found it easier to use these tools and achieve their expected outcomes. Please refer to Table 42 for a detailed summary of these findings.

SDOxFurniture toolkit

In the assessment, the SDOxFurniture toolkit surpassed the ICSxFurniture toolkit across all three dimensions. Notably, all three tools within the SDOxFurniture toolkit exhibit higher ratings for both usability and success. When it comes to comprehensibility, each of the three tools achieves ratings between 75% and 80%.

Table 43 Questionnaire results from 21 LeNs members_SDOxFurniture toolkit

rating: 1= very unsatisfied; 2=unsatisfied; 3= moderately satisfied; 4=satisfied; 5= very satisfied						
tools	1	2	3	4	5	4+5
Comprehensibility: Are the SDOxFurniture toolkit (and integrated tools) easily understandable (for the function and aim)?						
Environmental analysis checklist tool	0%	0%	25%	40%	35%	75%
Idea boards	0%	0%	20%	45%	35%	80%
Radar diagram	0%	0%	20%	40%	40%	80%
Usability: Are the SDOxFurniture toolkit (and integrated tools) easily used?						
Environmental analysis checklist tool	0%	0%	15%	50%	35%	85%
Idea boards	0%	0%	15%	60%	25%	85%
Radar diagram	0%	0%	10%	65%	25%	90%
Success/Usefulness: To what extent do you think the SDOxFurniture toolkit (and integrated tools) are helpful in fulfilling its aims?						
Environmental analysis checklist tool	0%	5%	5%	40%	50%	90%
Idea boards	0%	5%	5%	55%	35%	90%
Radar diagram	0%	5%	5%	40%	50%	90%

In terms of usability, all the tools receive impressive ratings ranging from 85% to 90%, signifying that they are easy or very easy to use. Furthermore, for success, all three tools receive a remarkable 90% rating in terms of satisfaction.

Among these tools, the radar diagram consistently receives the highest evaluation, followed by the idea boards and the environmental analysis checklist. Please refer to Table 43 for a detailed summary of these assessments.

Innovation diagram

Table 44 Questionnaire results from 21 LeNs members_Innovation diagram

rating: 1= very unsatisfied; 2=unsatisfied; 3= moderately satisfied; 4=satisfied; 5= very satisfied						
tool	1	2	3	4	5	4+5
Comprehensibility: is the Innovation Diagram x Furniture tool easily understandable (for the function, aim)?						
Innovation diagram	0%	0%	14%	33%	52%	86%
Usability: is the Innovation Diagram x Furniture tool easily used?						
Innovation diagram	0%	0%	14%	38%	48%	86%
Success/Usefulness: To what extent do you think the Innovation Diagram x Furniture tool is helpful to fulfill its aims?						
Innovation diagram	0%	0%	5%	57%	38%	95%

The Innovation diagram receives favorable evaluation results across all three dimensions. In terms of comprehensibility, 86% of participants found it to be easily and very easily understandable. Similarly, for usability, 86% of participants indicated that it was easy and very easy to use. Most notably, in terms of success, an overwhelming 95% of participants expressed satisfaction or very high satisfaction with the tool's outcomes. Please refer to Table 44 for a detailed summary of these assessments.

9.4 Conclusions

Following several rounds of evaluation and subsequent refinements, these tools have reached their final versions. In comparison to the initial release, participants expressed significantly higher levels of satisfaction with the comprehensibility, usability, and effectiveness of these tools.

However, it's important to note that not all feedback and suggestions received during the evaluation process were implemented. Firstly, some suggestions proved unattainable within the confines of the Excel platform, and certain evaluation functions couldn't be replicated in alternative platforms. Future research endeavors will involve monitoring the potential integration of these features as related platforms undergo updates.

Secondly, participants offered varying and sometimes contradictory suggestions. For instance, regarding the eco-idea boards, some participants believed that overly detailed guidelines hindered innovation, while others appreciated the comprehensive design guidelines for their capacity to stimulate creativity. The study aimed to provide comprehensive design guidelines and possibilities for sustainable innovation. Additionally, it's worth highlighting that the tools and toolkit developed in this research are modular, allowing users to seamlessly integrate them into their own design processes, even in the context of aesthetic innovation.

Although with some limits, such as the lack of testing in furniture companies in real long-term projects, the testing activity tried to reach comprehensive results using a triangulation strategy by collecting information from a diverse range of individuals and groups (furniture designers, master students with the background of furniture design or Design for sustainability, teachers, researchers, and experts with the background of furniture design and/or Design for Sustainability), using a variety of methods (workshop, interview, focus group, questionnaire). This strategy reduces the risk of chance associations and systematic bias due to a specific method and allows a better assessment of the generality of the explanations that one develops (Maxwell, 2008).

Part IV Reflections

In the final stage, reflections were made, and the objectives, findings, and contributions to both theory and practice are synthesized in Chapter 9.1. Essentially, this research aims to establish a knowledge base, encompassing theoretical frameworks, approaches, guidelines, etc., and practical know-how, including methods, tools, etc., for Sustainable Furniture System Design. The primary focus is on Furniture Life Cycle Design (LCD) and Sustainable Furniture Product-Service System Design (PSSD).

Despite the theoretical and practical contributions, this research has certain limitations. Given its research focus, it predominantly centers on the application of Life Cycle Design (LCD) and Sustainable Product-Service System Design (S.PSSD) in the furniture sector as a means to address existing unsustainable furniture products and business models. However, there are still unexplored Design for Sustainability (DfS) approaches within the field that warrant further investigation.

The practical tools developed have undergone testing through six rounds of evaluation and improvement with furniture designers and experts. However, additional testing in various furniture company contexts and projects would provide valuable insights. Additionally, considering ongoing research activities such as the eco-design of products regulation by the Joint Research Center of the European Commission, scheduled for release in April 2024, new eco-design rules and guidelines may emerge. Therefore, it is crucial for this research to stay updated on these developments, as detailed in Chapter 9.2.

Given these considerations, there is a need for further work, including the application of the developed knowledge base and know-how in projects and design practices. As new functions are embedded in existing platforms or new platforms emerge, unresolved issues such as the collaboration functions of the ICSxFurniture toolkit and the SDOxFurniture toolkit will be addressed. Moreover, additional Design for Sustainability approaches should be explored and considered for application in the furniture sector. Furthermore, more specific guidelines tailored to particular furniture types or a certain company should be developed, as outlined in Chapter 9.3.

Nevertheless, the knowledge base and know-how generated through this research are made available in an open-access manner. This approach facilitates continuous improvement, modification, and upgrading by potential end-users. Leveraging the LeNS network community, which connects 150 universities worldwide working on Design for Sustainability, the dissemination of knowledge, updating, and further specification will be carried out by researchers in the same field. Additionally, in collaboration with other researchers, an open course and an open-access book are planned for publication, contributing further to knowledge dissemination, as outlined in Chapter 9.4.

Chapter 10 Conclusions and Discussion

10.1 Objectives and research findings

The research aimed to develop a knowledge base and know-how for Sustainable Furniture System Design, addressing both product life cycle design and sustainable product-service system levels (covered in chapters 6-8). This objective was driven by environmental issues stemming from the furniture system at both the product and production & consumption system levels, the considerable potential for the furniture system to transition to sustainability, the absence of regulations (discussed in Chapter 1), and the lack of furniture-specific system design knowledge, approaches, methods, and tools from both academic (chapter 2) and practical perspectives (covered in Chapters 4.3.3, and 5.3.3). The achievement of these objectives unfolded gradually through the systematic exploration of two main research questions. The research questions, objectives and relevant chapters are illustrated in Table 45.

Table 45 The research questions, objectives and relevant chapters

	Research questions	Research objectives/ purposes	chapters
preliminary research		0.1 to understand the contexts of sustainable furniture system design *(environmental unsustainability, potential for transformation, and policy contexts)* **(exploration)**	CH 1
		0.2 to define the scope of the resarch *(sustainable dimensions, DfS approaches most applicable for furniture, the existing gap in knowledge and know-how)* **(exploration)**	CH 2
	RQ1 What are the framework and characteristics of environmentally Sustainable Furniture Systems?	A to provide a comprehensive conceptual framework for sustainable furniture systems **(exploration)**	CH 4
	1.1 What are the innovation requirements and characteristics of environmentally sustainable furniture products (product level)?	A1 • to explore in detail furniture products' environmental impact and design insights from practice • develop furniture products' life cycle profile A2 to explore the sustainable characteristics, deisgn insights of furniture products	
	1.2 What are the characteristics of environmentally and economically Sustainable win-win furniture Product-Service Systems (PSS level)?	A3 to explore the sustainable characteristics, deisgn insights, potential win-win benefits of furniture S.PSSD A3 to develop an archetypal furniture S.PSS map	CH 5
Prototyping	RQ2 What new knowledge is needed to design environmentally Sustainable Furniture Systems?	B to develop knowledge and know-how for SFSD **(exploration and description)**	CH 6
	2.1 What new competencies, skills, methods and tools are needed for environmentally sustainable furniture Life Cycle Design (product level)?	B1 to develop furniture-specific system design guidelines (including furniture LCD and furniture S.PSSD) with priorities **(exploration)**	
Assessing	2.2 What new competencies, skills, methods and tools are needed for environmentally Sustainable furniture Product-Service System Design (PSS level)?	B2 to develop furniture system design method and tools **(description)**	CH 7- 8

10.1.1 The conceptual framework of environmentally sustainable furniture system

The research commenced with an examination of the sustainability contexts within the furniture sector. It became evident that the environmental issues were not solely confined to the furniture product (life cycle) but were also linked to the escalating production and consumption of furniture systems. Viable solutions, therefore, necessitated a combination of product innovation and Product-Service System innovation. Following a review of Design for Sustainability approaches, it was determined that Product Life Cycle Design and Sustainable Product-Service System Design emerged as promising avenues for addressing these challenges within the furniture industry.

The first step was to explore the framework and characteristics of an environmentally sustainable furniture system (on both Product and PSS levels). Below is the summary of how each objective was met to answer RQ 1.

The initial step involved an exploration of the conceptual framework of environmentally sustainable furniture systems at both the product and Product-Service System (PSS) levels. The following is a summary of how each objective was fulfilled to address Research Question 1.

(A1) To explore in detail furniture products' life cycle profile

The initial exploration employed the Life Cycle Assessment (LCA) approach, as detailed in Chapter 5.1. The LCA yielded two primary outcomes. Firstly, it provided a detailed conceptualization of the furniture system boundary, encompassing all activities (processes) directly or indirectly related to furniture before, during, and after its use. Secondly, the LCA offered insights into the furniture's life cycle environmental impact through quantitative data. Environmental impacts were calculated and compared for 25 pieces of furniture, revealing that sofas, closets, tables, and workspaces exhibited higher impacts compared to the other four groups (task chair, chair, stool, coffee table). Analyzing the LCA data uncovered a comprehensive trend regarding the environmental impact across various life cycle stages of furniture. Notably, the pre-production stage exerted the highest environmental impact, while the production and end-of-life/distribution phases displayed considerably lower impacts. Surprisingly, the use stage emerged as the phase with the lowest impact. These results provide a detailed understanding of the sources of environmental impact in furniture products and suggest directions for resolution.

(A2) To explore the sustainable characteristics, design insights of furniture products

Following the identification of life cycle activities and their environmental consequences, an exploration of the characteristics of existing furniture products was undertaken through best case studies and semi-structured interviews. The objective was to gather up-to-date knowledge about design interventions from exemplary cases and companies' interviews. Consequently, 15 design approaches with 37 detailed design approaches were identified and categorized according to 7 design strategies.

(A3-A4) To explore the sustainable characteristics and design insights of furniture Product-Service System

This was accomplished through a comprehensive study of 44 best cases and semi-structured interviews, achieving three main objectives. The first objective aimed at identifying design interventions for environmentally sustainable furniture PSSD, analyzing four key elements: provided products, offered services, involved stakeholders and business models. Ten business models and 31 types of services were identified. 3 types of furniture S.PSS were identified.

The second objective involved exploring potential benefits and characteristics of Furniture Sustainable Product-Service System Design (S.PSSD). Building upon proposed general win-win environmental-economic S.PSS benefits by researchers, the study hypothesized five such benefits applicable to the furniture sector. These win-win benefits were subsequently confirmed through the case study and semi-structured interviews.

The third objective sought to develop an archetypal Furniture S.PSS map based on defined insights. Using furniture use contexts as one dimension and furniture S.PSS types as another, the study created an Archetypal Furniture S.PSS Map, positioning the best cases and developing 20 promising visions.

(B1) To develop furniture-specific system design knowledge _ guidelines

This objective was fulfilled through a workshop with experts, building on previous findings and improved after experts' evaluations. Leveraging general Life Cycle Design (LCD)/Sustainable Product-Service System Design (S.PSSD) guidelines, the workshop started with a knowledge presentation phase in which the PhD candidate shared outcomes such as Life Cycle Assessment (LCA) results, case study findings, and insights from semi-structured interviews. The workshop then involved a structured process for developing furniture-specific guidelines. The process involved various specification actions, including specification of general guidelines by integrating furniture characteristics, introducing a new guideline, and removing a guideline if deemed irrelevant, etc. The result encompassed 7 furniture-specific strategies, 23 sub-strategies and 154 guidelines on the furniture product level. On the furniture S.PSSD level, 6 strategies and 46 guidelines were proposed. These guidelines represent crucial knowledge for furniture designers, offering valuable insights to significantly reduce environmental impact throughout the furniture system.

(B2) To develop furniture-specific system design know-how _ methods and tools

This objective was realized by creating furniture-specific Life Cycle Design (LCD) and Sustainable Product-Service System Design (S.PSSD) tools, addressing the identified lack of tools in furniture practice and incorporating the developed design knowledge.

At the furniture product level, the ICSxFurniture toolkit was formulated, comprising four integrated tools: Checklist for Existing Furniture Evaluation, Eco-Ideas Board, Checklist for Concept Improvement/LCD Strategies Pursuit Evaluation, and Multi-Strategic Radar.

At the furniture S.PSSD level, the SDOxFurniture toolkit, an innovation diagram, a system map were designed. The SDOxFurniture toolkit integrates four essential tools: Environmental Analysis Checklist, Idea Boards, Environmental Improvement Analysis Tool, Radar Diagram.

The ICSxFurniture and SDOxFurniture toolkits were meticulously organized, aligning each tool with specific strategies derived from the developed guidelines. The guidelines for each strategy serve as crucial knowledge for effectively utilizing these toolkits. To enhance the practical application of the tools, the analyzed best cases were intricately connected to the eco-idea boards (ICSxFurniture toolkit) and the idea boards (SDOxFurniture toolkit), providing a continuous source of inspiration during their use.

The newly developed tools underwent a rigorous testing and evaluation process, involving six rounds of evaluation studies with diverse user groups. Through these iterative rounds, the tools were refined and improved to ensure their comprehensibility, usability, and overall success.

10.1.2 Research contributions _ the new knowledge base and know-how for sustainable furniture system design

This research focused on exploring the application of Life Cycle Design (LCD) and Sustainable Product-Service System design (S.PSSD) within the furniture sector. The primary goal was to create a comprehensive knowledge base and provide practical know-how for companies, furniture designers, researchers, and future design professionals. The theoretical contributions of this study encompass enriched literature on furniture Life Cycle Design and Sustainable Furniture Product-Service System Design. It includes detailed environmental insights spanning the entire furniture life cycle and the broader production and consumption system. Additionally, a conceptual framework and comprehensive furniture-specific guidelines were developed for both the product and Product-Service System levels.

From a practical standpoint, this research introduced the ICSxFurniture toolkit, designed to facilitate sustainable furniture Life Cycle Design. It also presented the SDOxFurniture toolkit, an innovation diagramxFuniture and system mapxFurniture tailored for Sustainable Furniture Product-Service System design. Furthermore, the study compiled a repository of exemplary furniture products and Product-Service System best practices, offering valuable insights and inspirations.

These insights and tools developed are shared with the LeNS Network community, fostering collaborative knowledge dissemination and furthering the global discourse on Design for Sustainability.

Theoretical contribution

The theory of Design for Sustainability (DfS) has a well-established foundation dating back to the early 1990s. Initially, DfS focused on low-impact material and energy selection, then expanded to product design, Product-Service System design, Spatio-Social innovation, and more recently to socio-technical systems innovation (Ceschin & Gaziulusoy, 2019). However, the knowledge derived from broadly contextualized research methods tends to be overly general and abstract, limiting its utility in diverse settings (Cobb, 2001; Cobb et al., 2003; E. Baumgartner & Bell, 2002). The furniture system, which generates significant environmental impact throughout its life cycle and within the production and consumption system (see Chapter 1), has substantial potential for improvement (European Commission, 2020; Joint Research Center of the European Commission, 2023). Currently, the focus is mainly on initial levels of innovation (materials, components, and partially products, see Chapters 2-3) and calls for not only fundamental/ incremental/ evolutionary innovation at the product level but also radical/ revolutionary innovation at the Product Service System level. While general knowledge may not always prove effective in every setting, it can be adjusted, replaced, or adapted to suit specific contexts.

This Ph.D. research makes several key contributions to the theoretical knowledge of DfS within the furniture sector:

I. **A conceptual framework** for sustainable furniture system design was formulated, integrating the characteristics of furniture S.PSSD, Furniture LCD, and the win-win economic benefits and mechanism of furniture S.PSS that facilitate environmental Life Cycle Design. Specifically:
   - **Identified Comprehensive Environmental Impact:** The research identified and quantified the comprehensive environmental impact throughout the entire life cycle, spanning various dimensions. This comprehensive understanding and rich data serve as a foundation for addressing environmental challenges with a life cycle design perspective.
   - **Summarized Characteristics of Sustainable Furniture Products and Product-Service Systems:** For sustainable furniture product design, the research identified 15 design approaches, encompassing 37 detailed design approaches. On the furniture S.PSS design level, the characteristics of furniture S.PSS, including provided products, 31 various services, stakeholders and 10 business models were identified. The study revealed the win-win environmental and economic benefits of furniture S.PSS. These characteristics, serving as design insights, were integrated into the development of furniture-specific LCD and S.PSSD guidelines.
   - **Created An Archetypal Furniture S.PSS Map**, outlining 20 promising visions. Each vision encapsulates a potential furniture S.PSS scenario characterized and visually represented with a system map for clarity and understanding.

II. **Furniture-Specific system design Guidelines:** A total of 7 furniture-specific LCD strategies, 23 sub-strategies, and 154 guidelines were established. On the PSS level, 6 furniture-specific S.PSSD strategies and 46 guidelines were also developed.

While existing literature in the field primarily focused on evaluating and comparing specific materials, processes, or individual furniture products, there was a lack of a comprehensive and cohesive conceptual framework for sustainable furniture design. The application of Design for Sustainability (DfS) knowledge and know-how to address environmental challenges within the furniture sector was insufficient. The contributions of this research are novel and extensive. The integration of Life Cycle Assessment (LCA) data from 25 furniture pieces across 8 groups into 162 histograms provides valuable quantitative data and design insights for designers. Unlike current environmental data focusing mainly on particular materials/components/furniture, which may not offer insights for other designers external to that specific project, this work provides comprehensive data and design considerations for furniture from various categories, facilitating a general understanding of furniture's environmental impact and sustainable design focus, priorities, and strategies.

Regarding furniture Life Cycle Design (LCD), this research develops furniture-specific LCD strategies (with identified priorities), sub-strategies, and guidelines. While general LCD guidelines (Vezzoli, 2018) are well-established, as mentioned earlier, general knowledge may not be sufficient for specific contexts. Additionally, some researchers have developed office furniture LCD guidelines (L. I. Chaves, 2007), and as new knowledge emerges from the literature review, case studies, and expert insights, these guidelines should evolve accordingly. Both Vezzoli's and Chaves's knowledge provide valuable insights for the development of furniture-specific LCD guidelines.

This work also represents a significant advancement beyond Chaves' work by expanding knowledge to the furniture Sustainable Product-Service System Design (S.PSS) level. The Archetypal Furniture S.PSS Map offers a comprehensive overview of promising furniture S.PSSD models, serving as a valuable asset for those engaged in furniture S.PSSD endeavors. Additionally, furniture S.PSSD strategies and guidelines were developed, providing valuable references for furniture practitioners seeking to develop S.PSS in their specific contexts and for researchers aiming to understand S.PSS within the furniture sector.

Practical contribution

In addition to theoretical contributions, this research significantly contributes to sustainable furniture product Life Cycle Design and Sustainable Product-Service System Design by providing support for furniture companies, furniture designers and researchers, through a well-defined design method and a series of tools designed to assist at each stage of the design process. The identification of know-how gaps in furniture practice towards sustainability, derived from literature review and semi-structured interviews (Chapter 2, 4.3.3, 5.3.3), guided the development of the ICSxFurniture toolkit and SDOxFurniture toolkits. The knowledge developed in this research, such as the life cycle environmental impact, the developed sustainable furniture product/PSS case cards, and the furniture-specific LCD and S.PSSD guidelines were integrated into the tools to support evaluation and design orientation. For example, each eco-idea board is equipped with a list of guidelines as well as cases linked to the relevant guidelines, used to inspiring new sustainable ideas in the concept design stage.

The ICSxFurniture toolkit aids the furniture LCD process, covering strategic analysis, idea generation, and concept design. Simultaneously, the SDOxFurniture toolkit, along with the innovation diagramxFurniture and system mapxFurniture, facilitates sustainable furniture Product-Service System design.

The developed toolkits are designed with modularity in mind, featuring tools tailored to support various stages of the design process. This modular design offers flexibility in usage, allowing users to select tools based on their experience, objectives, and time constraints. For instance, if users wish to brainstorm promising sustainable furniture product/PSS design ideas, they can directly utilize the Eco-idea boards for either furniture products design or furniture S.PSSD, rather than starting from scratch. The integration of these tools into each stage of the design process is illustrated in Table 38 and Table 39.

However, it's important to note that these tools are not specifically designed for individuals without a background in Design for Sustainability (DfS). Even for users with relevant knowledge, there may be a learning curve associated with the toolkits. To address this, each tool is accompanied by a video presentation which aims to facilitate the learning process and ensure effective utilization of the toolkit functionalities.

In the penultimate version of these tools, participants who were involved in the evaluation process rated them positively. For comprehensibility, the scores of satisfaction ranged from 71% to 90%; for usability, the scores ranged from 75% to 90%; and for success, the scores ranged from 86% to 95%. The research contribution is illustrated in Figure 122.

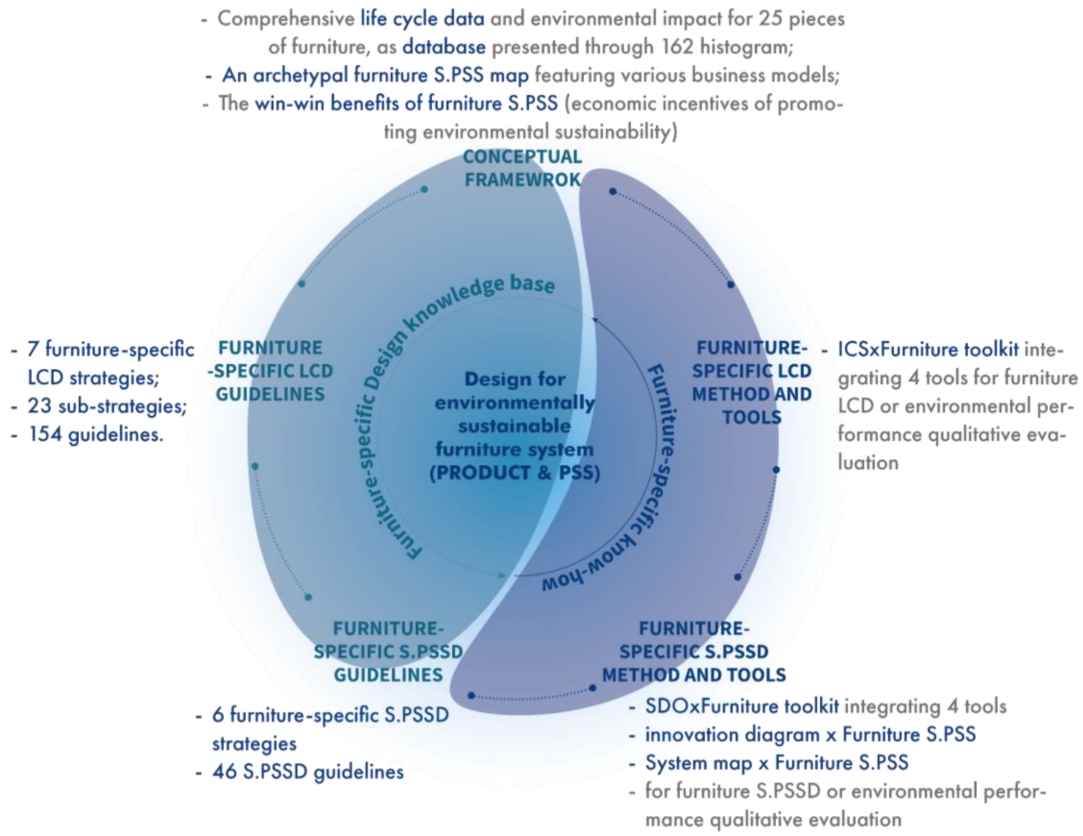


Figure 122 The research contributions

10.2 Research limitations

Due to time constraints, the research faced limitations regarding the scope of investigation and the evaluation of tools.

10.2.1 Research scope

In terms of the research subject, the primary aim was to develop theoretical insights and practical know-how into the application of Life Cycle Design (LCD) and Sustainable Product Service System design (S.PSSD) in the furniture sector. While recognizing the promise of applying LCD and S.PSSD as efficient and effective sustainable approaches, it is essential to acknowledge other opportunities to be explored, such as sustainable behavior design, regenerative design, and design for social innovation. However, exploring the potential application of other approaches in the furniture sector could be an interesting avenue for future research.

Given the unique characteristics of the furniture industry, its relevance, and potential for improvement, this research specifically concentrated on household and office furniture. However, it's important to note that there are various other categories of furniture that merit further investigation.

Addressing the sustainability dimension, this research emphasized tackling the most pressing issues within the furniture sector, specifically focusing on the environmental impact throughout the furniture's life cycle and the production and consumption system. The research prioritized environmental concerns while also considering economic benefits. However, the social dimension remains an area for future investigation.

10.2.2 Iterative toolkit's testing

The limitations related to the development and testing of tools are noteworthy. While the tools underwent six rounds of evaluation and refinement with different groups, their application in furniture companies was limited. Conducting tests within ongoing projects, collaborating with furniture designers and sustainable managers, could enhance the consolidation of results. This aspect is a potential avenue for future research, specifically focusing on the development of new furniture products or PSSs.

Another limitation is relevant to the tools' lack of collaboration functions. While I supervised a master's student in creating collaboration versions of Miro for the innovation diagram, concept sheet, and system map, it proved challenging to integrate collaboration functionality into the ICSxFurniture toolkit and SDOxFurniture toolkit. These two toolkits combine qualitative evaluation functions with Excel's formula function as support, making it difficult to integrate collaboration features, which are crucial during the design process. I have engaged in discussions with various experts, including programmers and designers. As of now, Excel remains the best solution to balance calculation functionality and open access requirements. However, further research will be conducted on this matter.

10.2.3 The changing research world

Furthermore, it is important to acknowledge that the design landscape is evolving rapidly. Emerging fields like Artificial Intelligence and Machine Learning are gaining prominence, and their potential applications in sustainable Furniture System Design are indeed interesting. However, their integration into sustainable furniture system design could enrich our understanding of furniture design, potentially leading to the development of new furniture S.PSS archetypal models, comprehensive design guidelines, and improved practical knowledge.

However, given the time constraints of the PhD research, it was not possible to comprehensively cover all aspects and anticipate emerging knowledge gaps. To address these limitations, all research outcomes, including the knowledge base and practical know-how, have been made open access. This enables researchers in the same field to contribute and update the knowledge base and know-how with the latest insights.

10.3 Further research directions

Design for sustainability is a vast and meaningful field that offers numerous avenues for exploration, and the furniture sector encompasses a wide range of categories. This research, however, has primarily focused on the application of Life Cycle Design (LCD) and Sustainable Product Service System Design (S.PSSD) approaches within the furniture sector, prioritizing their efficiency and effectiveness within the allocated time frame. This section outlines some recommendations for future work, drawing insights from testing activities and the broader research landscape.

10.3.1 Further application and testing of furniture system design tools

There is a need for continued application and testing of the developed furniture system design tools. Longer and more in-depth testing activities conducted in collaboration with furniture companies on real sustainable product development or furniture S.PSS development projects could yield valuable insights. Consider extending testing periods, testing could span the entire design journey, potentially lasting several months.

10.3.2 Tool improvements and collaboration functionality

Based on feedback from participants, the tools could benefit from a more collaborative platform. While Excel currently serves as the best choice, future versions could be developed once more advanced platforms or improved calculating functions of existing platforms are available. The goal is to enhance the comprehensibility, usability, and overall usefulness of the tools.

10.3.3 Tailored guidelines for specific furniture types

The current furniture knowledge base and know-how were developed with a focus on office furniture and household furniture. When utilized by furniture companies, it is recommended to create more detailed and specific guidelines and tools tailored to different types of furniture, considering their unique characteristics and sustainability requirements.

10.3.4 Exploring other opportunities in Sustainable Furniture Design

Beyond the scope of this research, there are numerous other opportunities in sustainable furniture system design that warrant exploration, such as sustainable behavior design, regenerative design, and design for the base of the pyramid within the furniture sector. Special attention can also be given to other furniture categories, such as outdoor furniture and transportation furniture, for in-depth analysis and improvement. Furthermore, the social dimension of sustainability in the furniture sector should be explored in greater detail, alongside environmental and economic dimensions.

In summary, while this research has made significant contributions by focusing on LCD and S.PSSD approaches in the furniture sector, there are opportunities for future research to expand and deepen the understanding of sustainable furniture design and its sustainable dimensions.

10.4 knowledge base and know-how dissemination

Considering the significance of having a well-established knowledge base and know-how, for both furniture designers and researchers involved in the development of Sustainable Furniture Systems, I am (together with other researchers) currently in the process of creating an open course and an open access book on sustainable furniture system design. The open course will be made available through the open learning platform LeNSLab Polimi, ensuring broad accessibility. Additionally, the open-access book will be published by FrancoAngeli, furthering the commitment to disseminating valuable knowledge in this domain.

10.4.1 The LeNSLab Polimi platform

The official website, serving as the open learning platform, incorporates a diverse range of learning resources. These encompass courses, lectures, design guidelines, and tools tailored for use by designers, students, researchers, professionals, and anyone interested in tackling sustainability challenges. Through this platform, all users can view, download, modify, and reuse these resources freely, in adherence to an open-source and copyleft philosophy. This means that all contents within the learning resources are accessible without any charges and with intellectual property rights (acknowledging authorship), yet there are no restrictions regarding the dissemination with the Creative Commons license.

The overarching goal is to enable individuals to pursue comprehensive online courses, access specific resources aligned with their interests, and facilitate educators worldwide in launching new courses. This can be achieved by adapting, utilizing, and contributing back to these learning resources, aligning them with specific requirements, institutional demands, or local contextual characteristics. In essence, the primary objective is to accelerate the dissemination of knowledge base and know-how in the realm of design for sustainability, promoting a collective effort towards a more sustainable future.

10.4.2 The open course

The development of an open course on furniture system design is currently in progress and will soon be accessible on the LeNSLab Polimi platform. This course encompasses both theoretical and practical insights derived from this research. It will be available to anyone with an internet connection, thereby facilitating the spread of knowledge on Sustainable Furniture System Design (SFSD). This initiative aims to benefit furniture designers, furniture companies, researchers, academics, and all individuals engaged in the field of SFSD by providing them with valuable resources and information.

As the open courses are ongoing projects, it is actively seeking input from potential audiences. This approach fosters an open and mutually beneficial learning process, promoting the exchange of viewpoints and increasing opportunities for collaboration. It also encourages the continuous improvement and expansion of the available resources.

10.4.3 The open-access book

To further disseminate the knowledge base and know-how developed in this research, a collaborative effort with FrancoAngeli is underway to create a book on sustainable furniture system design.

To broaden the dissemination of the knowledge base and know-how developed in this research, a collaborative initiative with FrancoAngeli is currently in progress to author a book named Design for Sustainable Furniture Systems.

This book provides a comprehensive understanding of sustainable development principles and the evolving landscape of sustainable furniture design research and practice. It delves into strategies for designing and developing environmentally sustainable products and Product-Service Systems (PSS). Specifically, at the furniture product level, the authors discuss the Life Cycle Design approach, along with strategies and guidelines for integrating environmental considerations into the design of sustainable furniture products. On the PSS level, the book explores promising types and business models aimed at making Sustainable Furniture Design economically viable and environmentally sound, known as Sustainable Product-Service Systems.

Furthermore, the book introduces a method and a set of tools to support Design for Sustainable Furniture Systems. It addresses the assessment of the environmental impact of both products and systems, with a particular focus on Life Cycle Assessment (LCA). Throughout the book, readers will find rich case studies that serve a double purpose: they clarify design options and highlight their applicability to various project contexts. This book is written as a valuable resource for those interested in sustainable furniture system design, providing both theoretical insights and practical guidance for sustainable practices in the industry.

10.4.4 Aim and Audience

The primary objective of both the open course and the open book is to empower readers with the essential knowledge and practical know-how required for sustainable furniture system design. Additionally, the overarching goal of the open course is to ensure the widespread dissemination of this developed knowledge base and expertise. By doing so, it aims to expedite potential discussions and collaborations with individuals and organizations engaged in sustainable furniture systems. The potential audience includes furniture designers, furniture companies, institutions, researchers, as well as future designers, see Figure 123.

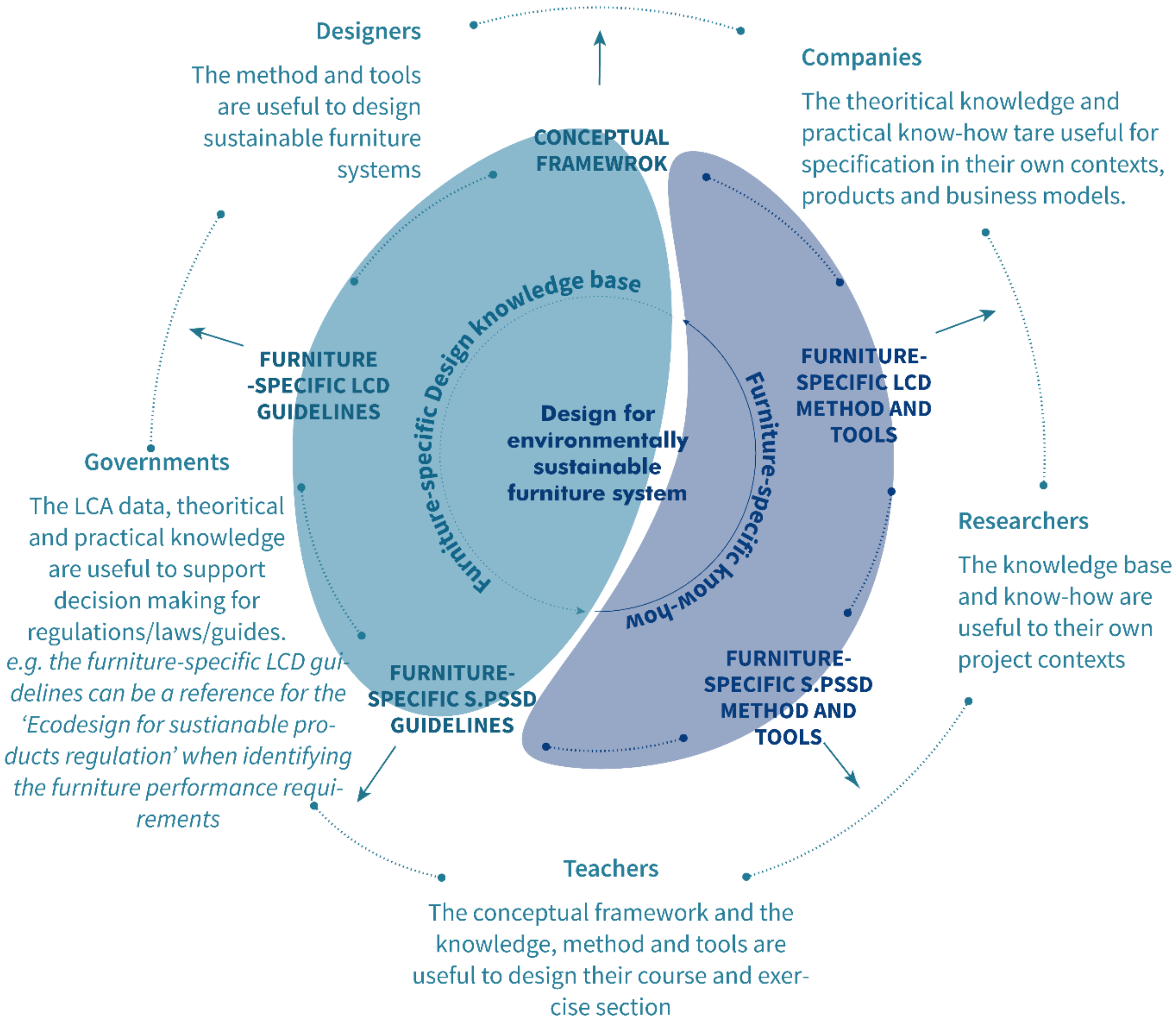


Figure 123 Potential final users of the knowledge base and know-how

In line with the ethos of this research and the principles of the LeNS network, all contents, including video lectures, slideshows, tools, and the book itself, will be made available in open source and under a copyleft license. This means that anyone can easily access, download, reuse, and remix these resources for their own educational and creative purposes.

References

Adams, R., Jeanrenaud, S., Bessant, J., Denyer, D., & Overy, P. (2015). *Sustainability-oriented Innovation: A Systematic Review*. 26. https://doi.org/10.1111/ijmr.12068

ADEME, Innovation Croissance, Phenix, & Crédoc. (2021). *Etude des gisements et causes des invendus non alimentaires et de leurs voies d'écoulement / Study of the sources and cause of non-food unsold products and their outlets* (p. 158). ADEMD.

Allameh, E., & Heidari, M. (2020). Sustainable Street Furniture. *Periodica Polytechnica Architecture*. https://doi.org/10.3311/PPar.12674

Anderson, T., & Shattuck, J. (2012). Design-Based Research: A Decade of Progress in Education Research? *Educational Researcher*, *41*(1), 16–25. https://doi.org/10.3102/0013189X11428813

Askham, C. (2011). Environmental product development: Replacement of an epoxy-based coating by a polyester-based coating. *International Journal of Life Cycle Assessment*, *16*(8), 819–828. Scopus. https://doi.org/10.1007/s11367-011-0302-x

Askham, C., Hanssen, O. J., Gade, A. L., Nereng, G., Aaser, C. P., & Christensen, P. (2012). Strategy tool trial for office furniture. *International Journal of Life Cycle Assessment*, *17*(6), 666–677. Scopus. https://doi.org/10.1007/s11367-012-0406-y

Aurich, J. C., Mannweiler, C., & Schweitzer, E. (2010). How to design and offer services successfully. *CIRP Journal of Manufacturing Science and Technology*, *2*(3), 136–143. https://doi.org/10.1016/j.cirpj.2010.03.002

Babarenda Gamage, G., Boyle, C., McLaren, S. J., & McLaren, J. (2008). Life cycle assessment of commercial furniture: A case study of Formway LIFE chair. *The International Journal of Life Cycle Assessment*, *13*(5), 401–411. https://doi.org/10.1007/s11367-008-0002-3

Babu, B. R., Parande, A. K., Raghu, S., & Kumar, T. P. (2007). *An Overview of Wastes Produced During Cotton Textile Processing*. *11*(1), 13.

Badiu, A., Badiu, I., & Dragomir, M. (2015). Studies regarding the use of reclaimed wood in the manufacture of modern furniture – part II. *Acta Technica Napocensis - Series: Applied Mathematics, Mechanics, And Engineering*, *58*(3), 231–238.

Bannan-Ritland, B. (2003). The Role of Design in Research: The Integrative Learning Design Framework. *Educational Researcher*, *32*(1), 21–24. https://doi.org/10.3102/0013189X032001021

Barab, S., & Squire, K. (2004). Design-Based Research: Putting a Stake in the Ground. *Journal of the Learning Sciences*, *13*(1), 1–14. https://doi.org/10.1207/s15327809jls1301_1

Barbero, S., & Ferrulli, E. (2023). Transizione ecologica e digitale. Il Design Sistemico nei processi di innovazione aperta delle PMI | Ecological and digital transition. Systemic Design in SMEs open innovation processes. *AGATHÓN*, 269–280. https://doi.org/10.19229/2464-9309/13232023

Barbero, S., & Toso, D. (2010). Systemic design of a productive chain: Reusing coffee waste as an input to agricultural production. *Environmental Quality Management*, *19*(3), 67–77. https://doi.org/10.1002/tqem.20254

Berrios, I., Zhang, J., Guo, B., Smith, J., & Zhang, Z. (2005). Volatile Organic Compounds (Vocs) Emissions From Sources In A Partitioned Office Environment And Their Impact On IAQ. *Indoor Air*, 6.

Besch, K. (2005). Product-service systems for office furniture: Barriers and opportunities on the European market. *Journal of Cleaner Production*, *13*(10–11), 1083–1094. https://doi.org/10.1016/j.jclepro.2004.12.003

Beuren, F. H., Gomes Ferreira, M. G., & Cauchick Miguel, P. A. (2013). Product-service systems: A literature review on integrated products and services. *Journal of Cleaner Production*, *47*, 222–231. https://doi.org/10.1016/j.jclepro.2012.12.028

Bhamra, T., & Hernandez, R. J. (2021). Thirty years of design for sustainability: An evolution of research, policy and practice. *Design Science*, *7*. https://doi.org/10.1017/dsj.2021.2

Bhamra, T., Lilley, D., & Tang, T. (2011). Design for Sustainable Behaviour: Using Products to Change Consumer Behaviour. *The Design Journal*, *14*(4), 427–445. https://doi.org/10.2752/175630611X13091688930453

Bistagnino, L. (2011). *Systemic design: Designing the productive and environmental sustainability*. Politecnico di Torino.

Blessing, L. T. M., & Chakrabarti, A. (2009). *DRM, a Design Research Methodology*. Springer London. https://doi.org/10.1007/978-1-84882-587-1

Boks, C., & McAloone, T. C. (2009). *The design of Eco Board Games as an umbrella approach to sustainable product design education*. *Sustainable Design*, 390–395. https://orbit.dtu.dk/en/publications/the-design-of-eco-board-games-as-an-umbrella-approach-to-sustaina

Borchardt, M., Poltosi, L. A. C., Sellitto, M. A., & Pereira, G. M. (2009). Adopting ecodesign practices: Case study of a midsized automotive supplier. *Environmental Quality Management*, *19*(1), 7–22. https://doi.org/10.1002/tqem.20232

Bosch, T., Verploegen, K., Grösser, S. N., & van Rhijn, G. (2017). Sustainable furniture that grows with end-users. In *Dynamics of Long-Life Assets: From Technology Adaptation to Upgrading the Business Model* (pp. 303–326). Scopus. https://doi.org/10.1007/978-3-319-45438-2_16

Bovea, M. D., & Vidal, R. (2004). Materials selection for sustainable product design: A case study of wood based furniture eco-design. *Materials and Design*, *25*(2), 111–116. Scopus. https://doi.org/10.1016/j.matdes.2003.09.018

Boydston, J. A. (Ed.). (1971). *The Early Works of John Dewey*. Southern Illinois University Press.

Braulio-Gonzalo, M., & Bovea, M. D. (2020). Criteria analysis of green public procurement in the Spanish furniture sector. *Journal of Cleaner Production*, *258*, 120704. https://doi.org/10.1016/j.jclepro.2020.120704

Brezet, H. (1997). Dynamics in ecodesign practice. *Industry and Environment*, *20*, 21–24.

Brezet, H., & Hemel, C. van. (1997). *Ecodesign: A promising approach to sustainable production and consumption*. United Nations Environment Programme, Industry and Environment, Cleaner Production ; Rathenau Institute ; Delft University of Technology.

Brookes, L. (2000). Energy efficiency fallacies revisited. *Energy Policy*, *28*(2000), 355–366.

Brown, A. L. (1992). Design Experiments: Theoretical and Methodological Challenges in Creating Complex Interventions in Classroom Settings. *Journal of the Learning Sciences*, *2*(2), 141–178. https://doi.org/10.1207/s15327809jls0202_2

Brown, A. L., & Campione, J. C. (1996). Psychological theory and the design of innovative learning environments: On procedures, principles, and systems. In *Innovations in learning: New environments for education* (pp. 289–325). Lawrence Erlbaum Associates, Inc.

Burchart-Korol, D. (2013). Life cycle assessment of steel production in Poland: A case study. *Journal of Cleaner Production*, *54*, 235–243. https://doi.org/10.1016/j.jclepro.2013.04.031

Byggeth, S., & Hochschorner, E. (2006). Handling trade-offs in Ecodesign tools for sustainable product development and procurement. *Journal of Cleaner Production*, *14*(15–16), 1420–1430. https://doi.org/10.1016/j.jclepro.2005.03.024

Castellani, V., Hidalgo, C., Gelabert, L., Riera, M. R., Escamilla, M., Sanyé Mengual, E., Sala, S., European Commission, & Joint Research Centre. (2019). *Consumer footprint: Basket of products indicator on household goods.* (JRC Technical Reports JRC116120; p. 177). Publications Office of the European Union. https://op.europa.eu/publication/manifestation_identifier/PUB_KJNA29710ENN

CEN Committee. (2018). *CEN TC 207 Furniture*. CEN Committee.

Ceschin, F. (2012). *The introduction and scaling up of sustainable Product-Service Systems. A new role for strategic design for sustainability* [Doctoral dissertation, Politecnico di Milano]. https://www.politesi.polimi.it/handle/10589/56785

Ceschin, F., & Gaziulusoy, I. (2016). Evolution of design for sustainability: From product design to design for system innovations and transitions. *Design Studies*, *47*, 118–163. https://doi.org/10.1016/j.destud.2016.09.002

Ceschin, F., & Gaziulusoy, İ. (2019). *Design for Sustainability: A Multi-level Framework from Products to Socio-technical Systems* (1st ed.). Routledge. https://doi.org/10.4324/9780429456510

Chapman, J. (2005). *Emotionally durable design: Objects, experiences, and empathy*. Earthscan.

Chapman, J. (2009). Design for (Emotional) Durability. *Design Issues*, *25*(4), 29–35. https://doi.org/10.1162/desi.2009.25.4.29

Chapman, J. (2012). Emotionally durable design: Objects, experiences and empathy. *Emotionally Durable Design: Objects, Experiences and Empathy*, 1–211. https://doi.org/10.4324/9781849771092

Charter, M., & Tischner, U. (Eds.). (2001). *Sustainable Solutions: Developing Products and Services for the Future* (1st ed.). Greenleaf Publishing Limited. https://www.taylorfrancis.com/books/9781351282475

Chaves, L. iten. (2009). *Panorama do design para a sustentabilidade*. 67–75.

Chaves, L. I. (2007). *Design for environmental sustainability: Design strategies, methods and tools in the furniture sector*. Politecnico di Milano.

Chaves, L. I. (2008). Design for sustainability: A methodological approach for the introduction of environmental requirements in the furniture sector. *Product: Management & Development*, *6*(2), 167–171.

Chaves, L. I. (2017). Design for Social Innovation: Distributed Economy, Collaborative Network and Creative Communities. *Blucher Design Proceedings*, 21–24. https://doi.org/10.5151/sbds-issd-2017-004

Chaves, L. I. (2018). Do design de produto às inovações sociais como resposta às causas diretas e indiretas dos impactos ambientais e sociais. In A. J. V. Arruda, *Design, Artefatos e Sistema Sustentável* (pp. 107–128). EDITORA BLUCHER. https://doi.org/10.5151/9788580392982-05

Cheung, W. M., Leong, J. T., & Vichare, P. (2017). Incorporating lean thinking and life cycle assessment to reduce environmental impacts of plastic injection moulded products. *Journal of Cleaner Production*, *167*, 759–775. https://doi.org/10.1016/j.jclepro.2017.08.208

Chick, A. (2012). Design for Social Innovation: Emerging Principles and Approaches. *Iridescent*, *2*(1), 78–90. https://doi.org/10.1080/19235003.2012.11428505

Çinar, H. (2005). Eco-design and furniture: Environmental impacts of wood-based panels, surface and edge finishes. *Forest Products Journal*, *55*(11), 27–33. Scopus.

Clean Production Standard-Wood-based Panel Industry (Particle Board) (2010). https://www.mee.gov.cn/gkml/hbb/bgth/201009/W020100930719561859100.pdf

Cobb, P. (2001). Supporting the improvement of learning and teaching in social and institutional context. In *Cognition and instruction: Twenty-five years of progress* (pp. 455–478). Lawrence Erlbaum Associates Publishers.

Cobb, P., Confrey, J., diSessa, A., Lehrer, R., & Schauble, L. (2003). Design Experiments in Educational Research. *Educational Researcher*, *32*(1), 9–13. JSTOR.

Collins, A. (1992). Toward a Design Science of Education. In E. Scanlon & T. O'Shea (Eds.), *New Directions in Educational Technology* (pp. 15–22). Springer. https://doi.org/10.1007/978-3-642-77750-9_2

Collins, A., Joseph, D., & Bielaczyc, K. (2004). Design Research: Theoretical and Methodological Issues. *Journal of the Learning Sciences*, *13*(1), 15–42. https://doi.org/10.1207/s15327809jls1301_2

Cook, M. B., Bhamra, T. A., & Lemon, M. (2006). The transfer and application of Product Service Systems: From academia to UK manufacturing firms. *Journal of Cleaner Production*, *14*(17), 1455–1465. https://doi.org/10.1016/j.jclepro.2006.01.018

Corbin, J. M., & Strauss, A. L. (2015). *Basics of qualitative research: Techniques and procedures for developing grounded theory* (4. ed). Sage.

Cordella, M., & Hidalgo, C. (2016). Analysis of key environmental areas in the design and labelling of furniture products: Application of a screening approach based on a literature review of LCA studies. *Sustainable Production and Consumption*, *8*, 64–77. Scopus. https://doi.org/10.1016/j.spc.2016.07.002

Creswell, J. W. (2009). *Research design: Qualitative, quantitative, and mixed methods approaches* (3. ed.). SAGE Publ.

Cross, N. (2006). *Designerly ways of knowing*. Springer.

CSIL. (2021, December 13). The world furniture market in 2022. *Design Diffusion*. https://www.designdiffusion.com/en/2021/12/13/the-world-furniture-market-in-2022/

CSIL, & CNFA. (2020). *World Furniture Outlook 2020*. Centre for Industry Studies; China National Furniture Association.

Daian, G., & Ozarska, B. (2009). Wood waste management practices and strategies to increase sustainability standards in the Australian wooden furniture manufacturing sector. *Journal of Cleaner Production*, *17*(17), 1594–1602. https://doi.org/10.1016/j.jclepro.2009.07.008

Denzin, N. K., & Lincoln, Y. S. (Eds.). (2018). *The SAGE handbook of qualitative research* (Fifth edition). SAGE.

Design Council. (2022). *Design Council Annual Review 2002. Review Literature and Arts of The Americas*. Design Council.

Dewey, J. (1967). *The Early Works, 1882-1898: 1895-1898. Early essays*. Southern Illinois University Press.

Dewey, J. (1997). *How We Think* (Revised ed. edition). Dover Publications.

Diamond, L. J., & Morlino, L. (2004). The Quality of Democracy: An Overview. *Journal of Democracy*, *15*(4), 20–31. https://doi.org/10.1353/jod.2004.0060

Dias, B. D. (2015). *Beyond Sustainability – Biophilic And Regenerative Design In Architecture*.

Diehl, J. C. (2010). *Product innovation knowledge for developing economics: Towards a systematic approach.* Technische Universiteit Delft.

Donatello, S., Moons, H., & Wolf, O. (2017). *Revision of EU Ecolabel criteria for furniture products: Final technical report.* (ISBN 978-92-79-71863-2, doi:10.2760/14246, JRC107824). Publications Office of the European Union. https://publications.jrc.ec.europa.eu/repository/handle/JRC107824

E. Baumgartner, & Bell, P. (2002). *What will we do with design principles? Design principles and principled design practice.* Annual Conference of the American Educational Research Association, New Orleans, LA.

Edelson, D. C. (2002). Design Research: What We Learn When We Engage in Design. *Journal of the Learning Sciences*, *11*(1), 105–121. https://doi.org/10.1207/S15327809JLS1101_4

Eisenhardt, K. M. (1989). Building Theories from Case Study Research. *The Academy of Management Review*, *14*(4), 532–550.

Elena Windolph, S., Schaltegger, S., & Herzig, C. (2014). Implementing corporate sustainability: What drives the application of sustainability management tools in Germany? *Sustainability Accounting, Management and Policy Journal*, *5*(4), 378–404. https://doi.org/10.1108/SAMPJ-01-2014-0002

El-Mously, H. (2018). Innovating green products as a mean to alleviate poverty in Upper Egypt. *Ain Shams Engineering Journal*, *9*(4), 2039–2056. https://doi.org/10.1016/j.asej.2017.02.001

Emili, S., Ceschin, F., & Harrison, D. (2016). Product–Service System applied to Distributed Renewable Energy: A classification system, 15 archetypal models and a strategic design tool. *Energy for Sustainable Development*, *32*, 71–98. https://doi.org/10.1016/j.esd.2016.03.004

Eshun, J. F., Potting, J., & Leemans, R. (2010). Inventory analysis of the timber industry in Ghana. *International Journal of Life Cycle Assessment*, *15*(7), 715–725. Scopus. https://doi.org/10.1007/s11367-010-0207-0

Estokova, A., & Porhincak, M. (2015). Environmental analysis of two building material alternatives in structures with the aim of sustainable construction. *Clean Technologies and Environmental Policy*, *17*(1), 75–83. https://doi.org/10.1007/s10098-014-0758-z

Estrada, R. D., Wyller, M., & Dahy, H. (2019). Aerochair Integrative design methodologies for lightweight carbon fiber furniture design: 37th Conference on Education and Research in Computer Aided Architectural Design in Europe and 23rd Conference of the Iberoamerican Society Digital Graphics, eCAADe SIGraDi 2019. *Architecture in the Age of the 4th Industrial Revolutio*, 691–700. https://doi.org/10.5151/proceedings-ecaadesigradi2019_665

European Commission. (2013a). *A Blueprint For The Eu Forest-Based Industries (Woodworking, Furniture, Pulp & Paper Manufacturing And Converting, Printing)* (Commission Staff Working Document SWD(2013) 343; Communication From The Commission To The European Parliament, The Council, The European Economic And Social Committee And The Committee Of The Regions A New Eu Forest Strategy: For Forests And The Forest-Based Sector, p. 41). European Commission. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52013SC0343&from=EN

European Commission. (2013b). *Revision of Ecolabel and Green Public Procurement criteria for the product group_wooden furniture* (JCR Scientific and Policy Reports) [JCR scientific and policy reports]. European Commission Joint Research Centre Institute for Prospective Technological Studies (IPTS).

European commission. (2018). *EU Green Public Procurement criteria for Furniture* (SWD(2017) 283 final/2). https://circabc.europa.eu/ui/group/44278090-3fae-4515-bcc2-44fd57c1d0d1/library/0788fd30-083f-4f9e-ba9e-86e9e432e822?p=1&n=10&sort=modified_DESC

European Commission. (2020). *Circular economy action plan: For a cleaner and more competitive Europe*. Publications Office of the European Union. https://data.europa.eu/doi/10.2779/05068

European Commission. (2023). *Consumption Footprint Platform | EPLCA* [Research]. Consumption Footprint Platform. https://eplca.jrc.ec.europa.eu/ConsumptionFootprintPlatform.html

European Commission & Joint Research Centre. (2010). *ILCD handbook: General guide for life cycle assessment : detailed guidance*. Publications Office of the European Union. http://lct.jrc.ec.europa.eu/pdf-directory/ILCD-Handbook-General-guide-for-LCA-DETAIL-online-12March2010.pdf

European Commission. Joint Research Centre. (2017). *Revision of EU Ecolabel criteria for furniture products: Final technical report.* Publications Office. https://data.europa.eu/doi/10.2760/59027

European Commission. Joint Research Centre. (2017). *Revision of the EU Green Public Procurement (GPP) criteria for furniture: Technical report : final version.* Publications Office. https://data.europa.eu/doi/10.2760/14246

Ewen, D. (2022). *Gispen's Environmentally sustainable furniture design approaches, strategies and tools* [Personal communication].

Fallman, D. (2008). The Interaction Design Research Triangle of Design Practice, Design Studies, and Design Exploration. *Design Issues*, *24*(3), 4–18.

Feil, A. A., De Brito Reiter, I., Oberherr, R., Strasburg, V. J., & Schreiber, D. (2022). Analysis and measurement of the sustainability level in the furniture industry. *Environment, Development and Sustainability*, *24*(12), 13657–13682. https://doi.org/10.1007/s10668-021-02005-8

Flokk AS. (2020). *1.1 Environmental Product Declaration—HÅG Creed 6004* (NEPD-2195-999-EN; p. 8). The Norwegian EPD Foundation. https://www.epd-norge.no/getfile.php/1313421-1589365411/EPDer/M%C3%B8bler/Sittem%C3%B8bler/NEPD-2195-999_HAG-Creed-6004.pdf

Forrest, A., Hilton, M., Ballinger, A., & Whittaker, D. (2017). *Circular Economy Opportunities In The Furniture Sector* (p. 55). European Environment Bureau.

Frantzeskaki, N., & Haan, H. (2009). Transitions: Two steps from theory to policy. *Futures*, *41*, 593–606. https://doi.org/10.1016/j.futures.2009.04.009

Frayling, C. (1993). Research in Art and Design. *Royal College of Art Research Papers*, *1*(1), 1–5.

Freeman, T. (2006). ‘Best practice’ in focus group research: Making sense of different views. *Journal of Advanced Nursing*, *56*(5), 491–497. https://doi.org/10.1111/j.1365-2648.2006.04043.x

Gassmann, O., Enkel, E., & Chesbrough, H. (2010). The future of open innovation: The future of open innovation. *R&D Management*, *40*(3), 213–221. https://doi.org/10.1111/j.1467-9310.2010.00605.x

Gaziulusoy, A. I. (2015). A critical review of approaches available for design and innovation teams through the perspective of sustainability science and system innovation theories. *Journal of Cleaner Production*, *107*, 366–377. https://doi.org/10.1016/j.jclepro.2015.01.012

Geels, F. (2006). Multi-Level Perspective on System Innovation: Relevance for Industrial Transformation. In *Understanding Industrial Transformation: Views from Different Disciplines* (pp. 163–186). https://doi.org/10.1007/1-4020-4418-6_9

Geng, A., Ning, Z., Zhang, H., & Yang, H. (2019). Quantifying the climate change mitigation potential of China’s furniture sector: Wood substitution benefits on emission reduction. *Ecological Indicators*, *103*, 363–372. https://doi.org/10.1016/j.ecolind.2019.04.036

Gibson, R. B. (2013). Avoiding sustainability trade-offs in environmental assessment. *Impact Assessment and Project Appraisal*, *31*(1), 2–12. https://doi.org/10.1080/14615517.2013.764633

Giraldo Nohra, C., Pereno, A., & Barbero, S. (2020). Systemic Design for Policy-Making: Towards the Next Circular Regions. *Sustainability*, *12*(11), Article 11. https://doi.org/10.3390/su12114494

Giudice, F., Rosa, G. L., & Risitano, A. (2006). *Product Design for the Environment: A Life Cycle Approach*. CRC Press.

Global Footprint Network. (2023). *Earth Overshoot Day home*. Earth Overshoot Day. https://overshoot.footprintnetwork.org/

Goedkoop, M. J., van Halen, C. J. G., te Riele, H. R. M., & Rommens, P. J. M. (1999). *Product Service systems, Ecological and Economic Basics*.

González-García, S., Ferro, F. S., Lopes Silva, D. A., Feijoo, G., Lahr, F. A. R., & Moreira, M. T. (2019). Cross-country comparison on environmental impacts of particleboard production in Brazil and Spain. *Resources, Conservation and Recycling*, *150*, 104434. https://doi.org/10.1016/j.resconrec.2019.104434

González-García, S., Lozano, R. G., Moreira, M. T., Gabarrell, X., i Pons, J. R., Feijoo, G., & Murphy, R. J. (2012). Eco-innovation of a wooden childhood furniture set: An example of environmental solutions in the wood sector. *Science of the Total Environment*, *426*, 318–326.

Gray, D. E. (2014). *Doing research in the real world (3rd)* (Reprinted). SAGE.

Grover, R., Emmitt, S., & Copping, A. (2019). A Representational Framework for Sustainable Design. In S. Syngellakis, *Eco-Architecture VII: Harmonisation between Architecture and Nature*. WIT Press.

Guba, E. G., & Lincoln, Y. S. (1994). Competing paradigms in qualitative research. In D. K. Norman & Y. S. Lincoln (Eds.), *Handbook of qualitative research* (pp. 105–117). Sage.

Gustafsson, L. M., & Börjesson, P. (2007). Life cycle assessment in green chemistry: A comparison of various industrial wood surface coatings. *International Journal of Life Cycle Assessment*, *12*(3), 151–159. Scopus. https://doi.org/10.1065/lca2006.11.280

Harding, K., Dennis, J., Vonblottnitz, H., & Harrison, S. (2007). Environmental analysis of plastic production processes: Comparing petroleum-based polypropylene and polyethylene with biologically-based poly-β-hydroxybutyric acid using life cycle analysis. *Journal of Biotechnology*, *130*(1), 57–66. https://doi.org/10.1016/j.jbiotec.2007.02.012

Hartini, S., Ciptomulyono, U., Anityasari, M., & Sriyanto. (2020). Manufacturing sustainability assessment using a lean manufacturing tool: A case study in the Indonesian wooden furniture industry. *International Journal of Lean Six Sigma*, *11*(5), 943–971. https://doi.org/10.1108/IJLSS-12-2017-0150

Heinemann, C., & Arsenio, F. (2022). *New EU eco-design proposals: Case studies to illustrate their potential impact* [06798511314-27]. European Environmental Bureau. https://eeb.org/wp-content/uploads/2022/12/Impact-of-EU-ecodesign-regs.pdf

Herrington, J., McKenney, S., Reeves, T., & Oliver, R. (2007). Design-based research and doctoral students: Guidelines for preparing a dissertation proposal. *Proceedings of ED-MEDIA 2007--World Conference on Educational Multimedia, Hypermedia & Telecommunications*, 4089–4097. https://www.learntechlib.org/primary/p/25967/

Herriott, R. E., & Firestone, W. A. (1983). Multisite Qualitative Policy Research: Optimizing Description and Generalizability. *Educational Researcher*, *12*(2), 14–19. https://doi.org/10.3102/0013189X012002014

Ika Rinawati, D., Sriyanto, Puspita Sari, D., & Cantya Prayodha, A. (2018). Eco-efficiency Analysis of Furniture Product Using Life Cycle Assessment. *E3S Web of Conferences*, *31*, 08005. https://doi.org/10.1051/e3sconf/20183108005

International Aluminium Institute. (2003). *Life Cycle Assessment of Aluminium: Inventory Data for the WorldwidePrihmary Aluminium Industry*. International Aluminium Institute.

Iritani, D. R., Silva, D. L., Saavedra, Y. M. B., Grael, P. F. F., & Ometto, A. R. (2015). Sustainable strategies analysis through Life Cycle Assessment: A case study in a furniture industry. *Journal of Cleaner Production*, *96*, 308–318.

ISO 14040: 2006, Environmental Management - Life Cycle Assessment - Principles and Framework, Pub. L. No. ISO 14040, 20 (2006). www.iso.org

ISO 14044: 2006 Environmental Management - Life Cycle Assessment - Requirements and Guidelines, Pub. L. No. ISO 14044, 46 (2006). www.iso.org

ISO 14025:2006(En), Environmental Labels and Declarations — Type III Environmental Declarations — Principles and Procedures (2006). https://www.iso.org/obp/ui/#iso:std:iso:14025:ed-1:v1:en

ISO/TR 14062. (2002). *Environmental management, integrating environmental aspects into product design and developmen t* [Technical report].

Jagtap, S., & Kandachar, P. (2011). Design for the Base of the Pyramid: Issues and Solutions. *ICORD 11: Proceedings of the 3rd International Conference on Research into Design Engineering, Bangalore, India, 10.-12.01.2011*, 480–488. https://www.designsociety.org/publication/32388/Design+for+the+Base+of+the+Pyramid%3A+Issues+and+Solutions

Joint Research Center of the European Commission. (2023). *Ecodesign for Sustainable Products Regulation—Preliminary study on new product priorities (draft)* [Technical Report].

Jones, P. H. (2014). Systemic Design Principles for Complex Social Systems. In G. S. Metcalf (Ed.), *Social Systems and Design* (pp. 91–128). Springer Japan. https://doi.org/10.1007/978-4-431-54478-4_4

Joseph, K., & Nithya, N. (2009). Material flows in the life cycle of leather. *Journal of Cleaner Production*, *1*, 7.

Kallio, H., Pietilä, A.-M., Johnson, M., & Kangasniemi, M. (2016). Systematic methodological review: Developing a framework for a qualitative semi-structured interview guide. *Journal of Advanced Nursing*, *72*(12), 2954–2965. https://doi.org/10.1111/jan.13031

Kemp, R., & Rotmans, J. (2004). Managing the Transition to Sustainable Mobility. *System Innovation and the Transition to Sustainability*, 137–167. https://doi.org/10.4337/9781845423421.00019

Keoleian, G. A., & Menerey, D. (1993). *Life cycle design guidance manual. Environmental requirements and the product system. Final report* (PB-93-164507/XAB). National Pollution Prevention Center, Ann Arbor, MI (United States). https://www.osti.gov/biblio/5886794

Khoo, H. H., Tan, R. B. H., & Chng, K. W. L. (2010). Environmental impacts of conventional plastic and bio-based carrier bags: Part 1: Life cycle production. *The International Journal of Life Cycle Assessment*, *15*(3), 284–293. https://doi.org/10.1007/s11367-010-0162-9

Krystofik, M., Luccitti, A., Parnell, K., & Thurston, M. (2018). Adaptive remanufacturing for multiple lifecycles: A case study in office furniture. *Resources, Conservation and Recycling*, *135*, 14–23. Scopus. https://doi.org/10.1016/j.resconrec.2017.07.028

Kumar R., B. A., Muslihudin, M., Nguyen, P. T., Alfian, F. Y., Hashim, W., Shankar, K., Hafizah, S., Mukodimah, S., Odarich, I. N., & Maseleno, A. (2019). Into the Furniture Woods: Analytical Hierarchy Process Method. *International Journal of Recent Technology and Engineering*, *8*(2S3), 1562–1567. https://doi.org/10.35940/ijrte.B1285.0782S319

Lähtinen, K., Alina Samaniego Vivanco, D., & Toppinen, A. (2014). Designers' wooden furniture ecodesign implementation in Scandinavian country-of-origin (COO) branding. *Journal of Product & Brand Management*, *23*(3), 180–191. https://doi.org/10.1108/JPBM-07-2013-0354

Leclercq-Vandelannoitte, A. (2021). The new paternalism? The workplace as a place to work—and to live. *Organization*, *28*(6), 949–975. https://doi.org/10.1177/13505084211015374

Li, S., Yuan, Y., Wang, J., & Guo, M. (2019). Do novel wooden composites provide an environmentally favorable alternative for panel-type furniture? *BioResources*, *14*(2), 2740–2758. Scopus. https://doi.org/10.15376/biores.14.2.2740-2758

Liu, W., Zhang, Y., Yao, Y., & Li, J. (2012). Indoor decorating and refurbishing materials and furniture volatile organic compounds emission labeling systems: A review. *Chinese Science Bulletin*, *57*(20), 2533–2543. https://doi.org/10.1007/s11434-012-5208-x

Ljungberg, L. Y. (2007). Materials selection and design for development of sustainable products. *Materials & Design*, *28*(2), 466–479. https://doi.org/10.1016/j.matdes.2005.09.006

London, D. (2017). *Embodied Carbon: Developing A Client Brief*. UK Green Building Council. https://www.ukgbc.org/wp-content/uploads/2017/09/UK-GBC-EC-Developing-Client-Brief.pdf

Lovarelli, D., Fusi, A., Pretolani, R., & Bacenetti, J. (2018). Delving the environmental impact of roundwood production from poplar plantations. *Science of The Total Environment*, *645*, 646–654. https://doi.org/10.1016/j.scitotenv.2018.06.386

Lu, W., Barbero, S., & Pereno, A. (2022). *Systemic Design For Elderly Healthcare: Analysis of the current responses in China, Italy and Japan*.

Maguire, M., & Delahunt, B. (2017). *Doing a Thematic Analysis: A Practical, Step-by-Step Guide for Learning and Teaching Scholars. 8*(3).

Mang, P., & Reed, B. (2012). Regenerative Development and Design. *Encyclopedia Sustainability Science & Technology*, *I*, 8855. https://doi.org/10.1007/978-1-4614-5828-9_303

Manzini, E. (2002). *Sustainable solutions. New business ideas and new ideas on business*. Politecnico di Milano.

Manzini, E., & Vezzoli, C. (2003). A strategic design approach to develop sustainable product service systems: Examples taken from the 'environmentally friendly innovation' Italian prize. *Journal of Cleaner Production*, *11*(8), 851–857. https://doi.org/10.1016/S0959-6526(02)00153-1

Manzini, E., Vezzoli, C., United Nations Environment Programme, Division of Technology, I., and Economics, Production and Consumption Unit, Politecnico di Milano, Interdepartmental Research Centre Innovation for the Environmental Sustainability, Lunds universitet, & International Institute for Industrial Environmental Economics. (2003). *Product-service systems and sustainability: Opportunities for sustainable solutions*. UNEP. http://www.unep.org/resourceefficiency/Portals/24147/scp/design/pdf/pss-imp-7.pdf

Marshall, C., & Rossman, G. B. (2010). *Designing Qualitative Research* (5th edition). SAGE Publications, Inc.

Maxwell, J. A. (2008). Designing a qualitative study. In L. Bickman & D. J. Rog (Eds.), *The SAGE Handbook of Applied Social Research Methods* (2nd ed., pp. 214–253). SAGE Publications.

McDonough, W., & Braungart, M. (2003). Towards a sustaining architecture for the 21st century: The promise of cradle-to-cradle design. *Industry and Environment*, *26*(2), 13–16.

Medeiros, D. L., Braghirolli, F. L., Ramlow, H., Ferri, G. N., & Kiperstok, A. (2019). Environmental improvement in the printing industry: The case study of self-adhesive labels. *Environmental Science and Pollution Research*, *26*(13), 13195–13209. https://doi.org/10.1007/s11356-019-04460-3

Medeiros, D. L., do Carmo Tavares, A. O., e Silva, Á. L. Q. R., & Kiperstok, A. (2017). Life cycle assessment in the furniture industry: The case study of an office cabinet. *The International Journal of Life Cycle Assessment*, *22*(11), 1823–1836.

Merriam, S. B. (1998). *Qualitative Research and Case Study Applications in Education: Revised and Expanded from Case Study Research in Education* (2nd Revised & Expanded edition). Jossey-Bass.

Michelsen, O., Fet, A. M., & Dahlsrud, A. (2006). Eco-efficiency in extended supply chains: A case study of furniture production. *Journal of Environmental Management*, *79*(3), 290–297. https://doi.org/10.1016/j.jenvman.2005.07.007

Miles, M. B., & Huberman, A. M. (1994). *Qualitative Data Analysis: An Expanded Sourcebook*. SAGE.

Mirabella, N., Castellani, V., & Sala, S. (2014). Forestry operations in the alpine context. Life cycle assessment to support the integrated assessment of forest wood short supply chain. *International Journal of Life Cycle Assessment*, *19*(8), 1524–1535. Scopus. https://doi.org/10.1007/s11367-014-0756-8

Mont, O. K. (2002). Clarifying the concept of product–service system. *Journal of Cleaner Production*, *10*(3), 237–245. https://doi.org/10.1016/S0959-6526(01)00039-7

Montagna, G., & Carvalho, C. (2018). *Textiles, Identity and Innovation: Design the Future: Proceedings of the 1st International Textile Design Conference (D_TEX 2017), November 2-4, 2017, Lisbon, Portugal*. CRC Press.

Mugge, R. (2007). *Product Attachment* [TU Delft]. https://repository.tudelft.nl/islandora/object/uuid%3A0a7cef79-cb04-4344-abb1-cff24e3c3a78

Mugge, R., Schoormans, J. P. L., & Schifferstein, H. N. J. (2005). Design Strategies to Postpone Consumers' Product Replacement: The Value of a Strong Person-Product Relationship. *The Design Journal*, *8*(2), 38–48. https://doi.org/10.2752/146069205789331637

Navarro, D. (2020). *Life cycle assessment and leather production*. 13.

Neuman, W. L. (2014). *Social research methods: Qualitative and quantitative approaches* (7. ed., Pearson new internat. ed). Pearson.

Notarnicola, B., Puig, R., Raggi, A., Fullana, P., Tassielli, G., Camillis, C. D., & Rius, A. (2011). *Life cycle assessment of Italian and Spanish bovine leather production systems*. 15.

Nunez, P., & Jones, S. (2016). Cradle to gate: Life cycle impact of primary aluminium production. *The International Journal of Life Cycle Assessment*, *21*(11), 1594–1604. https://doi.org/10.1007/s11367-015-1003-7

Olmez, G. M., Dilek, F. B., Karanfil, T., & Yetis, U. (2016). The environmental impacts of iron and steel industry: A life cycle assessment study. *Journal of Cleaner Production*, *130*, 195–201. https://doi.org/10.1016/j.jclepro.2015.09.139

Orangebox. (2019). *ARA - Orangebox*. ARA Cradle-to-Cradle Task Chair. https://www.orangebox.com/products/ARA

O'Riordan, T. (1989). The challenge for environmentalism. In *New Models in Geography—Vol 1*. Routledge.

Orrill, C. H., Hannafin, M. J., & Glazer, E. M. (2004). Disciplined Inquiry and the Study of Emerging Technology. In *Handbook of Research on Educational Communications and Technology* (2nd ed.). Routledge.

Panameño, R., Gutiérrez-Aguilar, C. M., Angel, B. E., Fábio-César, S., & Kiperstok, A. (2019). Cleaner Production and LCA as Complementary Tools in Environmental Assessment: Discussing Tradeoffs Assessment in a Case of Study within the Wood Sector in Brazil. *Sustainability (Switzerland)*, *11*(18). Scopus. https://doi.org/10.3390/su11185026

Park, Y., Kim, M., & Yoon, J. (2016). Generating New Product-Service System Concepts Using General Needs and Business System Evolution Patterns: A Furniture PSS Case. *Industrial Engineering and Management Systems*, *15*(2), 181–195. https://doi.org/10.7232/iems.2016.15.2.181

Patton, M. Q. (1999). Enhancing the quality and credibility of qualitative analysis. *Health Services Research*, *34*(5 Pt 2), 1189–1208.

Pergande, B., Nobre, P. L. A., Nakanishi, A. C., Zancul, E. S., Loss, L., & Horta, L. C. (2012). Product-Service System Types and Implementation Approach. In D. A. Dornfeld & B. S. Linke (Eds.), *Leveraging Technology for a Sustainable World* (pp. 43–48). Springer. https://doi.org/10.1007/978-3-642-29069-5_8

Pettersen, I. N., & Boks, C. (2008). The ethics in balancing control and freedom when engineering solutions for sustainable behaviour. *International Journal of Sustainable Engineering*, *1*(4), 287–297. https://doi.org/10.1080/19397030802559607

Phungrassami, H., & Usubharatana, P. (2015). Life cycle assessment and Eco-efficiency of Para-rubber wood production in Thailand. *Polish Journal of Environmental Studies*, *24*(5), 2113–2126. Scopus.

Pigosso, D. C. A., McAloone, T. C., & Rozenfeld, H. (2015). Characterization of the State-of-the-art and Identification of Main Trends for Ecodesign Tools and Methods: Classifying Three Decades of Research and Implementation. *Indian Institute of Science Journal*, *95*(4), 405–427.

Pope, C., & Mays, N. (Eds.). (2020). *Qualitative Research in Health Care* (1st ed.). Wiley. https://doi.org/10.1002/9781119410867

Product Category Rules: Furniture, Except Seats and Mattresses, § 8 ((Version 2.01)). https://www.environdec.com/pcr-library

Product Category Rules: Seats, 2009:02, version 3.0 26 ((Version 3.0).). https://www.environdec.com/pcr-library

Product Environmental Footprint Category Rules - Office Chair (Draft), 40 (2018).

Product Environmental Footprint Category Rules - Office Table (Draft), 41 (2018).

Rabionet, S. E. (2011). How I Learned to Design and Conduct Semi-Structured Interviews: An Ongoing and Continuous Journey. *Qualitative Report*, *16*(2), 563–566.

Rawles, K. (1995). Review of The Greening of Ethics: From Human Chauvinism to Deep Green Theory [Review of *Review of The Greening of Ethics: From Human Chauvinism to Deep Green Theory*, by R. Sylvan & D. Bennett]. *Journal of Applied Philosophy*, *12*(3), 305–307.

Reeves, T. C., Herrington, J., & Oliver, R. (2005). Design research: A socially responsible approach to instructional technology research in higher education. *Journal of Computing in Higher Education*, *16*(2), 96–115. https://doi.org/10.1007/BF02961476

Renda, A., Pelkmans, J., Schrefler, L., Luchetta, G., Simonelli, F., Mustilli, F., Julian, W., Matthias, B., Tomaselli, A. R., Tracogna, A., Zavatta, R., & Bolognini, A. (2014). *The Eu Furniture Market Situation And A Possible Furniture Products Initiative* (p. 307). European Commission, Centre for Industrial Studies (CSIL), Centre for European Policy Studies (CEPS), Demetra and Economisti Associati. https://www.ceps.eu/wp-content/uploads/2015/04/Final%20report_en.pdf

Richey, R. C., Klein, J. D., & Nelson, W. A. (2004). Developmental Research: Studies of Instructional Design and Development. In *Handbook of research on educational communications and technology, 2nd ed* (pp. 1099–1130). Lawrence Erlbaum Associates Publishers.

Robson, C., & McCartan, K. (2016). *Real world research: A resource for users of social research methods in applied settings* (Fourth Edition). Wiley.

Ryan, C. (2003). Learning from a decade (or so) of eco-design experience. *Journal of Industrial Ecology*, *7*(2), 10–12.

Ryan, C. (2013). Eco-Acupuncture: Designing and facilitating pathways for urban transformation, for a resilient low-carbon future. *Journal of Cleaner Production*, *50*, 189–199. https://doi.org/10.1016/j.jclepro.2012.11.029

Ryan, C., Gaziulusoy, I., McCormick, K., & Trudgeon, M. (2016). virtual city experimentation: A critical role for design visioning. In J. Evans, A. Karvonen, & R. Raven (Eds.), *The Experimental City* (pp. 61–76). Routledge.

Saade, M. R. M., Gomes, V., da Silva, M. G., Ugaya, C. M. L., Lasvaux, S., Passer, A., & Habert, G. (2019). Investigating transparency regarding ecoinvent users' system model choices. *The International Journal of Life Cycle Assessment*, *24*(1), 1–5. https://doi.org/10.1007/s11367-018-1509-x

Santos, G., Rebelo, M., Barros, S., & Pereira, M. (2012). Certification and integration of environment with quality and safety—A path to sustained success. In *Sustainable development—Authoritative and leading edge content for environmental management* (Vol. 1, pp. 193–218). InTech.

Schuler, A. T. (2003). *Identifying Future Competitive Business Strategies for the U.S. Residential Wood Furniture Industry: Benchmarking and Paradigm Shifts*. U.S. Department of Agriculture, Forest Service, Northeastern Research Station.

Selloni, D., & Corubolo, M. (2017). Design for Social Enterprises: How Design Thinking Can Support Social Innovation within Social Enterprises. *The Design Journal*, *20*(6), 775–794. https://doi.org/10.1080/14606925.2017.1372931

Shi, J., Puig, R., Sang, J., & Lin, W. (2016). A comprehensive evaluation of physical and environmental performances for wet-white leather manufacture. *Journal of Cleaner Production*, *139*, 1512–1519. Scopus. https://doi.org/10.1016/j.jclepro.2016.08.120

Silva, D. A. L., Lahr, F. A. R., Garcia, R. P., Freire, F. M. C. S., & Ometto, A. R. (2013). Life cycle assessment of medium density particleboard (MDP) produced in Brazil. *The International Journal of Life Cycle Assessment*, *18*(7), 1404–1411. https://doi.org/10.1007/s11367-013-0583-3

Smoca, A. (2019). *Hemp fibres reinforced bio-composites for sustainable design*. *19*(6.2), 471–478. Scopus. https://doi.org/10.5593/sgem2019/6.2/S27.060

Stahel, W. R. (1997). The Functional Economy: Cultural Change and Organizational Change. In *The Industrial Green Game: Implications for Environmental Design and Management*. National Academies Press.

Sundin, E., Ölundh Sandström, G., Lindahl, M., & Öhrwall Rönnbäck, A. (2009). Using Company–Academia Networks for Improving Product/Service Systems at Large Companies. In T. Sakao & M. Lindahl (Eds.), *Introduction to Product/Service-System Design* (pp. 185–196). Springer. https://doi.org/10.1007/978-1-84882-909-1_9

The international EPD system. (n.d.). *Product Category Rules*. The International EPD System. Retrieved 10 November 2021, from https://test1.environdec.com/PCR/

Thompson, C. (1999). Qualitative Research into Nurse Decision Making: Factors for Consideration in Theoretical Sampling. *Qualitative Health Research*, *9*(6), 815–828. https://doi.org/10.1177/104973239900900609

Tischner, U. (Ed.). (2001). Tools for ecodesign and sustainable product design. In *Sustainable Solutions: Developing Products and Services for the Future* (1st ed., pp. 263–274). Greenleaf Publishing Limited. https://www.taylorfrancis.com/books/9781351282475

Tongpool, R., Jirajariyavech, A., Yuvaniyama, C., & Mungcharoen, T. (2010). Analysis of steel production in Thailand: Environmental impacts and solutions. *Energy*, *35*(10), 4192–4200. https://doi.org/10.1016/j.energy.2010.07.003

Tracey, P., & Stott, N. (2017). Social innovation: A window on alternative ways of organizing and innovating. *Innovation*, *19*(1), 51–60. https://doi.org/10.1080/14479338.2016.1268924

Treasury. (2013). *Infrastructure Carbon Review*. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/260710/infrastructure_carbon_review_251113.pdf

Tromp, N., Hekkert, P., & Verbeek, P.-P. (2011). Design for Socially Responsible Behavior: A Classification of Influence Based on Intended User Experience. *Design Issues, 27*(3), 3–19. https://doi.org/10.1162/DESI_a_00087

Tukker, A. (2004). Eight types of product–service system: Eight ways to sustainability? Experiences from SusProNet. *Business Strategy and the Environment*, *13*(4), 246–260. https://doi.org/10.1002/bse.414

Ulrich, K. T., & Eppinger, S. D. (2012). *Product design and development* (5. ed). McGraw-Hill.

UNEP. (2002). *Product-service systems and sustainability: Opportunities for sustainable solutions*. UNEP. https://wedocs.unep.org/xmlui/handle/20.500.11822/8123

UNEP, & Delft University of Technology. (2017). *Design for Sustainability. A Step by Step Approach* (p. 110). United Nations Environment Programme.

United Nations. (2015). *Transforming our world: The 2030 Agenda for Sustainable Development*. https://sdgs.un.org/2030agenda

United Nations. (2023). *The Sustainable Development Goals Report 2023: Special Edition*. United Nations. https://doi.org/10.18356/9789210024914

United Nations, & World Commission on Environment and Development. (1987). *Our common future*. https://www.are.admin.ch/dam/are/it/dokumente/nachhaltige_entwicklung/dokumente/bericht/our_common_futurebrundtlandreport1987.pdf.download.pdf/our_common_futurebrundtlandreport1987.pdf

Van Halen, C., Vezzoli, C., & Wimmer, R. (2006). *Methodology for Product Service System Innovation: How to develop clean, clever and competitive strategies in companies*. Koninklijke Van Gorcum.

Vergragt, P. J., & van Grootveld, G. (1994). Sustainable technology development in the Netherlands: The first phase of the Dutch STD programme. *Journal of Cleaner Production*, *2*(3), 133–137. https://doi.org/10.1016/0959-6526(94)90035-3

Vezzoli, C. (2007). *System design for sustainability: Theory, methods and tools for a sustainable satisfaction-system design*. Maggioli.

Vezzoli, C. (2018). *Design for Environmental Sustainability* (2nd ed.). Springer London. http://link.springer.com/10.1007/978-1-4471-7364-9

Vezzoli, C., Bacchetti, E., & Ceschin, F. (2018). E.DRE—Estimator for Distributed Renewable Energy. In *Designing Sustainable Energy for All. Sustainable Product-Service System Design Applied to Distributed Renewable Energy* (pp. 159–165). Springer.

Vezzoli, C., Ceschin, F., & Diehl, J. C. (2015). Sustainable Product-Service System Design applied to Distributed Renewable Energy fostering the goal of sustainable energy for all. *Journal of Cleaner Production*, *97*, 134–136. https://doi.org/10.1016/j.jclepro.2015.02.069

Vezzoli, C., Conti, G. M., Macrì, L., & Motta, M. (2022). *Designing sustainable clothing systems: The design for environmentally sustainable textile clothes and its product-service systems*. FrancoAngeli.

Vezzoli, C., Garcia, B., & Kohtala, C. (2021a). *Design sustainability for all: The design of sustainable product-service system applied to distributed economics*. SPRINGER NATURE.

Vezzoli, C., Garcia, B., & Kohtala, C. (Eds.). (2021b). *Designing Sustainability for All: The Design of Sustainable Product-Service Systems Applied to Distributed Economies*. Springer International Publishing. https://doi.org/10.1007/978-3-030-66300-1

Vezzoli, C., Kohtala, C., & Srinivasan, A. (Eds.). (2014). *Product-service system design for sustainability*. Greenleaf Publishing.

Vezzoli, C., Macrì, L., Takacs, B., & Yang, D. (2022). *System Design for Sustainability in Practice* (1st ed.). Maggioli spa. https://doi.org/10.30448/uni.916.55745

Vezzoli, C., & Manzini, E. (2008). *Design for Environmental Sustainability* (2008° edizione). Springer Verlag.

Vezzoli, C., & Sciama, D. (2006). Life Cycle Design: From general methods to product type specific guidelines and checklists: a method adopted to develop a set of guidelines/checklist handbook for the eco-efficient design of NECTA vending machines. *Journal of Cleaner Production*, *14*(15–16), 1319–1325. https://doi.org/10.1016/j.jclepro.2005.11.011

Vezzoli, C., & Yang, D. (2021). *A Case Study Analysis of the Furniture System From Sustainable Product-Service System Design Perspective*. ISDRS 2021: The 27th International Sustainable Development Research Society conference, Sweden. https://www.diva-portal.org/smash/get/diva2:1608600/FULLTEXT01.pdf

Wang, F., & Hannafin, M. J. (2005). Design-based research and technology-enhanced learning environments. *Educational Technology Research and Development*, *53*(4), 5–23. https://doi.org/10.1007/BF02504682

Wang, S., Liu, S., Wang, C., & Zhang, R. (2018). Analysis on the environment impact of primary aluminum production in Henan based on life cycle assessment. *Light Metals*, *3*.

Weaver, P., Jansen, L., Grootveld, G. van, Spiegel, E. van, & Vergragt, P. (2017). *Sustainable Technology Development*. Routledge.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): Overview and methodology. *The International Journal of Life Cycle Assessment*, *21*(9), 1218–1230. https://doi.org/10.1007/s11367-016-1087-8

Wever, R. (2011). Design for volume optimization of packaging for durable goods. *Packaging Technology and Science*, *24*(4), 211–222. https://doi.org/10.1002/pts.927

Wever, R., van Onselen, L., Silvester, S., & Boks, C. (2010). Influence of packaging design on littering and waste behaviour. *Packaging Technology and Science*, *23*(5), 239–252. https://doi.org/10.1002/pts.892

World Aluminium. (2017). *Life Cycle Inventory Data and Environmental Metrics for the Primary Aluminium Industry* (p. 49). World Aluminium. http://www.world-aluminium.org/media/filer_public/2017/06/28/lca_report_2015_final.pdf

Xiong, X., Ma, Q., YingyingYuan, Wu, Z., & Zhang, M. (2020). Current situation and key manufacturing considerations of green furniture in China: A review. *Journal of Cleaner Production*, *267*, 121957. https://doi.org/10.1016/j.jclepro.2020.121957

Yang, C.-F., & Sung, T.-J. (2016). Service Design for Social Innovation through Participatory Action Research. *International Journal of Dsign*, *10*(1), 21–36.

Yang, D. (2023). Design for environmentally sustainable furniture systems – the knowledge and know-how of furniture life cycle design and furniture sustainable product-service system design. *The Design Journal*, 1–12. https://doi.org/10.1080/14606925.2023.2178717

Yang, D., & Vezzoli, C. (2023). Designing sustainable furniture: Guidelines to promote furniture Life Cycle Design. In K. Vaes & J. Verlinden (Eds.), *Connectivity and creativity in times of conflict* (pp. 94–97). Academia Press. https://doi.org/10.26530/9789401496476-019

Yin, R. K. (1994). *Case Study Research: Design and Methods* (1st ed.). Sage Publications.

Yin, R. K. (2014). *Case study research: Design and methods* (Fifth edition). SAGE.

Zancul, E. de S., Nobre, P. L. de A., Nakanishi, A. de C., Pergande, B., Loss, L., Horta, L. C. da, Beuren, F. H., & Cauchick Miguel, P. A. (2011). A preliminary analysis of product-service system (PSS) types and implementation. *Product Management & Development*, *9*(2), 137–143. https://doi.org/10.4322/pmd.2012.005

Author’s Publications related to the research topic

Journal

Yang, D. (2023). Design for environmentally sustainable furniture systems – the knowledge and know-how of furniture life cycle design and furniture sustainable product-service system design. The Design Journal, 1–12. https://doi.org/10.1080/14606925.2023.2178717

Book chapter

Vezzoli, C., Macrì, L., Takacs, B., & **Yang, D.** (2022). System Design for Sustainability in Practice (1st ed.). Maggioli spa. https://doi.org/10.30448/uni.916.55745

Conference

Yang, D., & Vezzoli, C. (2023). Designing sustainable furniture: Guidelines to promote furniture Life Cycle Design. In K. Vaes & J. Verlinden (Eds.), Connectivity and creativity in times of conflict (pp. 94–97). Academia Press. https://doi.org/10.26530/9789401496476-019

Yang, D. (2022). The application of Life Cycle Assessment in sustainable furniture system design. AHFE (2022) International Conference Proceedings, 47, 590–600. https://doi.org/10.54941/ahfe1001987

Vezzoli, C., & **Yang, D.** (2021). A Case Study Analysis of the Furniture System From Sustainable Product-Service System Design Perspective. ISDRS 2021: The 27th International Sustainable Development Research Society conference, Sweden. https://www.diva-portal.org/smash/get/diva2:1608600/FULLTEXT01.pdf