The Environmental Impact of Sleeping Pillows

Comparing polyester, down-feather and Fossflakes fillings

World's first pillow life cycle assessment

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Final report:

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"Humanity is waging war on nature…

It is time to flick the 'green switch'.

We have a chance to not simply reset the world economy but to transform it…

And we must do so together."

Antonio Guterres, United Nations Secretary-General

Executive Summary

This Life Cycle Assessment (LCA) report, prepared by Fossflakes A/S and reviewed by independent experts, marks a pioneering exploration into the environmental impact of sleeping pillows, comparing Fossflakes, polyester, and down-feather fillings.

Aimed at addressing the significant yet overlooked environmental footprint of perhaps hundreds of millions of pillows purchased annually, this study is the first of its kind to illuminate the environmental implications of pillow fill materials from a cradle-to-grave perspective.

Adhering strictly to ISO 14040 and 14044 standards, the LCA examines the production, delivery, use, and disposal stages of pillows, focusing on climate change, water consumption, and land use impacts.

Our analysis reveals substantial differences in the environmental burdens associated with the three types of pillow fillings, challenging preconceived notions about the environmental impact of natural versus synthetic materials.

Key findings

When comparing medium-sized pillows made of conventionally produced virgin material, transported 1,000 km from factory to consumer, with no laundry over a two-year life, and disposal by incineration, the key findings are as follows:

- **Material choice is paramount:** The LCA demonstrates notable disparities among the environmental footprints of pillows filled with Fossflakes, polyester fibres, and down-feather. These findings underscore the critical role of manufacturers' material selection in determining a pillow's overall environmental impact.

- **Synthetic fills outperform natural fills:** Contrary to common belief, pillows filled with Fossflakes, and polyester fibres generally exhibit lower environmental impacts compared to their down-feather counterparts. This finding emphasises the importance of assessing products based on data instead of preconceptions.

- **Comprehensive evaluation is essential:** The study highlights the importance of a holistic life cycle approach in assessing product environmental footprint, emphasising that all components, including the cotton shell, significantly contribute to a pillow's impact.

- **Need for industry and consumer action:** The findings show the potential for environmental improvements in the pillow industry and the influential role of informed consumer choice in driving demand for environmentally friendly products.

Recommendations

Based on our findings, we propose actionable recommendations for manufacturers, retailers, and consumers to reduce the environmental footprint of pillows. These include innovation in materials, transparency in environmental impacts, and advocacy for responsible disposal and recycling practices.

The insights from this LCA serve as a valuable guide for stakeholders towards making data-driven decisions that align with environmental sustainability goals. By sharing this report, we aim to foster a deeper understanding of the environmental aspects of pillow production and usage, encouraging a shift towards more sustainable practices in the industry.

Critical Review statement for the study

"The Environmental Impact of Sleeping Pillows" (2024)

Scope of the critical review

The reviewers had the task of assessing whether:

1) the methods used to carry out the LCA are consistent with the international standards ISO 14040 (2006) and ISO 14044 (2006),
2) the methods used to carry out the LCA are scientifically and technically valid,
3) the data used are appropriate and reasonable in relation to the goal of the study,
4) the interpretations reflect the limitations identified and the goal of the study, and
5) the study report is transparent and consistent.

Although a detailed review of individual dataset files and LCA models in the software was beyond the scope of this review, all modelling steps, calculations, and decisions are thoroughly documented in the appendix to ensure full transparency and context for the data.

The critical review panel was chosen to ensure the required LCA competence and expertise in the scientific and technical aspects of the studied product system.

Review process

The critical review process took place in the last stage of the LCA study. The review was based on ISO 14044 (2006) and ISO/TS 14071 (2014). The review process took place between April 2024 and October 2024.

The final report as an entity including appendices was evaluated by the review panel to represent a complete LCA study with the remark listed under "Specific remarks".

Further details on the review are available in appendix E.

Specific remarks

It was suggested by the LCA review panel to put a larger amount of the primary data collection and calculations into the actual LCA report rather than appendices, to enhance its readability as a stand-alone document.

While Fossflakes partially implemented this suggestion the company also prioritized safeguarding the confidentiality of sensitive information by keeping detailed modelling and background calculations in the appendices. This approach aligns with the methodology of the only comparable industry LCA—the International Down and Feather Bureau (IDFB) report *Life Cycle Assessment of Down Fill Material*—in the absence of standardized LCA reporting guidelines in the bedding and fill industry.

The review panel accepts this approach, as data is present and correct in the LCA report together with the appendices as a complete entity. Compliance with ISO 14040 and 14044 is achieved by providing full access to the review panel, as permitted for confidential data under these standards. However, for a comprehensive understanding of the exact modelling processes, inputs, and detailed assumptions, the reader would need access to both the report and all appendices.

Conclusion

The reviewers found that the study report is transparent, consistent, and technically valid, taking into regard the specific remarks above. The discussion of the results covers the relevant aspects, and the conclusions are well founded on the outcome of the study and in accordance with the defined goal.

As a final remark, the reviewers would like to highlight the open and constructive interactions with the Fossflakes team.

Review Panel's signatures		
Morten Søes Kokborg	Asger Alexander Wendt Karl	Poli Jacobsen
November 15th, 2024	November 19th, 2024	November 19th, 2024

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0 Definitions and Terminology

To aid understanding of the report for readers unfamiliar with LCA, definitions of key terms are provided below. They are sourced from ISO 14040:2006, which provides the principles and framework for conducting life cycle assessment.

Characterization: The step in LCA where the inputs and outputs are categorized and assigned to environmental impact categories.

Life Cycle Assessment (LCA): A method to evaluate the environmental impacts of a product throughout its life cycle, from raw material extraction to disposal, following ISO 14040 and 14044 standards.

Life Cycle Inventory (LCI): Data collection on inputs (e.g., raw materials, energy) and outputs (e.g., emissions, waste) associated with a product's life cycle.

Life Cycle Impact Assessment (LCIA): The phase of LCA that evaluates potential environmental impacts from the inventory data.

Critical Review: A review ensuring the quality and credibility of the LCA study.

Impact Category: A classification of environmental concerns, like climate change or water use.

Primary Data: Data collected specifically for the current study.

Secondary Data: Data sourced from external databases or literature.

Reference Flow: The quantitative measure of inputs and outputs used to fulfill a product's function.

Sensitivity Analysis: Determines how variations in input data affect the LCA results.

System Boundary: Defines which processes are included in the product's life cycle analysis.

Uncertainty Analysis: Evaluates the reliability of LCA results by quantifying uncertainties.

Allocation: Assigning environmental burdens to multiple products from the same process.

Functional Unit: A measure used as a basis for comparison in LCA (e.g., one pillow with a two-year lifespan).

Cut-off Criteria: Rules for deciding which processes are included or excluded in LCA.

Normalization: Scaling LCIA results against reference values to contextualize the magnitude of impacts.

Cradle-to-Grave: Analysis covering the full life cycle from raw material extraction to disposal.

Cradle-to-Gate: A partial life cycle assessment covering from raw material extraction to the factory gate.

Down-feather: A combination of down and feathers from birds, used in products like pillows. Although often labelled as a "down product" by retailers, this term includes both down and feathers. In this study, we avoid using "down" alone to prevent confusion. It refers to the marketable (usable) plumage of ducks or geese.

Municipal Solid Waste (MSW): Waste collected from households and businesses, typically disposed of through landfilling or incineration.

Climate Impact: Used interchangeably in this study with “climate change impact” or “GWP” to refer to global warming potential.

Pillow loft: The height or thickness of a pillow, equivalent to "medium height" in this study.

***General* manufacturer:** Refers to an average or global manufacturer, representing typical industry practices using global datasets.

Impact Assessment Methods: Techniques to evaluate potential impacts from inventory data, like ReCiPe 2016 for climate change, water use, etc.

Incineration with Energy Recovery: A waste treatment process in which Municipal Solid Waste (MSW) are burned to generate energy, considered as part of the end-of-life phase.

Economic Allocation: Dividing environmental burdens among co-products based on their economic value.

End-of-Life (EoL) Treatment: Processes like incineration or recycling used when a product reaches the end of its useful life.

ReCiPe Methodology: An LCA impact assessment method translating inventory data into environmental impact scores, using the Hierarchist perspective.

Pedigree Matrix: A tool assessing the quality of LCI data based on reliability, completeness, and relevance.

OpenLCA: An open-source software tool for modeling and analyzing product life cycles.

Hierarchist Perspective (H): In ReCiPe, a balanced approach to impact assessment based on scientific consensus.

Hot-Spot Analysis: Identifies life cycle stages that contribute most to environmental impact.

Global (GLO) Datasets: Average global data used when region-specific data is unavailable.

Environmental Footprint: The total environmental impact of a product, including carbon, water, and land use.

1 Introduction

The world's first life cycle assessment of sleeping pillows

In an era where we grapple with climate crisis, biodiversity collapse, and acute resource depletion, the imperative for all stakeholders - manufacturers, retailers and consumers - to critically evaluate the environmental footprint of everyday products has never been more pressing.

Against this backdrop, the ubiquitous sleeping pillow, with a market size of $13-30 billion[1,2] and many millions of pillows sold every year, is a product of significant environmental consequence.

Fossflakes A/S is proud to presents the world's first life cycle assessment of sleeping pillows, setting a new benchmark by comparing Fossflakes, polyester, and down-feather fillings.

This study aims to show the impact of each pillow from cradle to grave, thereby empowering industry players and consumers with the knowledge to make choices that align with our collective pursuit of sustainability.

Following international standards

Conducted in adherence with the ISO 14040 and 14044 standards, this life cycle assessment examines and compares the production, delivery, and end-of-life stages of three different types of sleeping pillow.

It includes four main steps:

1. Goal & scope definition
2. Life cycle inventory
3. Life cycle impact assessment
4. Interpretation

2 Goal & scope definition

Fossflakes A/S is a Danish manufacturer of premium pillows and duvets selling via distributors and retailers worldwide, as a well as direct to consumers by e-commerce. Its products are filled with a unique patented mix of polyester fibre and polyethylene flakes, which provide comfort and support.

[1] Pillows Market Analysis 2024-2028, May 2024, Technavio https://www.technavio.com/report/pillows-market-size-industry-analysis
[2] Sleeping Pillow Market Size, Share, Growth, Forecast 2030, August 2023, Zion Market Research https://www.zionmarketresearch.com/report/sleeping-pillow-market

2.1 Objectives

As a key part of its corporate sustainability programme, Fossflakes aims to reduce the environmental impact of its products. Pillows are their top-selling product and therefore a focus of attention. A cradle-to-grave life cycle assessment of the Fossflakes pillow enables data-driven decisions for the future development of the product.

To our knowledge, no other pillow manufacturers have published similar life cycle assessments of their products, which makes it difficult for consumers to consider the environment in their choice of pillow. To enable this comparison, we include polyester and down-feather filled pillows in the analysis.

The audience for this report is Fossflakes' management as well as distributors, retailers and consumers of pillows. The report is therefore intended for public disclosure and may be used in Fossflakes' marketing and sustainability reporting and communications.

Accordingly, the study is conducted in compliance with international and national standards, namely ISO 14040 [1], ISO 14044 [2] and Guidance on The Use of Environmental and Ethical Claims by the Danish Consumer Ombudsman [3].

2.2 Function

The purpose of a sleeping pillow is to provide support and comfort for the head, neck, and shoulders while sleeping. It helps maintain proper alignment of the spine, reduces pressure points, and promotes relaxation, thus facilitating a more restful and comfortable sleep experience. Additionally, a pillow can also help alleviate or prevent neck pain and stiffness by providing adequate support to the neck muscles and vertebrae.

2.3 Functional unit

The functional unit assessed in this LCA is a medium-loft 50 cm x 70 cm sleeping pillow, designed to provide head support and comfort during sleep. The pillow comprises a 130 g cotton shell and 700 g of filling. It is assumed to be transported (distribution) 1000 km by truck to the consumer and used over a two-year lifespan, with no machine washes, tumble drying, or other operations throughout its use phase. Finally, the pillow is disposed of in Northern Europe, where incineration is the primary method of waste treatment.

This specific pillow type was selected for two primary reasons: 1) it represents one of the most commonly used pillow sizes in Europe, and 2) it was the bestselling pillow for Fossflakes in 2023, making it highly relevant for comparison in this study (see Appendix A on the ': Rationale and Background Data for Pillow Size and Weight Metrics' for details on the justifications that led to this choice).

To ensure a clear and consistent comparison across different pillow types, the same mass of fill and shell was assumed for all three pillow types being analysed. The use of cotton as the shell material was standardized to focus solely on the differences in fill materials, avoiding the introduction of variability from other shell materials that could affect properties such as feel, hygiene, and durability. The specific weights of the shell and filling are based on Fossflakes' 50x70 cm medium-loft pillow.

Given the inherent variability in the amount of fill and shell required to achieve a medium-loft pillow, which can arise from factors such as economic considerations, material functionality, and regional definitions of loft, this standardized approach was deemed necessary. For example, medium pillows were defined as having a height of '3-5 inches' (7.6-12.7 cm) on an American website [4], whereas pillows from the international homeware retailer JYSK [5], analysed for this study, ranged from 10 to 17 cm. See Appendix A for more details, including the specific pillows examined.

A sensitivity analysis was conducted to assess the impact of this variability on the results and to explore different scenarios, ensuring the robustness of the conclusions drawn from the LCA.

2.4 System boundaries

This assessment spans the full, cradle-to-grave life cycle of a pillow: the production of raw materials, their processing into components, manufacturing into a pillow, distribution to the consumer, use, and eventual disposal.

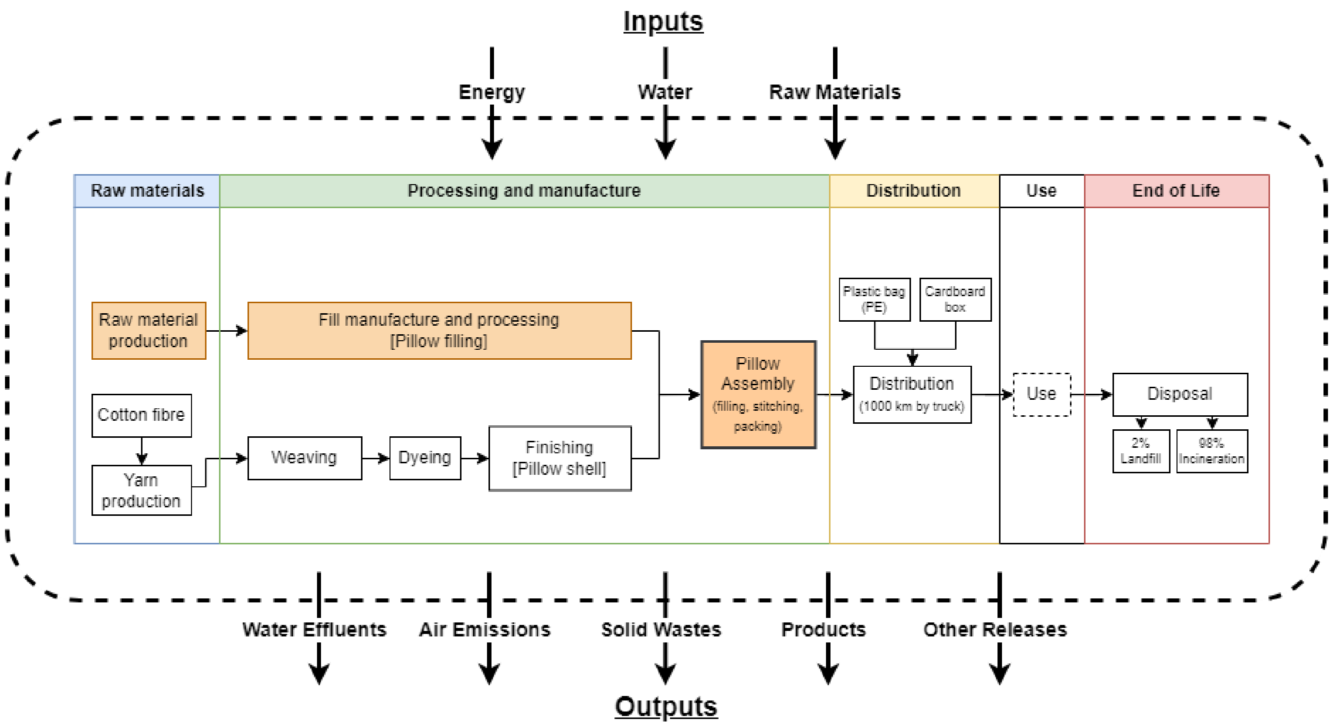

Figure 1: The general framework of the pillow's system boundary diagram. Orange boxes: details of process and material vary depending on the pillow fill-type

Figure 1 shows the general system boundaries and the below Figure 2, Figure 3 and Figure 4 display the specific differences between each of the three pillows, i.e. focusing only on the processing of the filling. As shown in the illustrations, inputs and outputs occur across all phases of production. This means that energy use (whether electricity or heat) and materials (such as plastic, down-feather, or water) are modelled where relevant throughout all phases. Similarly, outputs such as air emissions, solid waste, or wastewater are considered. Primary data was mainly collected for the actual products (or components) and waste materials from production, whereas more detailed data on aspects like air emissions were sourced from existing datasets (secondary data).

The use phase is shown, but not included in our calculations, as the dotted line indicates, due to the assumption of no impact (no washing or drying assumed) from this phase. Going into further detail, there are minor differences in the locations and transportation distances of the cotton shell, and lastly the disposal is also different to suit individual filling materials. More details on this will be provided in the This study follows ISO 14040 and 14044 standards, ensuring a systematic approach, but certain limitations of the LCA methodology must be noted. The data used are often subject to temporal, geographic, and technological variations, which may not always reflect the most current or site-specific conditions. For example, using global energy data instead of Denmark-specific data could result in 6-7% variation in the total climate impact of the Fossflakes pillow (see section 5.2.1 for more). Such generalizations may affect the accuracy of results, especially in areas like energy sourcing and transportation logistics.

The cut-off approach assigns the full production burden to the initial use of materials, excluding future recycling or reuse impacts. Simplifications were also made for ancillary processes, such as the transportation of packaging materials and yarn, relying on market datasets. These choices introduce 0.1-0.2% variability in total climate impact, with even smaller effects on water and land use (see section 5.2.2 for more).

Additionally, the characterization models used in LCIA (both midpoint and endpoint categories) rely on assumptions that may not fully capture all environmental interactions. This is especially relevant for midpoint results, which may not fully reflect long-term environmental damage. Site-specific factors, such as local energy mixes and waste management practices, are generalized, leading to possible discrepancies in real-world applications. However, both the sensitivity analyses and a '*Further investigation of limitations*' were conducted to explore the significance of key assumptions and ensure that conclusions remain robust.

Life Cycle Inventory.

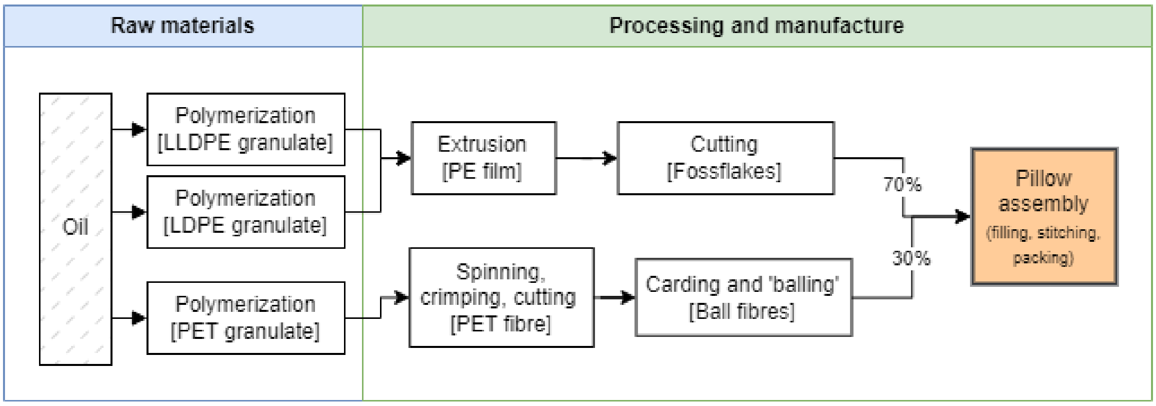

Figure 2: System boundary diagram for the Fossflakes filling

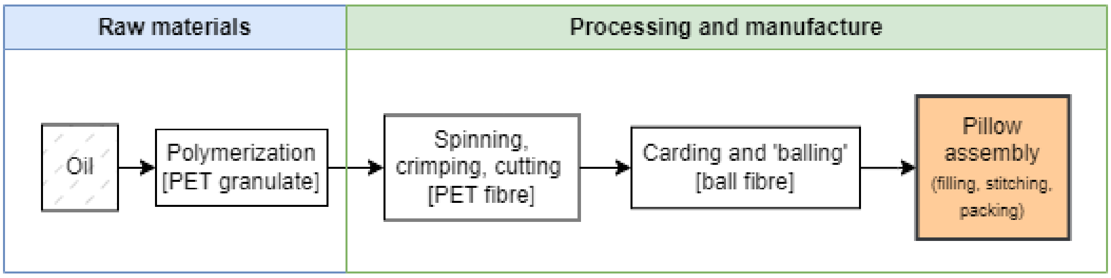

Figure 3: System boundary diagram for the Fossflakes filling

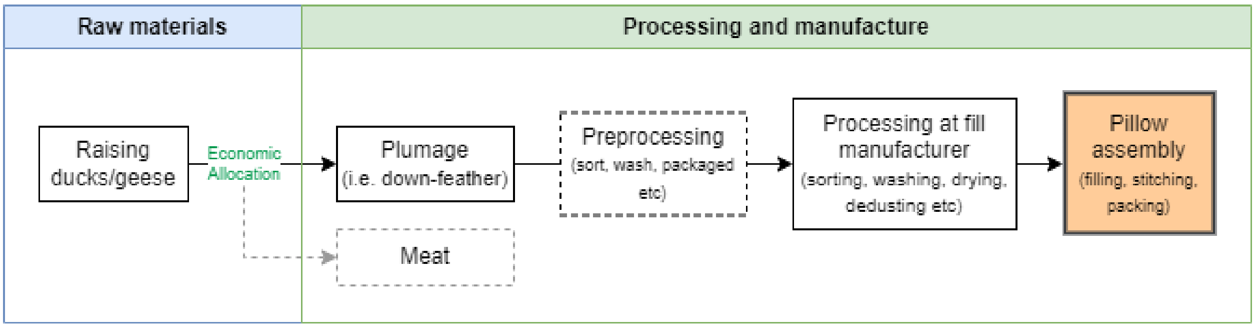

Figure 4: System boundary diagram for the down-feather filling

2.5 Excluded Processes

To streamline the analysis and focus on the most significant environmental impacts, the following processes were excluded from this assessment:

- Human activities e.g. employee travel to and from work.
- R&D e.g. inputs related to development of the studied products.
- Services e.g. IT, business travel, consultancy, marketing.
- Buildings & equipment e.g. the construction of factories and production machinery.

- Retail e.g. store/e-commerce operations and retail packaging (only distribution packaging).

2.6 Assumptions

Assumptions are the predefined conditions and simplifications made about certain aspects of a product's life cycle, such as material sources or usage patterns, to facilitate the analysis when exact data is not available and to enhance the comparability of the systems.

This assessment is based on the following assumptions:

- **Recycling:** No recycling element is considered in the materials used in the primary product or its disposal. This is in line with current industry practice and a consequence of the lack of suitable recycled material.

- **1,000 km distribution distance:** The distance from the factory to the consumer is assumed to be 1,000 km by road (truck). According to Eurostat data from 2022 [6], 41% of goods travel between 300 and 999 km at the EU level, making 1,000 km a conservative estimate for this study. This estimate aligns with Fossflakes' internal analysis, which found an average distribution distance of 1,028 km per product (see 9 Appendix F under '**Error! Reference source not found.** Distribution'). For reference, this distance places the Fossflakes factory within reach of several European capitals (e.g. Stockholm, Brussels, Amsterdam, and Berlin) and was used to approximate the cradle-to-grave life cycle for all three pillows equally. While it does not affect the comparison, this inclusion provides a more complete picture of the real impact of producing or buying a pillow. A sensitivity analysis on different scenarios, such as a various lengths of truck journey or use of ship transport, confirmed that these variations do not significantly impact the overall assessment.

- **Same distribution packaging:** All three pillows are assumed to have the same type and amount of distribution packaging, which differs from retail packaging. Distribution packaging is used for bulk transport, such as shipping pillows to retailers. Retail packaging was not included in this study due to variations manufacturer preferences and practices and the potential complexity in representing this. The pillows are sealed in a plastic bag for hygiene and placed in a cardboard box for shipping protection. This packaging choice is standard for pillows of the same size. The specific packaging weights were based on data from Fossflakes pillow production, as it was the only source with detailed information and is representative of industry practices.

- **Same shell material and quality for all three pillows:** This report focuses on pillow shells made of cotton, assuming they undergo the same processes and are of the same quality, except for transportation differences. Fossflakes pillows have specific transportation routes from known suppliers, while the other pillows use market averages. Although Fossflakes textiles adhere to the Oeko-Tex 100 standard, this was not modelled, as it was outside the study's scope. Down-feather pillow shells are generally heavier than polyester fibre pillows due to the requirement of being down-proof, which means they need a tighter weave to prevent filling from poking through, which also have the added benefit of increased blockage of dust mites [7]. Fossflakes actively choose a higher-quality, tighter weave cotton shell for their pillows to take advantage of these benefits. In contrast, synthetic pillow shells are often made from cheaper, loosely woven fabrics that are more permeable to allergens, which is why they are lighter [8] [9]. Assuming the same shell weight in this analysis allows for a standardized comparison, ignoring differences in fabric quality and functionality.

- **Weight of materials:** For a medium 50 cm x 70 cm pillow, differences in the weights of the cotton shell and filling were outlined in the 'Functional unit' section. To ensure a fair comparison, the cotton weight was standardized across all three pillows, with the weight from the Fossflakes pillow used as the benchmark. The filling weight data was obtained from a single online retailer, as other retailers did not provide specific measurements for both the fill and shell weights. This method highlights the environmental impact differences between the fillings. However, recognizing potential variations in pillow properties, a sensitivity analysis was conducted to examine the effects of different weights for the filling and shell, including variations within the same product category. See 9 Appendix A for more.

- **Two-year life:** Due to a lack of reliable data or studies on how long pillows last or how long people use them, we assume a life of two years for all filling types. This aligns with retailers' and manufacturers' guidelines on the replacement of pillows (see 9 Appendix A's Table 33 with specific references). The limiting factor behind this recommendation of changing the pillow, is often due to hygiene considerations (e.g. due to build-up of dust mites, fungus and other allergens) [10], and secondarily due to the pillow's material durability [11] which is all influenced by the consumers usage of the pillow. Depending on the user, the pillow can be exposed to varying levels of degradation, influenced by factors such as the user's weight, sweat or moisture levels, climate (i.e. temperature and humidity), maintenance (such as fluffing, washing, drying, and detergent use), and movement during sleep. This introduces significant variability in the pillow's lifespan. The impact of this choice of equal lifetime will be investigated in the sensitivity analysis (section 5.1.3).

- **No laundering during use phase:** Due to the lack of comprehensive studies on people's pillow laundering habits, it was assumed that no machine washing or drying occurs during a pillow's two-year lifespan. This assumption is based on a combination of expert judgment and limited online sources, which suggest significant variability in laundering habits and indicate that many people may never wash their pillows [12]. As one source states, “Many people don't wash their pillows simply because they don't know that they should” [13]. The impact of washing and drying, or not doing so, will be explored in the sensitivity analysis (section 5.1.5), including the different laundering requirements for various types of pillows.

- **Incineration as primary disposal treatment:** In this study, we assume that 98% of the pillow is incinerated at the end of its life, with the remaining 2% going to landfill. This assumption is based on the common municipal solid waste (MSW) treatment practices in Denmark, where incineration is the predominant method for disposing of this type of waste (via ‘*market for municipal solid waste – DK*’, Ecoinvent). This approach is however also relevant for Northern Europe, which is the region considered for all post-gate activities (i.e., distribution, use, and end-of-life (EoL) stages) in this study. In most Northern European countries, less than 5% of MSW is sent to landfill [14][3], and since the pillow is presumed to be non-recyclable, the remaining waste (>95%) is assumed to be treated through incineration. The analysis also includes the transport from the consumer’s home to the incineration plant via a recycling centre. For more detailed information on waste treatment and energy recovery practices, please refer to the section for LCI Data Collection or Appendix F for more detail on the specific modelling.

- **Global pillow manufacturer:** To ensure the assessment reflects typical down-feather and polyester fibre pillow manufacturers, the data and flows used are, in most cases, based on the broadest geographic or market activities available (e.g., GLO, RoW).

- **10% of animal allocated:** The environmental impact of raising ducks and geese cannot be wholly attributed to the down and feathers but must be shared with co-products like meat. Deciding on the correct allocation is important to gaining an accurate picture of the impact of a down-feather pillow. A life cycle assessment of down-feather fill commissioned by the International Down & Feather Bureau (IDFB) used an allocation of 10% based on the economic value of the down-feather and feather compared to the other co-products [15]. Our assessment will use the same 10% default allocation and includes a sensitivity analysis in the range of 2% to 50%, in line with the IDFB report.

[3] In the report see results under ‘Table 3.1 Municipal solid waste (MSW) management and selected policy instruments in European countries, 2001–2015’. Percentage MSW landfilled per MSW generated, 2014: DK 1%, DE 1%, NE 1%, NO 3%, SE 1%.

- **Duck representing both duck and goose:** To model the raising of duck and geese, which are the most typical sources of down and feather, a dataset for the cradle to slaughter (or "farm-gate") of a duck was used, due to lack of data on geese. No distinction between the two types of down-feathers is made throughout the study.

2.7 Recycling & waste

In this study, we adopt the cut-off approach for handling recycling impacts. According to this method, the environmental impact of producing a material (such as farming, mining or manufacture) is assigned to its initial use, while any impacts related to recycling or refurbishing (like collecting and processing used cardboard boxes) are allocated to its subsequent use. Similarly, any environmental effects from disposing or treating waste are attributed to the phase in which they occur. We apply this approach when analysing data from secondary sources like Ecoinvent and Agribalyse. However, in the sensitivity analysis, a system expansion is used to explore the potential energy recovery from incinerating a pillow in a waste-to-energy (W2E) plant.

2.8 Impact assessment method

Impact assessment methods convert data, such as energy use and raw material production, into measurable environmental impacts. This study utilizes the ReCiPe 2016 v1.03 Midpoint (H) method [16], a widely recognized tool in LCA for translating inventory data into specific environmental impact categories, such as global warming and resource depletion. The 'Midpoint' approach focuses on specific environmental problems rather than final damage outcomes, allowing for a more detailed and precise analysis. The Hierarchist (H) perspective, being the default and most widely accepted, offers a balanced and consensus-driven assessment, making it particularly relevant for this study. By using ReCiPe Midpoint (H), we align with established practices in similar research [15], ensuring our results are both comprehensive and comparable.

This study focuses on three key impact categories: climate change, water consumption, and land use. These were selected since they were expected to be the important, based on the differences between the pillow's materials and the pillow itself. Additionally, the categories were found to be readily understandable and of greatest interest stakeholders.

1. **Climate change - global warming potential** (GWP100)
   Climate change impact, often measured in terms of global warming potential (GWP100), quantifies the amount of greenhouse gases emitted throughout a product's life cycle, expressed as kilograms of CO_2 equivalent. This impact category is crucial because it reflects a product's contribution to global warming, a pressing environmental issue characterised by rising global temperatures, changing weather patterns, and severe ecological consequences. Addressing the climate change impact of products is essential for mitigating global warming and achieving sustainable

environmental stewardship.

2. **Water consumption potential** (WCP)
   Water consumption impact assesses the volume of water used directly and indirectly throughout a product's life cycle, indicating the strain on freshwater resources. This impact is increasingly important in the context of global water scarcity, as excessive water use can lead to depletion of water bodies, degradation of aquatic ecosystems, and conflict over water resources. Understanding and minimising water consumption in product life cycles is critical for conserving water resources and ensuring their sustainable use for future generations.

3. **Land use - agricultural land occupation** (LOP)
   Land use impact, particularly agricultural land occupation, measures the amount of land used or altered due to the production of a product, typically quantified in square metres per year. This impact is significant as it is one of the main drivers of global biodiversity loss, i.e. it encompasses the consequences of deforestation, habitat destruction and changes in land use from natural ecosystems to agricultural or industrial uses [17]. Sustainable land management is vital for preserving ecosystems, maintaining biodiversity, and ensuring the long-term viability of natural resources.

We will test the significance of this choice by comparing the impact of each pillow across 14 additional impact categories, to check for unexpected hotspots. This comparison can be found in the sensitivity analysis section of the report. The additional impact categories are as follows:

1. Terrestrial acidification
2. Freshwater ecotoxicity
3. Marine ecotoxicity
4. Terrestrial ecotoxicity
5. Fossil fuel use
6. Freshwater eutrophication
7. Carcinogenic human toxicity
8. Non-carcinogenic human toxicity
9. Ionising radiation
10. Surplus metal/mineral ore
11. Ozone depletion
12. Particulate matter formation
13. Photochemical oxidant – human health
14. Photochemical oxidant formation - terrestrial health

2.9 Calculation tool

For system modelling we used the open-source software openLCA[4] created by GreenDelta. This software allowed us to standardise data flows in line with our chosen functional unit and perform key tasks like life cycle inventory, impact assessment, and various analyses, such as evaluating contributions, sensitivity, and uncertainty. OpenLCA is known for its flexibility and open-source nature, allowing for detailed LCA studies with customizable options to suit various needs [18].

2.10 Critical review

To ensure the reliability and transparency of the LCA findings, a critical review was conducted, as required for LCAs involving public comparative assertions. This review, carried out by independent experts, evaluated the methodology, data sources, interpretations, and conclusions to ensure compliance with ISO 14040 and 14044 standards.

The review process included an initial evaluation of the draft report, feedback sessions, and a final review. The panel used a structured checklist to identify potential biases, uncertainties, and methodological issues. Feedback was provided through reports and meetings, leading to necessary revisions. The review also assessed:

- Adherence to ISO 14040/14044 standards.
- Scientific and technical validity of the methods used.
- Appropriateness of the data for the study's goal.
- Alignment of interpretations with the goal of the study.
- Transparency and consistency in the report.

As a result of the review, adjustments were made, including refining data sources, modifying allocation methods, and clarifying interpretations.

The members of the review panel and their role are specified in table 1 below.

Table 1: The members of the critical review panel

Member	Role	Affiliation
Morten Søes Kokborg	LCA lead reviewer	Rambøll Danmark A/S
Asger Alexander Wendt Karl	LCA expert	Danish Technological Institute
Poli Jacobsen	Pillow industry expert	DYKON A/S

[4] OpenLCA - An open source and free software for Sustainability and Life Cycle Assessment. https://www.openlca.org/

Where feedback could not be fully addressed due to data limitations, these issues were noted in the report. Further details on the review process and remarks are provided in 9 Appendix E.

2.11 Limitations of the study

This study is constrained by several factors that should be considered when interpreting the results. Due to a lack of primary data from certain suppliers, secondary datasets from the Ecoinvent database were used for many background processes. While these datasets are generally reliable, they may not capture nuances specific to the product systems, such as transport routes and energy consumption at individual production sites. For example, we were unable to model a small part of the down-feather pillow production, specifically the processes between slaughter and fill manufacturer, including the slaughter itself, pre-washing, and transport. These data gaps are estimated to contribute to a 2-10% variation in the final results.

The study assumes a two-year pillow lifespan, based on industry standards and hygiene considerations, which may not accurately reflect individual user behaviour. Sensitivity analysis showed that factors such as pillow material (shell and filling), distribution distances, and usage habits could result in 1-20% variability in climate impact, however with the less common scenarios needed to reach the higher end. For instance, washing and tumble-drying pillows twice a year could increase climate impact by 21%, with smaller impacts on water use (4%) and land use (14%) (section 5.1.5).

A few assumptions introduce greater variability: adjusting the pillow lifespan to one or three years could alter impacts by -30% to +100% and changing the allocation for bird farming from 10% to 2% could reduce climate impact by up to 50% (for more see section 5.1.1 and 5.1.3 in the *Sensitivity analysis*). While these assumptions were tested in sensitivity analyses, they still represent key uncertainties. Despite this, the study is comprehensive, and the assumptions are transparent, ensuring robustness in the conclusions.

2.12 Limitations of the LCA Methodology

This study follows ISO 14040 and 14044 standards, ensuring a systematic approach, but certain limitations of the LCA methodology must be noted. The data used are often subject to temporal, geographic, and technological variations, which may not always reflect the most current or site-specific conditions. For example, using global energy data instead of Denmark-specific data could result in 6-7% variation in the total climate impact of the Fossflakes pillow (see section 5.2.1 for more). Such generalizations may affect the accuracy of results, especially in areas like energy sourcing and transportation logistics.

The cut-off approach assigns the full production burden to the initial use of materials, excluding future recycling or reuse impacts. Simplifications were also made for ancillary processes, such as the transportation of packaging materials and yarn, relying on market datasets. These choices introduce 0.1-0.2% variability in total climate impact, with even smaller effects on water and land use (see section 5.2.2 for more).

Additionally, the characterization models used in LCIA (both midpoint and endpoint categories) rely on assumptions that may not fully capture all environmental interactions. This is especially relevant for midpoint results, which may not fully reflect long-term environmental damage. Site-specific factors, such as local energy mixes and waste management practices, are generalized, leading to possible discrepancies in real-world applications. However, both the sensitivity analyses and a '*Further investigation of limitations*' were conducted to explore the significance of key assumptions and ensure that conclusions remain robust.

3 Life Cycle Inventory

The Life Cycle Inventory (LCI) provides a comprehensive list of all inputs and outputs associated with a product and the processes it undergoes, including materials, waste, energy, and emissions. This analysis employs consistent assumptions and frameworks for all three pillow types. Consequently, any variations in environmental impacts can primarily be attributed to the type of filling material used, i.e. down-feather, polyester fibre, and the Fossflakes fill. This approach facilitates a clear comparison of the impacts of different pillow types while also considering the total impact of each pillow. This ensures that the observed differences are meaningful within the context of the pillow's "entire product life cycle", rather than being limited to a selected part, which is also in compliance with the guidelines outlined by the Danish Consumer Ombudsman in the guide on the use of environmental claims [3]. The following sections describe the key process steps and reasoning behind them, with more detail on the exact modelling (e.g. how it looks in the LCA software) in Appendix F.

3.1 LCI Data Collection

In this study, we combined primary and secondary data sources to create a comprehensive life cycle inventory. Primary data was used whenever available, specifically for the midstream manufacturing processes at the respective factories of Fossflakes and the down-feather pillow and fill manufacturer. This data includes detailed records on energy, water, material usage and waste materials from production. For the Fossflakes pillow, additional primary data was gathered on parts of the upstream value chain, such as material and electricity usage and specific information on transportation distances between suppliers.

For the polyester fibre pillow, we extrapolated data from the midstream Fossflakes production processes where applicable and supplemented with secondary data from established databases. Secondary data was also used for all processes where primary data was not available, including raw material extraction, processing of material inputs, transportation, and disposal. This approach was necessary due to the lack of direct measurements or proprietary information for certain processes. We relied on the databases Ecoinvent v3.9.1[5] [19] and AGRIBALYSE v3.1.1 [20], which provided data on a wide range of materials and processes relevant to our study, such as the production of polyester fibres - a key component in both the Fossflakes and polyester pillows. Detailed explanations for each pillow's life cycle inventory can be found in their respective LCI sections below.

The general assumptions for distribution, use, and end-of-life treatment, are applied uniformly across the different pillow types to ensure fairness in the comparative analysis. Examples of this are same method and distance for distribution, same method of waste treatment (same incineration-to-landfill ratio) and a product lifetime of 2 years. The specifics and basis of these choices will be elaborated on in the sections below as well.

For the Fossflakes pillow, country specific electricity grid mixes and similar regional datasets for heat/gas, water etc, were used for most of the value chain. For the polyester and down-feather pillows, a GLO or Rest of World electricity mix was used. The necessity of adopting a global value chain for the down-feather and polyester fibre pillow, rather than focusing more precisely on a specific location or country, stems from the widespread distribution of manufacturers worldwide. While China is a major contributor to the global pillow production, many producers are also based in Europe and other regions [21]. Because the Fossflakes pillow is made and primarily sold in Europe, focusing solely on Chinese production would be too narrow and limit the report's applicability. Instead, we chose a more general approach to allow for comparisons across different manufacturers and geographies. Adopting a localized weighting would require significant assumptions due to the diverse production locations and specific market dynamics in Europe for distribution, use, and end-of-life phases. This uncertainty around these assumptions was avoided by using three (mostly) similar phases after the production of the pillow (i.e. post cradle-to-gate).

Each process, dataset provider, data quality rating and further comments are detailed in Appendix F, section F.1.

3.1.1 Fossflakes Pillow

The Fossflakes pillow was modelled largely with primary data, due to the availability of company specific data on energy and water bills, waste and machinery wattage. We were also able to retrieve information from suppliers with access to upstream transport routes reaching relatively far into the value-chain. In some cases, processes were modelled on secondary

[5] Recommendation: Readers seeking additional information on the datasets and modelling specifics used in this study can refer to the Ecoinvent ecoQuery tool. This resource provides detailed documentation and access to related datasets, which can be explored at: https://ecoquery.ecoinvent.org/3.11/cutoff/search

data combined with company specific detail on inputs/outputs (primary data). In other cases, they were fully based on secondary data.

All primary data was provided by Fossflakes internal experts and upstream suppliers in late 2023, using the latest available data. It was modelled solely using the Ecoinvent database.

Certain nuances in the Fossflakes product quality were not modelled in this first study. For example, its use of cotton certified under OEKO-TEX class I, a standard that assures textiles are safe for human contact and meet stringent ecological requirements [22]. These include requirements on chemicals (dye, pesticides, heavy metals etc.), allergen control, pH level and colour, to name some of the overall aspects. To model chemicals at this level was deemed beyond the scope of this study, resulting in an identical model for the production of cotton shells across all three pillow types.

Cradle-to-Gate

The raw material acquisition and initial processing for the Fossflakes pillow include the extraction and initial processing of materials such as polyester granulate for the fibres, polyethylene granulates for the Fossflakes pillow and cotton yarn for the textile. All Fossflakes pillows have a ratio of 70% Fossflakes (PE) and 30% fibres (PET).

For the plastics, the process begins with crude oil extraction, followed by polymerization and formation into granulate. The polyester granulates are then transported to a factory where they are spanned, drawn, crimped, and lastly cut to reach their specific length and structure [23]. A dataset for the specific fibre type used, Hollow Conjugated Siliconized (HCS) polyester fibres, was unavailable, but the '*fibre, polyester*' dataset resembled it closely. The polyethylene granulate is similarly transported to another manufacturer which will turn the granulate into PE film either by normal extrusion (*'extrusion, plastic* film') or co-extrusion (*'extrusion, co-extrusion*') taking place in Denmark or Sweden, respectively. Approximately two thirds of all PE film used by Fossflakes comes from the Danish manufacturer and the remaining one third from the Swedish manufacturer. Both datasets were recontextualized by changing the geography of the dataset flows where relevant (e.g. electricity mix) and altering certain amounts to match data supplied from the manufacturers themselves (e.g. waste percentage or specific electricity usage per kg produced).

After this first processing of the materials, the filling materials are supplied to the Fossflakes factory in Skive, Denmark. Here, the PE film is processed to become Fossflakes' unique flakes, and the polyester fibres are carded (i.e. disentangled) and rolled into balls of specific sizes, all of which are electrically powered. When the filling is ready, it is mixed and blown into the pillow-shells, sewn, and packaged. To distinguish between the environmental impact of filling and textile processing and pillow assembly, water, electricity, and heat were allocated to these two steps based on the known energy usage of machinery, expert judgment, and energy/water bills.

The manufacturing of the Fossflakes cotton shell occurs in China, primarily in Hangzhou (30%) and Shijiazhuang (70%). This process includes weaving, dyeing, and 'finishing' the textile. The dyeing process (*'batch dyeing, fibre, cotton – RoW'*) removes natural colours, while the finishing process (*'finishing, textile, woven cotton – GLO'*) adds flame retardants, softeners, and other properties.

The understanding of the overall processes involved in the production of a pillow's cotton shell is based on literature related to bed and duvet covers, as specific information on pillow covers was not available [24] [25] [26]. These items often adhere to similar standards. For all four processes, we relied on secondary data from Ecoinvent because no primary data could be obtained from the manufacturers. The dataset for textile production (*'textile, woven cotton - GLO'*) represents a specific quality of "36 grams per square meter (gsm) with a yarn of 20 Tex (Nm50)," which slightly differs from the Fossflakes specifications of 'TC233 – 100% Cotton cambric – construction 133*100 40/40 – OEKO-TEX certificate class 1' shell[6]. Minimal transport between textile processing steps is assumed. The dataset also includes yarn as a global market activity, accounting for potential imports and transport to the textile manufacturer.

Although the Fossflakes cotton shells are OEKO-TEX certified, this certification was not reflected in the model, which may lead to inaccurate impacts due to the assumed use of harsher chemicals and processes.

When the shell is finished, it is transported to the Fossflakes factory in Skive, DK. It is important to note that the cotton shell modelling differs slightly between the Fossflakes pillow and other pillows, such as down-feather and polyester fibre pillows. For Fossflakes pillows, the cotton shell production process includes specific transport by truck and ship from the locations in China to Skive. In contrast, the down-feather and polyester fibre pillows utilize a dataset that encompasses market activities, including transport up- and downstream of the product, to align with modelling the 'general' industry-standard pillow.

Distribution

During the distribution phase, the pillows are bundled and wrapped in polyethylene, packed in cardboard boxes, and distributed via truck (*'freight, lorry, unspecified - RER'*) 1,000 km to customers. This activity is assumed to take place within EU. The weight of distribution packaging per pillow was based on measurements of Fossflakes own standard distribution packaging (Table 2).

Packaging	Weight pr pillow [kg/p]
Cardboard box (1.16 kg / 10p)	0.116
PE film bag (0.55 kg / 5 p)	0.11

Table 2: The basis used for the distribution packaging weight and type

[6] The "construction 133*100 40/40" indicates a thread count of 133 (warp) and 100 (weft) with a yarn count of 40 Ne (equivalent to 25 Tex, Nm 67.6). Estimated GSM for this fabric is around 90-110 gsm, compared to the 36 gsm and 20 Tex (Nm 50) of the used textile dataset.

The market activity version of both packaging materials' datasets ('corrugated board box' and 'packaging film, low density polyethylene') was used since no further knowledge on the specific supplier was found.

The end-of-life of the packaging materials was also included in the modelling of the pillow's Distribution phase. This decision was made because it was deemed most relevant to consider packaging as an expenditure associated with distribution.

Use

The use phase is assumed to be two years for all three pillow types. Use involves the consumer taking possession of the product until its end of life. No washing or drying is included in the main part of the study, i.e. the use phase has no impact. Due to insufficient data and potential significant variations in how long people keep their pillows and how often they wash them, laundry was only included in the sensitivity analysis, as were various lifetimes. Data found on a manufacturer's website were used to model the wash/drying process, using the Ecoinvent database.

End-of-Life

At the end-of-life phase, the product is transported to a waste treatment facility, where energy recovery is achieved mainly (98%) via incineration. The specific transportation distance of 41,53 km from user to waste facility is extrapolated from a dataset on the market-activity of municipal solid waste treatment in DK. Such a high percentage of incinerated waste was chosen as the standard based on values obtained from the 'market for municipal solid waste - DK', but this resembled most of the Northern European countries' percentage of incineration e.g. Sweden, Norway and Germany [14]. For each of the pillow's materials, i.e. polyester, polyethylene and cotton, a matching dataset for both the incineration and landfill of that product was used, to make sure that the impact of incineration and landfill would be as realistic as possible, compared to using an average of all municipal solid waste.

Part	Dataset (Ecoinvent)	
	Incineration	**Landfill**
Cotton shell	treatment of waste textile, soiled - CH	treatment of municipal solid waste, sanitary landfill - RoW
Fossflakes (PE film)	treatment of waste polyethylene, municipal incineration - RoW	treatment of waste polyethylene, sanitary landfill - RoW
Polyester fibres	treatment of waste polyethylene terephthalate, municipal incineration - RoW	treatment of waste polyethylene terephthalate, sanitary landfill - RoW

Table 3: Datasets used for the disposal phase of the pillows

As can be seen from Table 3 the treatment of landfilled textile, still had to be represented by the more general dataset 'treatment of municipal solid waste, sanitary landfill'. System expansion to include potential energy recovered from electricity and heat by the incineration is investigated in the sensitivity analysis using numbers from each of the Ecoinvent datasets on the incineration of each material.

3.1.2 Polyester Fibre Pillow

The polyester fibre pillow was modelled using a combination of primary data extrapolated from Fossflakes own processes (since polyester fibre is part of the Fossflakes pillow also), and secondary data such as market activities for transportation and waste percentages.

Cradle to Gate

The polyester fibre filling and shell are produced using the same processes as Fossflakes, with the dataset adjusted to represent global ('GLO') markets for broader applicability. Since market activities include average transportation, there was no need for additional transport modelling, as was the case for the Fossflakes pillows.

For the final manufacturing and assembly stages, data were extrapolated from Fossflakes' polyester fibre process, using the same values for assembly (blowing, sewing, packing) and fibre processing (carding, balling), excluding electricity for cutting PE film.

Heat and water usage were not modelled, as they vary significantly by factory location and number of employees and have a minimal impact on the overall LCA.

Distribution

Distribution of the fibre filled pillow was modelled exactly the same as for the Fossflakes pillow: the geography of the datasets, the distance transported, and the type and amount of packaging material needed.

Use

The use phase of the fibre filled pillow was modelled the same as for the Fossflakes pillow. See previous section for details.

End-of-Life

The end of life of the fibre pillow closely resembles the end of life of the Fossflakes pillow, however now the only impacts from landfill, incineration and energy recovery are from cotton and polyester.

3.1.3 Down-Feather Pillow

The process of gathering data and modelling the down-feather pillow required two different databases (Ecoinvent and Agribalyse) due to a lack of specific datasets and literature. A Danish down-feather pillow and duvet manufacturer agreed to supply their expertise and usage data for its own processes. This was then recontextualized to represent an arbitrary down-feather manufacturer, by changing the geography of the dataset providers to 'GLO'.

Cradle to Gate

To model the life cycle of the down-feather pillow from cradle to gate, we used data from the Ecoinvent and Agribalyse databases due to the lack of specific datasets for down-feather products. Data provided by a Danish down-feather pillow manufacturer was adapted to a global context (GLO) by adjusting the geographical scope in the datasets.

Since down-feathers are a co-product of raising ducks or geese, a 10% allocation of the environmental impact from raising these birds was attributed to down-feather production, based on the economic value relative to meat. This approach aligns with methodologies found in similar studies, such as the IDFB report, which also uses this economic allocation. The initial stages of raw material acquisition, specifically raising the bird, were modelled using the '*Duck for roasting, conventional, at farm gate - FR'* dataset from AGRIBALYSE v3.1.1. This dataset was chosen as the most suitable option available and was also utilized in the similar literature on down-feather filling [15], ensuring consistency in methodology and comparability of results. However, data on usage, waste, and resources for certain initial stages, such as slaughter, plucking, storage, pre-wash, and transportation, were not available and should be addressed in future studies.

For this modelling, we assumed that the average weight of ducks and geese used for down-feather production is 3 kg. Additionally, it was estimated that approximately 1 kg of usable down-feather is produced for every 10 birds, translating to 100 grams of down-feather per bird. The effect of the allocation and assumed weighting on how this phase was modelled can be seen in Table 4 and Table 5 below.

Allocation - Raising 1 bird		
Flow	**Amount [kg]**	**Allocation**
Bird meat	2.9	90%
Down-feather	**0.1**	**10%**
Total (bird)	3	100%

Table 4: The basis assumption of 10% allocation of the bird's impact to the down-feather, based on economic value.

Allocation - Producing 1 kg down-feather			
Flow	**Amount [kg]**	**Allocation**	**Impact measured in unit of [kg] '*duck for roasting*'**
Bird meat	29	90%	-
Down-feather	**1**	**10%**	**2.9**

Table 5: Calculating the impact of 1kg feather based on the 10% economical allocation

This assumption was applied without taking any further account of differences between the source being ducks or geese for the sake of simplification, recognizing the variability in actual weights and down-to-feather ratios (further details on these assumptions and their validation can be found in Appendix B: Assumptions and Data Validation for Down-Feather Pillow).

The manufacturing (i.e. further processing) phase includes de-dusting, washing, rinsing, drying, steaming, and sorting feathers and down [27], with energy and water usage data sourced from a Danish manufacturer and extrapolated using global market datasets (GLO). The final manufacturing process, where the filling is blown into the shell and sewn closed, follows the same procedure as with Fossflakes and polyester fibre pillows.

Distribution

The distribution of the down-feather pillow was modeled similarly to the Fossflakes pillow, using the same geographic datasets, transport distances, and packaging materials.

Use

The use phase was modeled identically to that of the Fossflakes pillow, detailed in the previous section.

End-of-Life

The EoL phase for the down-feather pillow follows a similar approach to the Fossflakes and polyester fibre pillows, using the same datasets for the cotton shell. However, due to the unique nature of down and feather materials, which are primarily composed of keratin and do not fit typical waste categories, specific datasets were unavailable. Thus, a generic dataset for average municipal solid waste (incineration and landfill) was used, acknowledging the significant uncertainty this introduces due to differences in how down-feather might behave in waste-to-energy (W2E) plants

3.2 Data Quality

In practice, all data used in an LCA study is a mixture of measured, estimated, extrapolated, and calculated data. Conducting an LCA requires extensive data, and the quality of these data is rarely homogeneous. Therefore, comprehensive descriptions of the LCI and its quality are crucial, as seen in the detailed analyses of each phase and the primary processes of the various pillows.

This study utilized the well-established databases Ecoinvent and Agribalyse, which provide robust data and transparency. Ecoinvent, one of the largest and most comprehensive LCA databases, is continuously updated and offers extensive coverage across a wide range of sectors. It is s datasets are known for their high level of detail and transparency, making them particularly useful for modeling diverse environmental impacts [19].

Agribalyse, on the other hand, is particularly strong in agricultural data, providing detailed datasets for various crops and food products. However, Agribalyse' focus on French geography can be seen as a limitation when attempting to generalize findings to other regions. In this study, Agribalyse was used specifically to determine the impact from raising the ducks/geese i.e. the raw material phase for the down-feather pillow's filling. This choice was driven by necessity, as there were no better alternatives, and it aligns with similar use in other literature as previously stated [15].

The principal inclusions, exclusions, and assumptions for the three systems studied are detailed under the Goal and Scope sections and further elaborated in both the LCI and the appendices. The LCI is generally complete, considering of all relevant flows, materials, processes, and transports, except for some parts of the down-feather pillow supply chain—specifically, the processes between the farm/slaughter and the factory, such as prewashing and transport, which remain unknown.

To evaluate the quality of the data and manage uncertainty, the Pedigree matrix was employed as a Data Quality Rating (DQR) system [28]. This matrix ranks each flow or process across five categories: Reliability, Completeness, Temporal Correlation, Geographical Correlation, and Further Technological Correlation (see Appendix D for more detail on the Pedigree Matrix). Despite this structured evaluation, it's important to note that the quality of data is ultimately based on a holistic human assessment.

The data in this study is generally considered high quality due to the detailed knowledge of both processes and specific amounts needed. Site-specific data for raw materials, energy, and waste from the manufacturing process, all from 2022, were represented with Ecoinvent datasets. Other environmental aspects were modeled using generic data or a combination of primary and secondary data, as described in the LCI sections.

However, the overall quality of the LCI for both polyester and down-feather pillows is limited by the reliability of the data due to the small number of data points, leading to higher statistical uncertainty and less reliable results. This issue is compounded by a lack of resources, scope, and time, as well as reluctance from manufacturers to supply data, perhaps due to perceived conflicts of interest with the report's author.

Additionally, the niche market of pillow manufacturing lacks widespread LCA data and standardized frameworks, such as means testing all types of fill quality and lifetime, Environmental Product Declarations (EPDs) and Product Category Rules (PCRs), further complicating data reliability.

To mitigate these data limitations, several strategies were employed:

- Expert judgments were sought in plastics, waste management, the pillow industry, and down-feather production, and the study was reviewed by a board of two LCA reviewers and one experienced industry reviewer.
- A comprehensive sensitivity analysis was conducted to identify and highlight potential hotspots and showcase the many sources of variance.
- Transparency was prioritized by clearly detailing the study's limitations.
- General global (GLO) datasets were used to ensure broad applicability of the analysis.
- A conservative approach was taken, systematically choosing worst-case scenarios or conservative estimates in modeling the Fossflakes pillow to counter potential bias, given that Fossflakes is the author of this report.

4 Results of Life Cycle Impact Assessment

The following section presents the findings from the life cycle impact assessment (LCIA), detailing and comparing the environmental impacts across the life cycle of each product within the three selected impact categories. To avoid any selection bias, results for all midpoint impact categories are also included and are displayed at the end of the results section.

As you review the results, note that a top-down approach has been applied, beginning with an overview of the overall results and gradually moving to more detailed analyses. This approach is particularly relevant when comparing the Fossflakes and polyester fibre pillows to the down-feather pillow, where the most significant differences are observed. The underlying reasons for these differences will be explained in later sections, where the impacts of the pillows are broken down, e.g., by the shell and the filling (section 4.1.4). This is followed by a detailed analysis of the raw material extraction for the down-feather pillow's filling, including the environmental impact of raising ducks, which, as shown in the results, is a major contributor to the pillow's overall environmental impact.

4.1 Overall results

Table 6 and Figure 5 below show an overall picture of the Fossflakes and polyester fibre filled pillows having a similar impact across climate change, water use and land use. By comparison, the down-feather pillow has a significantly higher impact in all three categories, most notably land use.

Looking at impact categories individually, the best performer in climate change is the Fossflakes pillow, in water impact Fossflakes and polyester fibre are joint top, while in land impact the polyester filled pillow takes first place.

Results per functional unit (1 pillow)	Climate (kg CO2-Eq)	Water (m3)	Land (m2*a crop-Eq)
Fossflakes	7.90	0.78	1.13
Polyester fibre	8.26	0.78	1.10
Down-feather	11.80	0.91	11.26

Table 6: The overall cradle to grave environmental impact of a Fossflakes pillow, a down-feather pillow, and a polyester fibre pillow across key impact categories

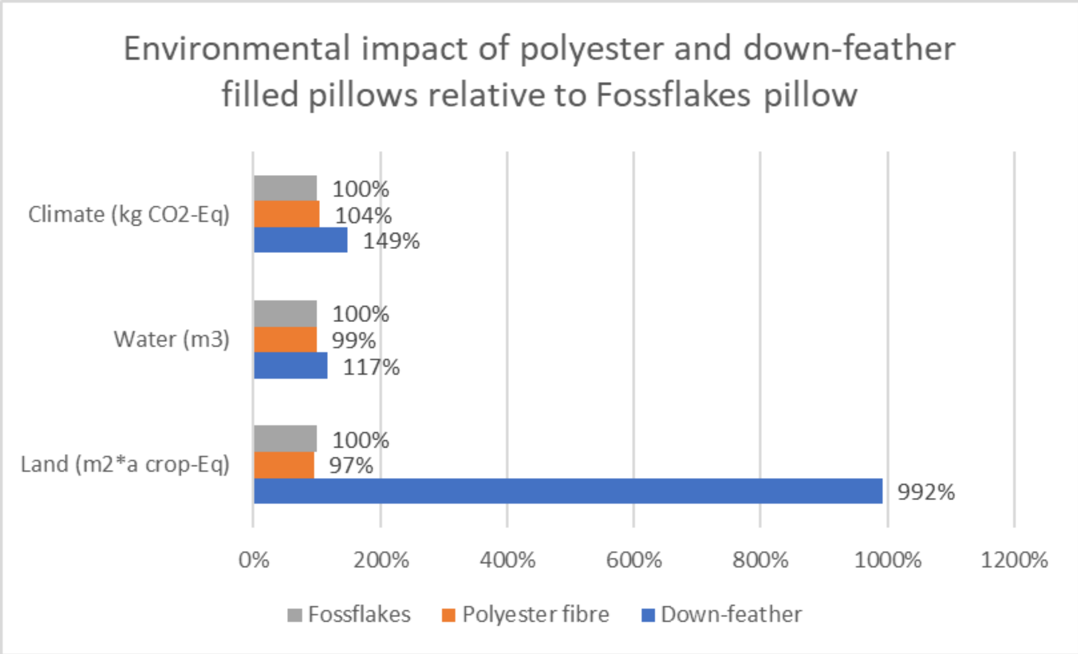

Figure 5: A relative comparison of the overall environmental impact of the pillows, with the Fossflakes pillow used as the control.

4.1.1 Climate impact by life cycle stage

Table 7 and Figure 6 show that for all pillows, raw material extraction is the largest contributor to climate change impact, with manufacturing in second place.

Comparing the pillows' climate impact by life cycle stage, we see that the most significant difference is in the extraction phase. Here, the impact of the down-feather pillow is approximately 2.5 to 2.9 times higher than the Fossflakes and polyester fibre filled pillows.

Although the down-feather pillow is the clear best performer in the disposal phase, this is insufficient to offset its impact in the extraction phase, resulting in an overall climate impact significantly higher than the Fossflakes and polyester filled pillows

Climate (kg CO2-Eq)	Fossflakes	Polyester fibre	Down-feather
Total	**7.904**	**8.259**	**11.799**
Raw Material	3.02	3.52	8.68
Manufacture	1.85	2.15	1.59
Distribution	1.06	1.06	1.06
Disposal	1.98	1.52	0.47

Table 7: Climate impact of each pillow by life cycle stage.

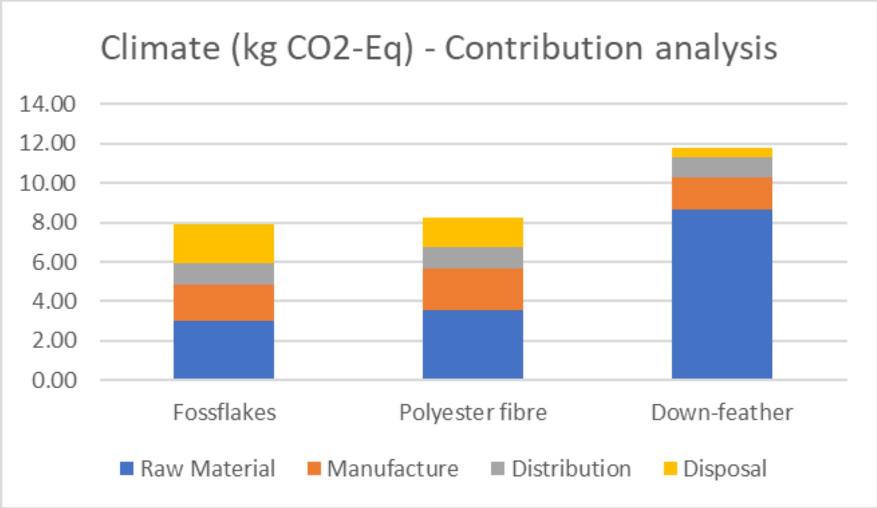

Figure 6: Contribution analysis of the climate impact of each pillow by life cycle stage.

4.1.2 Water use impact by life cycle stage

In terms of water impact, Table 8 and Figure 7 illustrate that the three pillows perform similarly across all life cycle stages, with a slightly larger water impact for the down-feather pillow during raw material extraction.

Raw material extraction and pillow manufacturing account for virtually all the water impact of a pillow's life cycle and share the impact approximately equally. Distribution and disposal have very little water impact. The effect of laundering the pillows does increase water usage throughout their life cycle; however, this is independent of the pillow type and depends on the user's habits. This aspect is explored later in the sensitivity analysis under section 5.1.5 .

Water (m3)	Fossflakes	Polyester fibre	Down-feather
Total	**0.781**	**0.775**	**0.912**
Raw Material	0.74	0.74	0.89
Manufacture	0.03	0.02	0.02
Distribution	0.01	0.01	0.01
Disposal	0.00	0.00	0.00

Table 8: Water impact of each pillow by life cycle stage.

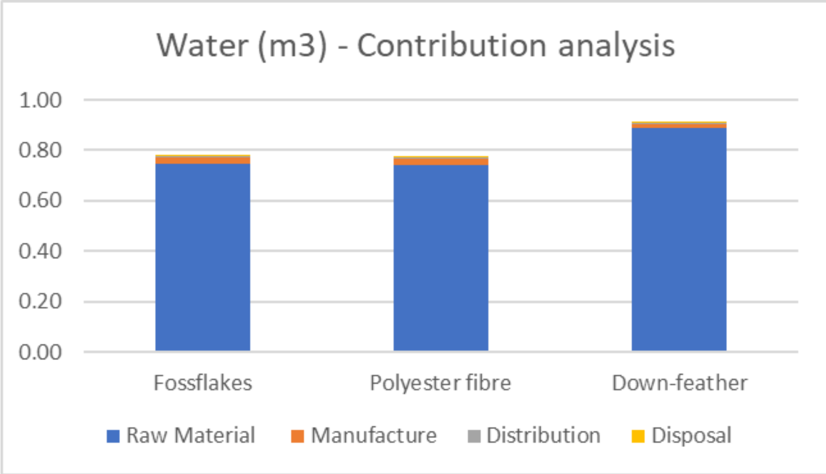

Figure 7: Water impact of each pillow by life cycle stage.

4.1.3 Land use impact by life cycle stage

As seen in Table 9 and Figure 8, the land use impact of all three pillows is primarily driven by raw material extraction and manufacturing. Distribution and disposal have relatively little land impact.

All three pillow types perform similarly across life cycle stages with the notable exception of raw material production where the down-feather pillow's land impact is 11 times higher than the Fossflakes and polyester fibre filled pillows.

Land (m2*a crop-Eq)	Fossflakes	Polyester fibre	Down-feather
Total	**1.13**	**1.10**	**11.26**
Raw Material	0.96	0.97	11.14
Manufacture	0.08	0.03	0.02
Distribution	0.09	0.09	0.09
Disposal	0.00	0.00	0.00

Table 9: Land impact of each pillow by life cycle stage.

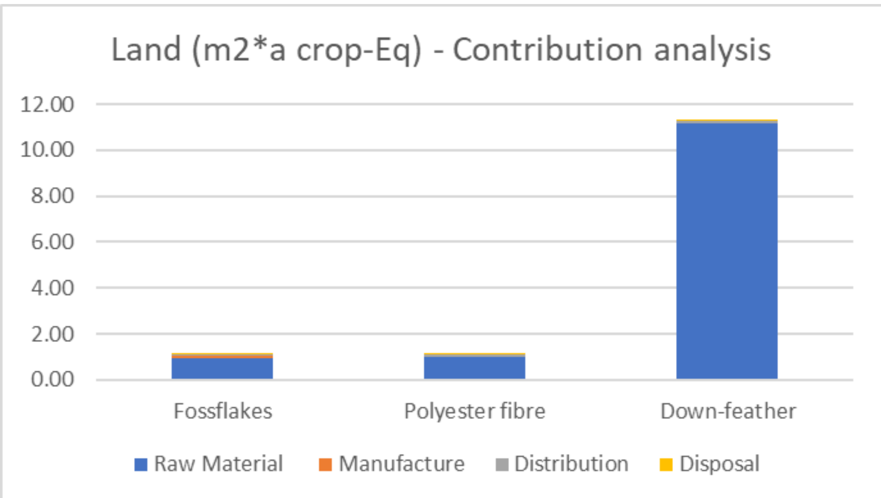

Figure 8: Contribution analysis of the land impact of each pillow by life cycle stage.

4.1.4 Impact of cotton shell versus filling

With the main difference between the pillow types being the filling, it is important to analyse how much of the environmental impact of the pillows is driven by the cotton and how much by the filling. See table 9-11 and figure 9-11 for details.

Climate (kg CO2-Eq)	Fossflakes	Polyester fibre	Down-feather
Total	**7.90**	**8.26**	**11.80**
Cotton shell	2.47	2.45	2.45
Filling	5.43	5.81	9.35
Raw Material (Cotton shell)	1.2E+00	1.2E+00	1.2E+00
Manufacture (Cotton shell)	1.0E+00	1.0E+00	1.0E+00
Distribution (Cotton shell)	1.7E-01	1.7E-01	1.7E-01
EoL (Cotton Shell)	9.9E-02	9.9E-02	9.9E-02
Raw Material (Filling)	1.8E+00	2.3E+00	7.5E+00
Manufacture (Filling)	8.2E-01	1.2E+00	5.9E-01
Distribution (Filling)	8.9E-01	8.9E-01	8.9E-01
EoL (Filling)	1.9E+00	1.4E+00	3.7E-01

Table 10: The climate impact of each pillow by phase and separated by cotton shell and pillow filling

Water (m3)	Fossflakes	Polyester fibre	Down-feather
Total	**0.78**	**0.78**	**0.91**
Cotton shell	0.74	0.73	0.73
Filling	0.04	0.04	0.18
Raw Material (Cotton shell)	7.2E-01	7.2E-01	7.2E-01
Manufacture (Cotton shell)	1.7E-02	1.4E-02	1.4E-02
Distribution (Cotton shell)	1.2E-03	1.2E-03	1.2E-03
EoL (Cotton Shell)	2.7E-04	2.7E-04	2.7E-04
Raw Material (Filling)	2.5E-02	2.5E-02	1.7E-01
Manufacture (Filling)	1.2E-02	1.0E-02	1.6E-03
Distribution (Filling)	6.3E-03	6.3E-03	6.3E-03
EoL (Filling)	1.3E-03	1.1E-03	1.1E-03

Table 11: The water usage of each pillow by phase and separated by cotton shell and pillow filling.

Land (m2*a crop-Eq)	Fossflakes	Polyester fibre	Down-feather
Total	**1.135**	**1.099**	**11.255**
Cotton shell	0.98	0.97	0.97
Filling	0.16	0.13	10.28
Raw Material (Cotton shell)	9.4E-01	9.4E-01	9.4E-01
Manufacture (Cotton shell)	2.0E-02	1.6E-02	1.6E-02
Distribution (Cotton shell)	1.5E-02	1.5E-02	1.5E-02
EoL (Cotton Shell)	1.4E-04	1.4E-04	1.4E-04
Raw Material (Filling)	1.8E-02	3.2E-02	1.0E+01
Manufacture (Filling)	6.0E-02	1.4E-02	5.2E-03
Distribution (Filling)	7.9E-02	7.9E-02	7.9E-02
EoL (Filling)	5.1E-04	4.7E-04	8.9E-04

Table 12: The land use of each pillow by phase and separated by cotton shell and pillow filling

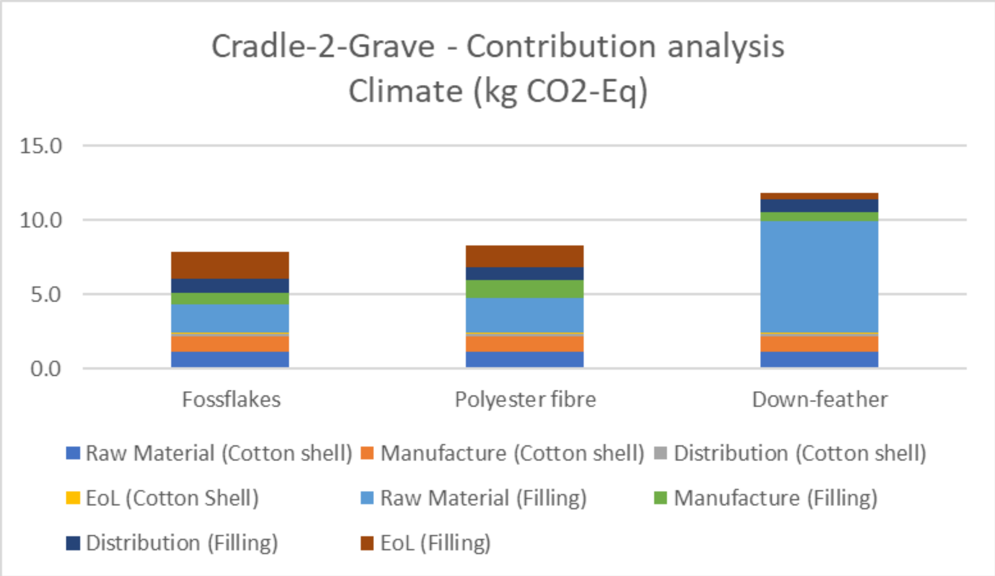

Figure 9: Climate impact of pillows by phase broken down by cotton shell and filling

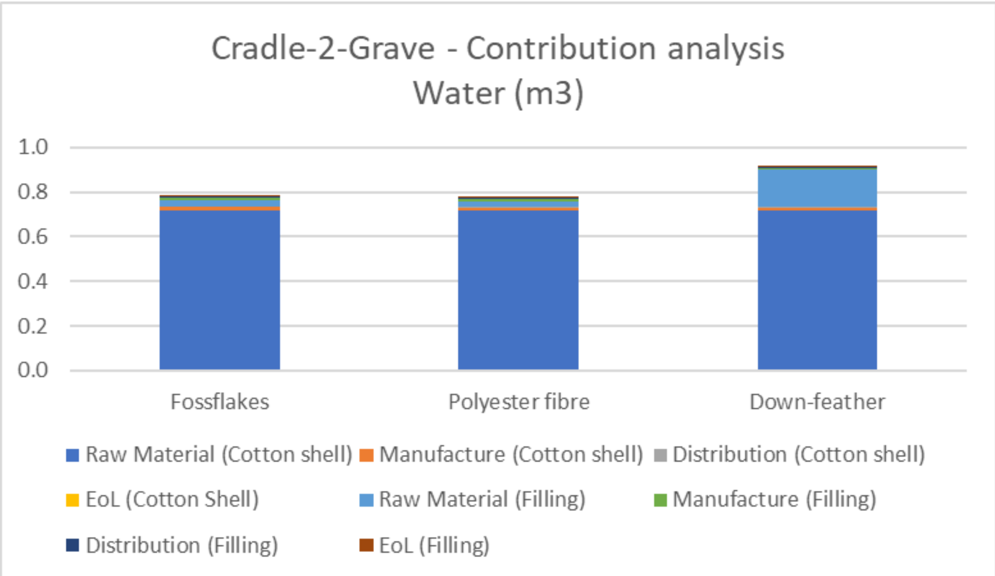

Figure 10: Water use impact of pillows by phase broken down by cotton shell and filling

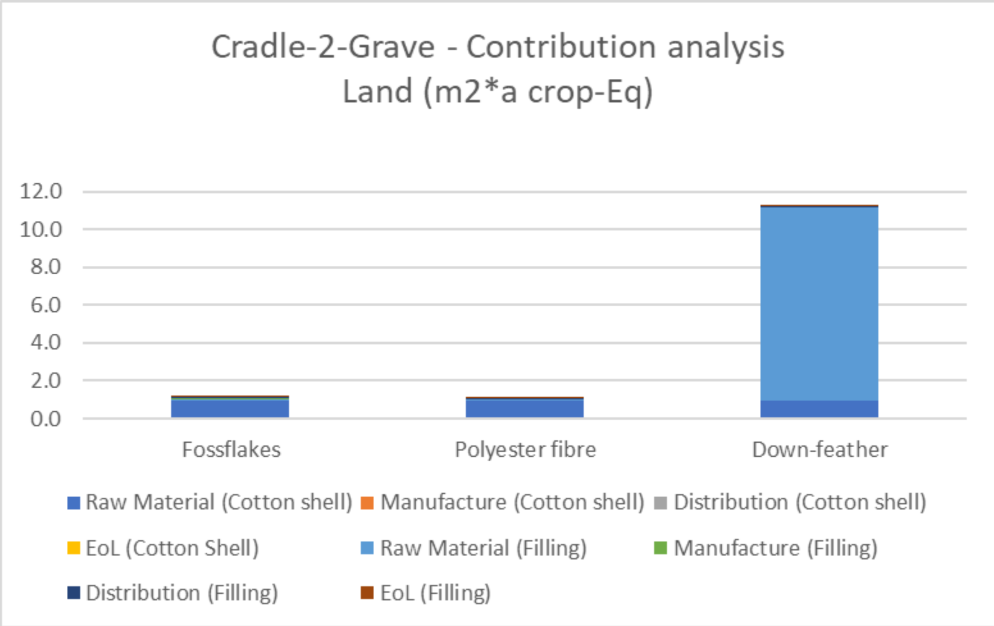

Figure 11: Land use impact of pillows by phase broken down by cotton shell and filling

In terms of climate impact, approximately 2.45 kg CO_2-Eq of each pillow derives from the cotton shell. The impact of the Fossflakes pillow's cotton shell is slightly higher at 2.47, due to it using specific transport routes from suppliers whereas the two other pillows use secondary data (market activities) to model this. Although the climate impact of the filling is greater than that of the shell for all three pillows - 5.43 kg CO_2-Eq for Fossflakes, 5.81 kg CO_2-Eq for polyester fibre, and 9.35 kg CO_2-Eq for down-feather - it is important to note that the cotton shell weighs only 130g compared to the 700g filling. This emphasizes cotton as a significant hotspot when used as the shell material for the pillow.

For water use, most of each pillow's impact derives from the cotton shell – between 0.73-0.74 m^3. The impact of the filling is only 0.04 m^3 for both Fossflakes and polyester fibre and 0.18 m^3 for down-feather due to its heaver usage during its Raw Material phase, i.e. when raising the birds.

Finally, for land use, the cotton shell contributes between 0.97-0.98 m^2*a crop-Eq. While the filling contributions are only 0.16 m^2*a crop-Eq for Fossflakes and 0.13 m^2*a crop-Eq for polyester, the down-feather filling accounts for a far higher 10.28 m^2*a crop-Eq. This number reflects the land-use intensity of raising ducks and the growing of their feed as will be shown in detail in the detailed contribution analysis on its raw material phase.

4.2 Distribution

The chart below shows the contribution of packaging and transport to the environmental impact of distributing a pillow from factory to consumer. Across climate change, water use and land use, the packaging contributes 86%-97% of the impact with transport accounting for only 3% to 14% of the impact.

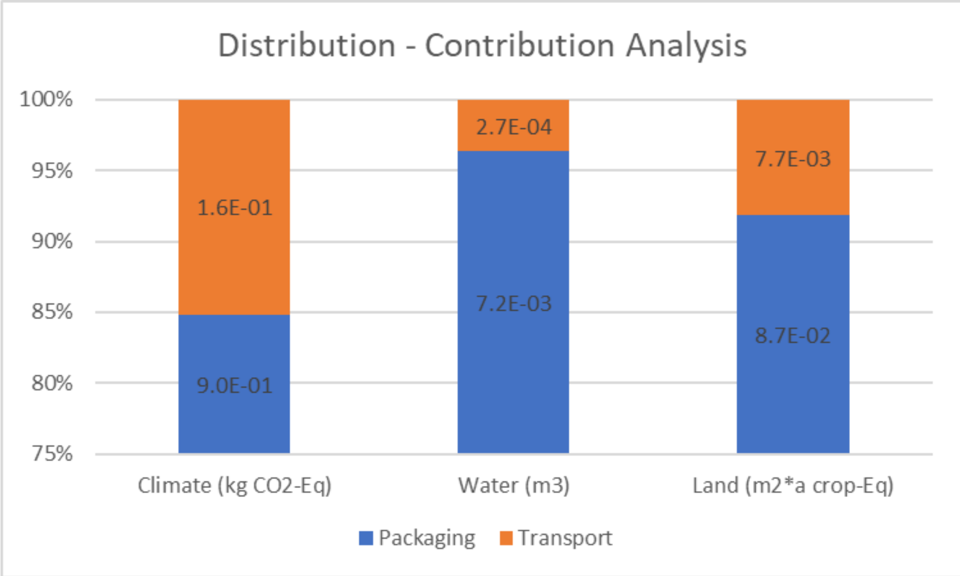

Figure 12: Contribution analysis of the distribution impact of a pillow showing the significant impact of packaging compared to transport.

4.3 Down-feather filling raw material extraction: Raising ducks

As seen from the earlier overall results of the down-feather pillow, the production of the raw filling product, i.e. the raising of ducks/geese for their down and feather, is one of the biggest contributors to its overall environmental impact. Below are the results of a contribution analysis of this process; Table 13 displays the overall contributors of duck raising (‘*Duck for roasting’*), while Table 14 shows the detailed contribution of the duck feed which is the biggest source of impact. It's important to remember that the required amount of '*Duck for roasting*' - 2.03 kg - results from the economic allocation method, as detailed earlier in section 3.1.3 .

Process	Required amount	Unit	Climate (kg CO2-Eq)	Water (m3)	Land (m2*a crop-Eq)
Duck for roasting, conventional, at farm gate - FR	**2.03**	**kg**	**7.494**	**0.170**	**10.197**
Duck for roasting, conventional, at farm gate - FR - *[DIRECT CONTRIBUTION*]*	2.03E+00	kg	1.7E+00	0.0E+00	0.0E+00
Duck, duck feed, conv prod, at farm gate - FR	5.75E+00	kg	5.1E+00	1.5E-01	9.7E+00
Heat, central or small-scale, natural gas {Europe without Switzerland}| heat production, natural gas, at boiler condensing modulating <100kW | Cut-off, S - Copied from Ecoinvent	4.05E+00	MJ	3.0E-01	1.4E-04	3.2E-04
Reproductive, reproductive feed, at farm gate - FR	2.12E-01	kg	1.9E-01	6.8E-03	3.6E-01
Duck, future reproductive feed, conv prod, at farm gate - FR	6.48E-02	kg	5.8E-02	1.7E-03	1.1E-01
Duck building, natural skylight ventilation, slatted concrete floor - FR	1.10E-02	m2*a	4.5E-02	6.6E-04	2.6E-02
Heat, central or small-scale, other than natural gas {CH}| heat production, light fuel oil, at boiler 100kW condensing, non-modulating | Cut-off, S - Copied from Ecoinvent - CH	3.69E-01	MJ	3.2E-02	3.0E-05	5.4E-05
Electricity, low voltage {FR}| market for | Cut-off, S - Copied from Ecoinvent - FR	7.38E-01	MJ	1.8E-02	1.0E-03	5.8E-04
One-side mechanical ventilation,steel siding and fibre cement roofing - FR	1.06E-03	m2*a	4.9E-03	4.1E-05	1.6E-03
Tap water {Europe without Switzerland}| market for | Cut-off, S - Copied from Ecoinvent	1.23E+01	kg	4.0E-03	1.2E-02	8.5E-05
High-extraction mechanical ventilation,steel sandwich pannel siding and fibre cement roofing - FR	2.27E-04	m2*a	1.0E-03	8.9E-06	3.4E-04
Wheat straw, animal feed, average practices - FR	1.31E-02	kg	7.3E-04	1.1E-06	4.4E-06

Table 13: Contribution analysis of the impact of producing (growing) 2.03 kg of 'Duck for roasting' (Agribalyse dataset).

The primary contributions to the environmental impact of raising ducks come from the production and use of duck feed, which is the most significant factor affecting climate change, water usage, and land use.

Process	Required amount	Unit	Climate (kg CO2-Eq)	Water (m3)	Land (m2*a crop-Eq)
Duck, duck feed, conv prod, at farm gate - FR	**5.75E+00**	**kg**	**5.117**	**0.148**	**9.703**
Soybean meal BR, crushing in Brazil, animal feed, at french port, average - FR	8.6E-01	kg	2.0E+00	2.2E-03	3.1E+00
Soft wheat grain, conventional, stored and transported, processing - FR	2.5E+00	kg	1.3E+00	1.3E-02	3.4E+00
Maize grain dried, conventional, stored and transported, processing - FR	1.6E+00	kg	8.8E-01	1.2E-01	1.8E+00
Soybean oil BR, crushing in Brazil, animal feed, at french port, average - FR	7.5E-02	kg	3.7E-01	7.9E-04	5.0E-01
Rapeseed oil, crude, conventional, animal feed, at plant - FR	2.1E-01	kg	1.3E-01	8.5E-04	2.5E-01
Soybean extruded BR, animal feed, at french transformation plant - FR	3.4E-02	kg	8.8E-02	1.6E-04	1.2E-01
…	…	…	…	…	…

Table 14: Contribution analysis of 'Duck feed' which is the most impactful input of 'Duck for roasting'. Only displays the top 6 most contributing processes – the dataset has many more processes in its LCI (this is indicated by the '…' at the bottom).

Within the duck feed component, the production of soybean meal, soft wheat grain and dried maize grain are found to be the largest contributors to land usage and climate impact, with maize being the major driver of water usage.

4.4 All Midpoint Results

To determine whether focusing on three impact categories affects the overall findings of the LCA, an assessment was conducted across all midpoint impact categories (Table 15).

Impact category	Unit	Fossflakes Pillow	Polyester Fibre Pillow	Down-feather Pillow
Terrestrial acidification	kg SO2-Eq	2.27E-02	2.44E-02	1.39E-01
Global warming	kg CO2-Eq	7.36E+00	7.72E+00	1.13E+01
Freshwater ecotoxicity	kg 1,4-DCB-Eq	4.12E-01	4.11E-01	4.90E-01
Marine ecotoxicity	kg 1,4-DCB-Eq	5.27E-01	5.22E-01	6.12E-01
Terrestrial ecotoxicity	kg 1,4-DCB-Eq	2.50E+01	2.57E+01	2.26E+01
Fossil resource scarcity	kg oil-Eq	2.04E+00	2.09E+00	1.45E+00
Freshwater eutrophication	kg P-Eq	1.84E-03	2.24E-03	2.92E-03
Marine eutrophication	kg N-Eq	7.23E-03	7.39E-03	1.59E-02
Human carcinogenic toxicity	kg 1,4-DCB-Eq	2.30E-01	2.82E-01	2.83E-01
Human non-carcinogenic toxicity	kg 1,4-DCB-Eq	6.16E+00	6.54E+00	1.16E+01
Ionizing radiation	kBq Co-60-Eq	3.15E-01	3.23E-01	5.67E-01
Land use	m2*a crop-Eq	1.13E+00	1.09E+00	1.12E+01
Mineral resource scarcity	kg Cu-Eq	4.38E-02	5.02E-02	5.72E-02
Stratospheric ozone depletion	kg CFC-11-Eq	1.53E-05	2.53E-05	7.42E-05
Fine particulate matter formation	kg PM2.5-Eq	7.81E-03	9.42E-03	2.48E-02
Ozone formation, Human health	kg NOx-Eq	1.54E-02	1.62E-02	2.13E-02
Ozone formation, Terrestrial ecosystems	kg NOx-Eq	1.62E-02	1.73E-02	2.21E-02
Water consumption	m3	7.67E-01	7.62E-01	8.99E-01

Table 15: Environmental performance of each pillow for all 18 ReCiPe impact categories. Green = least impactful // Yellow = second most impactful // Red = most impactful. The relative impact of pillows versus the best performer in each category is also shown.

The comparative analysis across all 18 ReCiPe impact categories shows that the environmental performance of the Fossflakes and polyester fibre pillows is generally quite similar, while the down-feather pillow tends to have a higher environmental impact in several categories. These results are normalized below in Figure 13, with the maximum result set to 100% for each impact category, allowing for a clear comparison of relative impacts.

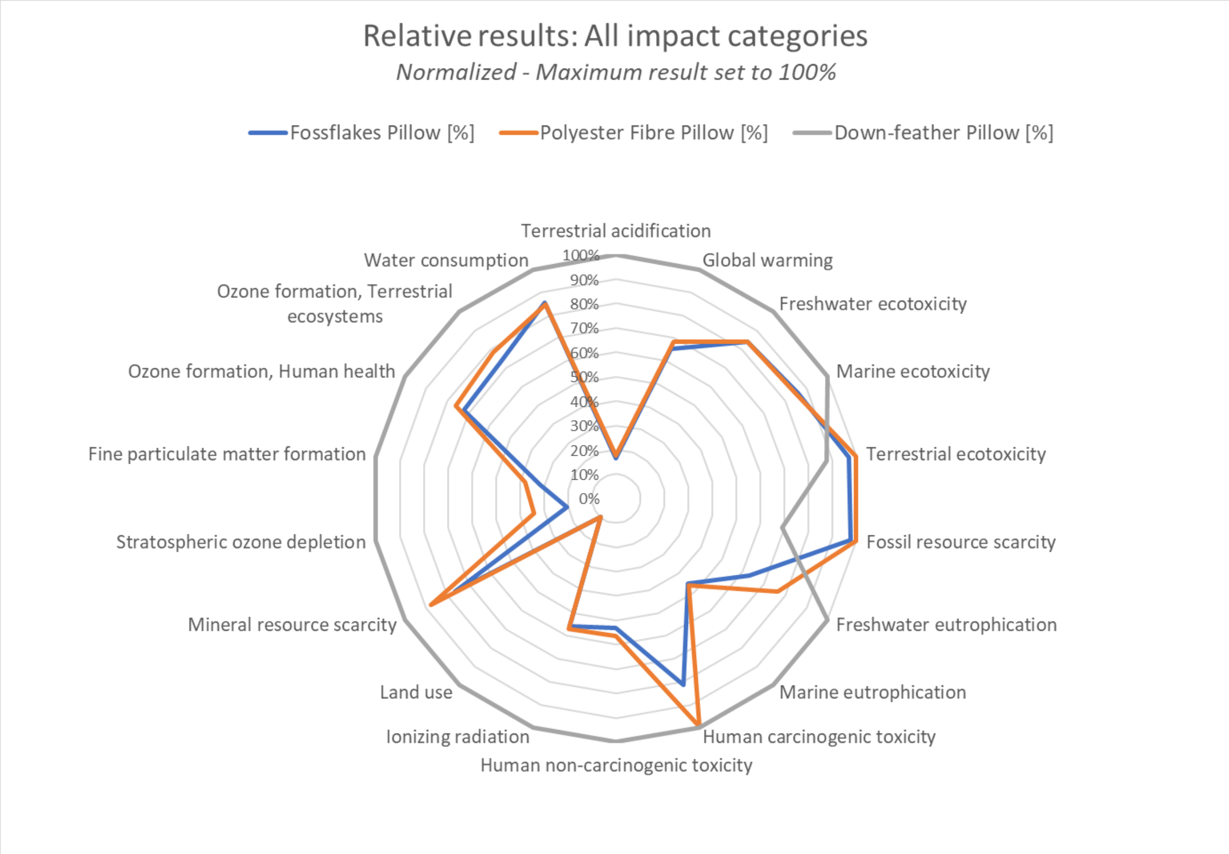

Figure 13 Comparison of the three pillows across all 18 impact categories. Highest contributor within a category is set to 100% and the others measured in relation to that.

The results show that the Fossflakes and polyester fibre pillows perform similarly across most impact categories, with only minor differences in freshwater eutrophication, human carcinogenic toxicity, mineral resource scarcity, and stratospheric ozone depletion. These differences are relatively small compared to the larger discrepancies between these pillows and the down-feather pillow.

The down-feather pillow exhibits significantly higher impacts in several categories, including terrestrial acidification, marine eutrophication, human carcinogenic toxicity, ionizing radiation, land use, stratospheric ozone depletion, and fine particulate matter formation, indicating a generally worse environmental performance.

Although the down-feather pillow has lower impacts in some areas, such as terrestrial ecotoxicity and fossil resource scarcity - likely due to its lack of petrochemical-derived materials - these advantages are relatively minor. In most categories, the down-feather pillow's higher impacts outweigh these benefits.

5 Interpretation

In this section, we critically assess the results of the life cycle impact assessment (LCIA) by examining the foundational elements that could influence the findings, namely the key assumptions, uncertainties, and potentially sensitive parameters. These elements are essential to understand the robustness and reliability of the conclusions drawn from this study.

Throughout the study, several assumptions were necessary, such as assuming a two-year lifespan for the pillows, no laundering during the use phase, and incineration as the default end-of-life treatment. These were adopted due to the absence of reliable data or to standardize comparisons across different pillow types, which helps in determining the extent of their influence on the environmental impact. However, there are inherent uncertainties due to limitations in available data, particularly related to global material sourcing and the allocation of environmental impacts in the life cycle of down-feather pillows. These uncertainties arise from variabilities in production processes, regional waste management practices, and secondary data quality. To address these, sensitivity analyses are conducted to explore how changes in key parameters could affect the results.

Additionally, parameters such as the economic allocation of environmental burden in the supply chain, assumptions regarding transportation distances, and the specific weight of pillow materials are identified as sensitive due to their potential to significantly alter the environmental profiles of the different pillow types. By conducting sensitivity analyses on these parameters, we aim to ensure the robustness of our conclusions and provide a comprehensive interpretation of the LCA results. This approach allows us to present a transparent and reliable understanding of the environmental implications associated with different pillow choices, ensuring that the study's conclusions remain valid under various scenarios.

5.1 Sensitivity analysis

Sensitivity analysis is conducted to evaluate how changes in key assumptions and parameters might affect the outcomes of our study, ensuring that our conclusions remain robust under various scenarios.

In the following section we will test the sensitivity of the results to changes in the assumptions and limitations made in this study. It will be analysed in the order of the most fundamental for the study, i.e. bird allocation used for the down-feather pillow and the weight and lifetime assumed for the pillows, followed by more specific for the individual phases of distribution, use and EoL.

5.1.1 Bird allocation

As stated, we assume that 10% of the economic value of the bird is allocated to the down and feathers, in line with another life cycle assessment of down-feather [15] - however this was only covering for cradle-to-gate. This economic allocation is an essential factor because it influences the distribution of environmental impacts across different products derived from the bird. To account for variability, we performed a sensitivity analysis over a broad range, from 2% to 50%, similar to the approach used in existing studies. The results of this analysis are presented in Figure 14 below, along with the impacts for Fossflakes and polyester fibre-filled pillows.

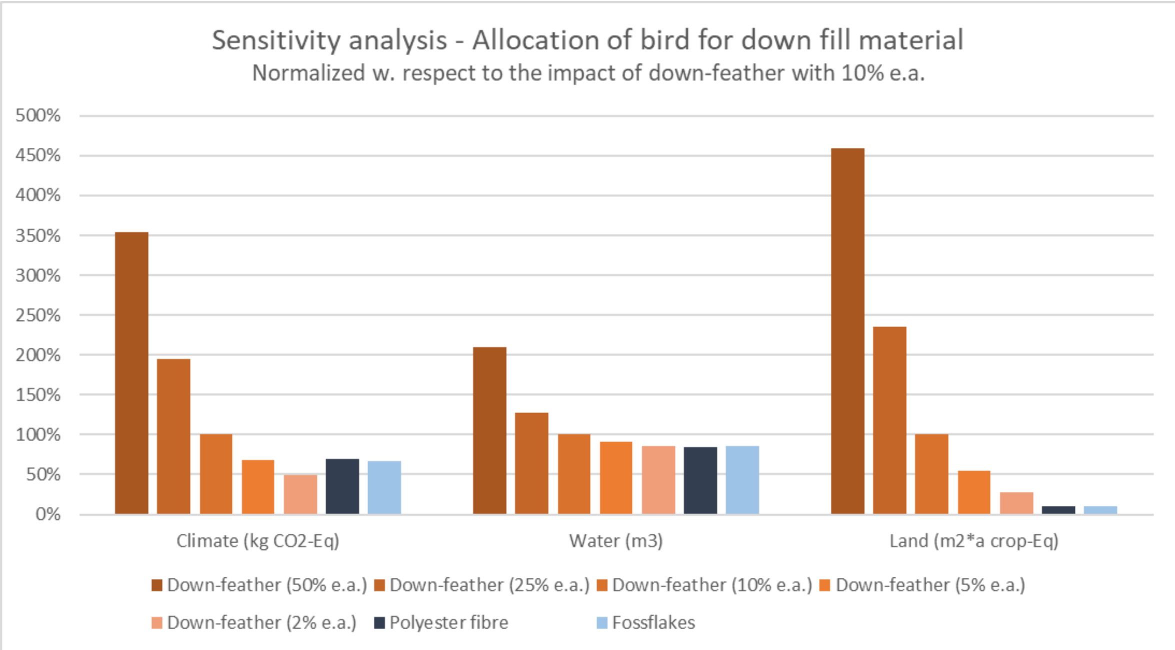

Figure 14: Sensitivity analysis of the full life cycle impact of down-feather pillows with varying economic allocations (e.a.). Fossflakes and polyester fibre-filled pillows are included for comparison.

Figure 14 shows that the climate change and land use impacts are particularly sensitive to variations in the economic allocation (denoted 'e.a.' in the figure). The down-feather pillow only has a lower climate change impact than the Fossflakes and polyester fibre pillow when the allocation is at 2%. In all other scenarios, the down-feather pillow exhibits significantly higher climate and land use impacts compared to the Fossflakes and polyester-filled pillows. However, the water usage of the down-feather pillow is less sensitive to different allocations and remains close to the same as for the Fossflakes and polyester fibre pillow for both an allocation of 5% and 2%. This is because the cotton shell plays a relatively larger role in the water impact category than in the other two categories.

5.1.2 Pillow weight

So far, we have assumed that the weight of the cotton and filling in polyester fibre and down-feather filled pillows is the same as the Fossflakes pillow. Let's explore what happens when we allow for weight variations as seen in pillows from different manufacturers.

Table 16 below illustrates the cradle-to-grave impact of various weight scenarios across all three impact categories. The ranges for the two parameters - filling and shell weight - are based on data gathered from the website of JYSK, a major European bedding retailer, using information from several of its national websites. Other retailers were not included in this analysis because almost none were found to provide both filling and shell weights, rendering their data insufficient for this purpose. The data focused on 50x70 cm medium-height pillows made from both polyester and down-feather fillings. While polyester fibre pillows generally tend to have lighter fill and shell weights, all three pillow types were calculated within the same weight range: shell weight ranging between 70 and 210 grams, and filling weights between 500 and 900 grams. These specific ranges were based on the variation in the sample of pillows gathered. The decision of keeping the range similar for all three pillows was made for two main reasons:

1. The sample size was relatively small, with only 9 down-feather pillows and 12 polyester fibre pillows (of which only 6 had shells made of cotton) found within the relevant category on the selected website. This limited sample size increases uncertainty. Although it is important to acknowledge the possible relation between a certain pillow type and its material usage, narrowing the weight range based solely on these numbers was deemed too restrictive.
2. Although the data was gathered specifically for 50x70 cm pillows, the analysis can serve as a general tool for readers and stakeholders to self-assess and compare other pillow sizes. The size itself is not critical; rather, it is the weight that matters. Therefore, the range was kept flexible. If a reader has a pillow of a different size or weight and of similar materials, they can use the following analysis as a reference or guide for their own comparison.

The impacts corresponding to the functional unit are highlighted in the matrices below for all three pillow types.

		Climate (kg CO2-Eq)					Water (m3)					Land (m2*a crop-Eq)				
		Filling weight (g)														
	Shell weight (g)	500	600	**700**	800	900	500	600	**700**	800	900	500	600	**700**	800	900
Fossflakes	70	5.21	5.99	6.76	7.54	8.31	0.43	0.43	0.44	0.45	0.45	0.64	0.66	0.68	0.71	0.73
	90	5.59	6.37	7.14	7.92	8.69	0.54	0.55	0.55	0.56	0.57	0.79	0.81	0.83	0.86	0.88
	110	5.97	6.75	7.52	8.30	9.08	0.65	0.66	0.67	0.67	0.68	0.94	0.96	0.98	1.01	1.03
	130	6.35	7.13	**7.90**	8.68	9.46	0.77	0.77	**0.78**	0.79	0.79	1.09	1.11	**1.13**	1.16	1.18
	150	6.73	7.51	8.28	9.06	9.84	0.88	0.89	0.89	0.90	0.91	1.24	1.26	1.28	1.31	1.33
	170	7.11	7.89	8.67	9.44	10.22	0.99	1.00	1.01	1.01	1.02	1.39	1.41	1.44	1.46	1.48
	190	7.49	8.27	9.05	9.82	10.60	1.11	1.11	1.12	1.13	1.13	1.54	1.56	1.59	1.61	1.63
	210	7.87	8.65	9.43	10.20	10.98	1.22	1.23	1.23	1.24	1.25	1.69	1.71	1.74	1.76	1.78
Polyester fibre	70	5.47	6.30	7.13	7.96	8.79	0.43	0.43	0.44	0.44	0.45	0.61	0.63	0.65	0.67	0.69
	90	5.85	6.68	7.51	8.34	9.17	0.54	0.54	0.55	0.56	0.56	0.76	0.78	0.80	0.82	0.84
	110	6.22	7.05	7.88	8.71	9.54	0.65	0.66	0.66	0.67	0.67	0.91	0.93	0.95	0.97	0.99
	130	6.60	7.43	**8.26**	9.09	9.92	0.76	0.77	**0.78**	0.78	0.79	1.06	1.08	**1.10**	1.12	1.14
	150	6.98	7.81	8.64	9.47	10.30	0.88	0.88	0.89	0.89	0.90	1.21	1.23	1.25	1.27	1.28
	170	7.35	8.18	9.01	9.84	10.67	0.99	0.99	1.00	1.01	1.01	1.36	1.38	1.40	1.42	1.43
	190	7.73	8.56	9.39	10.22	11.05	1.10	1.11	1.11	1.12	1.13	1.51	1.53	1.55	1.57	1.58
	210	8.11	8.94	9.77	10.60	11.43	1.21	1.22	1.23	1.23	1.24	1.66	1.68	1.70	1.72	1.73
Down-feather	70	8.00	9.33	10.67	12.00	13.34	0.52	0.55	0.57	0.60	0.63	7.87	9.34	10.81	12.28	13.74
	90	8.37	9.71	11.05	12.38	13.72	0.64	0.66	0.69	0.71	0.74	8.02	9.49	10.96	12.42	13.89
	110	8.75	10.09	11.42	12.76	14.09	0.75	0.77	0.80	0.83	0.85	8.17	9.64	11.11	12.57	14.04
	130	9.13	10.46	**11.80**	13.14	14.47	0.86	0.89	**0.91**	0.94	0.96	8.32	9.79	**11.26**	12.72	14.19
	150	9.51	10.84	12.18	13.51	14.85	0.97	1.00	1.02	1.05	1.08	8.47	9.94	11.41	12.87	14.34
	170	9.88	11.22	12.55	13.89	15.22	1.09	1.11	1.14	1.16	1.19	8.62	10.09	11.55	13.02	14.49
	190	10.26	11.59	12.93	14.27	15.60	1.20	1.22	1.25	1.28	1.30	8.77	10.24	11.70	13.17	14.64
	210	10.64	11.97	13.31	14.64	15.98	1.31	1.34	1.36	1.39	1.41	8.92	10.39	11.85	13.32	14.79

Table 16: Variations in the environmental impact of pillows by weight of cotton and filling. Colour scale: green indicates a lower impact compared to the Fossflakes pillow, white represents an equal or nearly equal impact, and red or purple (if significantly worse) a higher impact.

Table 16 should, however, be assessed with an understanding of the typical weight distributions found in polyester and down-feather pillows. The specific details of the pillow samples can be found in Appendix A (including the websites, product names, etc.).

To better evaluate which weight scenarios in Table 16 are more probable, boxplots displaying the fill and shell weights of each pillow type are presented below in Figure 15. The two sets of boxplots highlight both the central tendencies and the variance that occurs, even though they are all the same pillow size and height. It is important to again note that the sample size is relatively small, leading to some uncertainty in representativeness; however, these data still provide valuable guidance.

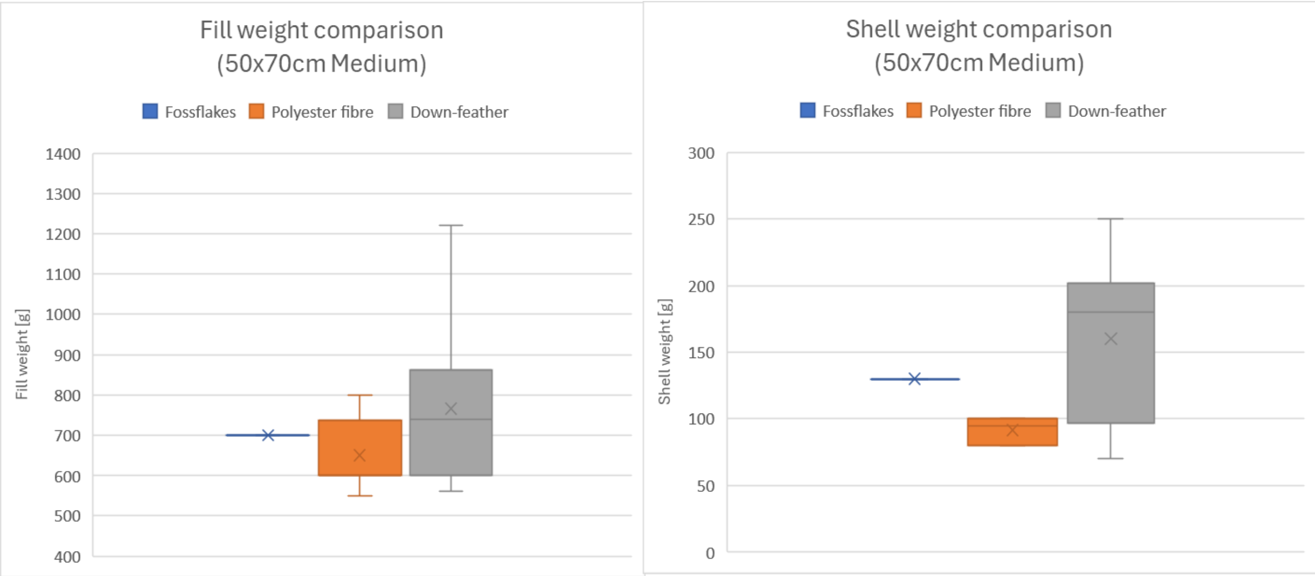

Figure 15: Boxplots of fill and shell weights for polyester fibre and down-feather Pillows (50x70 cm medium-height) with Fossflakes weight included for reference.

To supply more detail to accompany the boxplots, Table 17 shows the sample size, average, median, standard deviation, and standard error for both the shell and fill weights of polyester fibre and down-feather pillows. This helps us better understand the range and typical weights we see in the boxplots.

	Fill weight		Shell weight	
	Polyester fibre	**Down-feather**	**Polyester fibre**	**Down-feather**
Sample size	12	9	6	9
Mean	650	766	92	160
Median	600	740	95	180
Std. deviation	90	204	10	62
Std. error	26	65	4	21

Table 17:Statistical summary of fill and shell weights for polyester fibre and down-feather pillows.

The distribution in Figure 15 (boxplots) indicates that an average polyester pillow can likely have a smaller environmental impact than Fossflakes pillows across all three impact categories if it were to have a cotton shell of a weight in the range around its median of 95g. For down-feather pillows, while they may achieve lower water usage for a lighter shell, almost no scenario within the investigated boundaries will result in it having a lower climate impact or land usage. Given the observed distributions, it is less likely that down-feather pillows will have a lower overall impact than Fossflakes pillows.

The gradient colour patterns reveal that in down-feather pillows, filling weight primarily influences climate impact and land usage, as shown by horizontal colour changes. For polyester fibre and Fossflakes pillows, the diagonal gradients indicate that both shell and filling weights influence climate impact, while land usage is more affected by shell weight, indicated by vertical changes. In all pillow types, the cotton shell is the main contributor to water usage, shown by vertical colour changes. These findings align with the initial conclusions in the results section.

Although Fossflakes pillows have a lower impact per kilogram than polyester pillows in the chosen functional unit, the lower filling content and lighter cotton shell of polyester pillows can make them less impactful overall. However, equal quality and function are crucial considerations, particularly for the lowest and highest weight scenarios of polyester fibre and down-feather pillows. For example, the lowest weight options might border on being medium-low or low pillows potentially challenging their suitability for direct comparison.

The selected shell weight of 130 grams for polyester fibre pillows differs from the observed median of 95 grams, based on data from six pillows, even when considering a standard deviation of ±10 grams. As briefly mentioned in the introduction of this study (Goal & Scope section), the decision to use the same material and mass aims to maintain similar properties and qualities. This choice assumes that variations within the same pillow category (e.g. 50x70 cm, medium height) are somewhat related to the fill's characteristics, such as its lifetime, feel, and bounce. For the shell, a heavier, more tightly woven fabric may provide better hygiene by preventing dust mites and other allergens from entering the pillow [9].

Future studies should explore the relationship between both filling and shell weight, quality and properties more thoroughly, considering different pillow fill and shell types to better compare these and understand their environmental impact.

5.1.3 Pillow lifetime

The lifetime of a pillow is a crucial factor in determining its overall environmental impact. For example, a pillow with double the climate impact of another but a lifespan three times longer would have a lower impact over time.

This study initially assumed a two-year lifespan for all three pillow types. To explore how changes in lifespan affect their environmental impact, we varied the lifetimes and analysed the results. Figure 16 illustrates these impacts over a two-year period. It helps display this such that for a pillow lasting only one year, two pillows would be required to cover the two-year span, effectively doubling its impact compared to a pillow with a two-year lifespan.

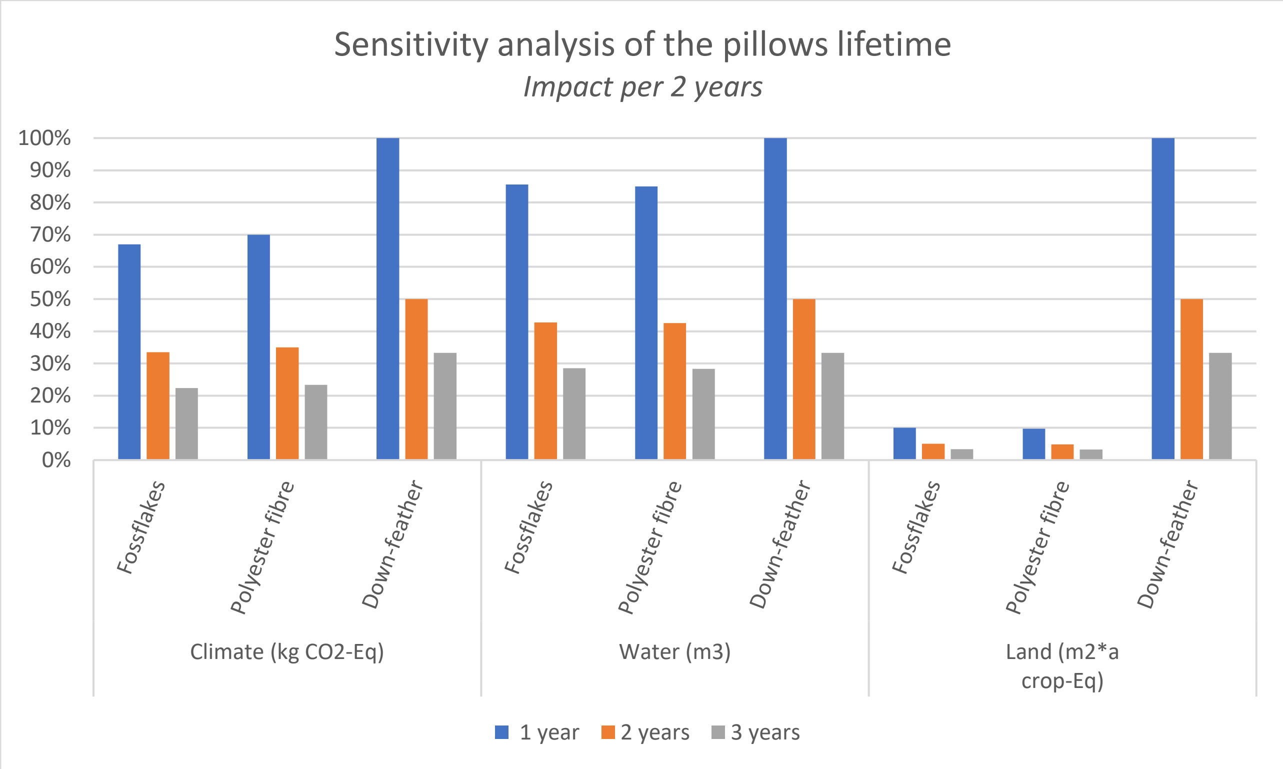

Figure 16: The environmental impact of pillow choice over a two-year period, given a replacement cycle of one, two and three years. Normalized so that the largest impact within each impact category is set to 100%.

For example, if a down-feather pillow lasts three years while Fossflakes and polyester fibre pillows last two years, the down-feather pillow has a similar climate impact and slightly lower water usage, but still a significantly higher land use. On the other hand, if the down-feather pillow lasts two years and the Fossflakes and polyester fibre pillows last three years, the climate impact of the down-feather pillow is roughly double, water usage a little less than double and its land use is about 15 times higher.

If Fossflakes and polyester fibre pillows last one year while the down-feather pillow lasts three years, the down-feather pillow exhibits about half the climate impact, around 40% of the water usage, but double the land use. Conversely, if the down-feather pillow lasts one year and the Fossflakes and polyester fibre pillows last three years, the down-feather pillow's climate impact is over four times higher, with land use at least 18 times greater. These results clearly show that the relative significance of impacts, especially for climate impact and water usage, heavily depends on the product's lifetime.

An immediate online search will suggest to the user that down-feather pillows in general have a longer lifespan compared to polyester fibre pillows, although none were found to have supporting studies to back up this claim. Conducting a sensitivity analysis, such as the one above, helps address these claims and is therefore highly relevant. However, it's important to consider the rationale presented in the Goal and Scope section: a two-year lifespan for all pillow types was assumed due to a lack of reliable data or studies on pillow longevity of specific the pillow types. This assumption is backed up by hygiene considerations, such as the build-up of dust mites, fungus, and other allergens [10], as well as alignment with retailers' and manufacturers' guidelines on pillow replacement (see 9 Appendix A's Table 33 for supporting sources). The impact of this assumption will be examined in the sensitivity analysis (section 6.1.3).

5.1.4 Distribution Distance and Modes

While we initially assumed that pillows are transported 1000 km by road (truck) from the factory to the consumer, they can also be shipped over much longer distances globally. This sensitivity analysis examines how the manufacturer's location at the origin or the consumer's location at the destination, whether in Asia, North America, or other regions, and the subsequent transport distances and modes, influence the overall environmental impact. For instance, pillows produced in Shanghai, China, and shipped to Rotterdam, Netherlands (20,000 km by sea), followed by a 500 km truck delivery across Europe, or pillows made in Los Angeles, USA, shipped to Tokyo, Japan (20,000 km by sea) with a 500 km truck journey to local retailers, demonstrate the impact of long-distance distribution.

Given these scenarios, we evaluated how varying transport distances and methods affect the results. Air transport is excluded due to the low cost, non-perishable nature, and high volume of pillows, which do not justify the high cost of air freight. Figure 17 presents only the climate change impact, as variations in water and land use impacts were minimal

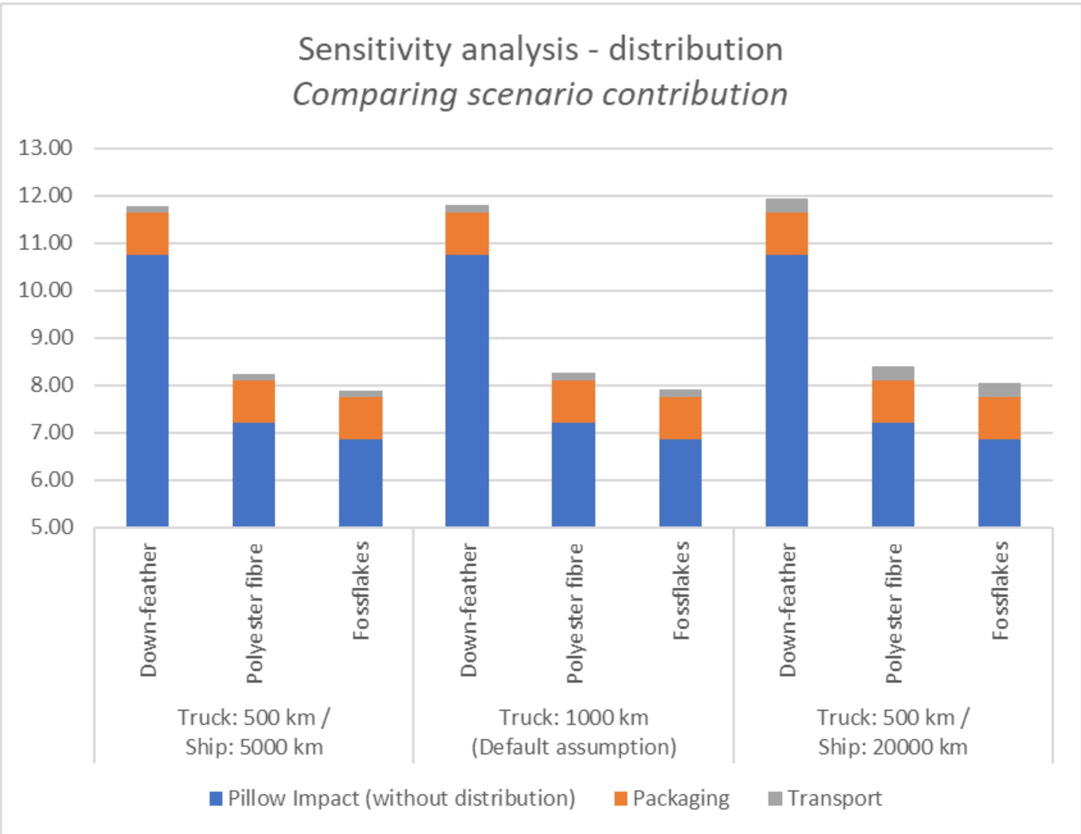

Figure 17: The impact of different shipping distances and modes on climate change impact.

The sensitivity analysis shows that changes in distribution distances and transport modes have a minimal effect on the overall environmental impact of the pillows. For instance, even with the extended scenario of a 500 km truck journey combined with a 20,000 km sea voyage, the difference in impact remains relatively small compared to the total impact of the pillows. This variation does not significantly alter the comparative results between different pillow types.

5.1.5 Pillow use and maintenance: Washing and drying

In our analysis, we initially assumed that consumers do not wash or dry their pillows over a two-year lifespan. To explore the impact of this assumption, we considered three scenarios: no laundering, laundering once per year, and laundering twice per year. Each scenario includes two drying methods after machine washing: air-drying or tumble-drying. For down-feather pillows, air drying is not included due to the higher risk of mould and odours associated with *the* organic materials, as the feathers can trap moisture for longer periods, creating a damp environment that encourages bacterial growth and unpleasant smells [29]. Table 18 below shows the environmental impact of a single laundering. The modelling and inventory of these calculations, including the specific datasets, assumptions and data on the process of washing and drying, are detailed in Appendix F under section F.6.

Process	Climate (kg CO2-Eq)	Water (m3)	Land (m2*a crop-Eq)
1x Tumble dry (1 pillow)	2.4E-01	3.1E-03	7.8E-03
1x Machine wash (1 pillow)	1.7E-01	4.2E-03	3.3E-02

Table 18: Environmental impact of washing and drying a pillow.

To understand the impact of laundering, we examined the worst-case scenario - washing and tumble drying a pillow twice a year - and calculated how much this contributes to the pillow's total environmental footprint. For simplicity and to just illustrate the sensitivity of our assumptions, we used just the Fossflakes pillow as a reference in this analysis (Table 19).

Process		Climate (kg CO2-Eq)	Water (m3)	Land (m2*a crop-Eq)
Twice a year	Machine wash & air-dry	9%	2%	12%
	Machine wash & tumbledry	21%	4%	14%

Table 19: Relative total impact of wash and drying processes for the Fossflakes pillow, shown as a percentage of climate impact, water use (m^3), and land use for reference to their significance.

Laundering primarily impacts climate change rather than water or land use, with tumble drying having a higher effect due to its electricity consumption. Washing and tumble drying a pillow twice yearly can add 9-21% to the climate impact and 12-14% to land use, which is significant. However, for scenarios involving washing and drying just once per year (about half of these percentages), such as 4.5% of the climate impact and 6% of land use, the impact may be considered minor. Additionally, not laundering at all is also a viable scenario. An interesting observation is that while laundering might intuitively seem like a water-intensive part of the pillow's life cycle, it still uses far less water than producing the cotton shell.

To visualize how laundering affects the overall comparison between the pillow's environmental impact, Figure 18 compares all assessed scenarios:

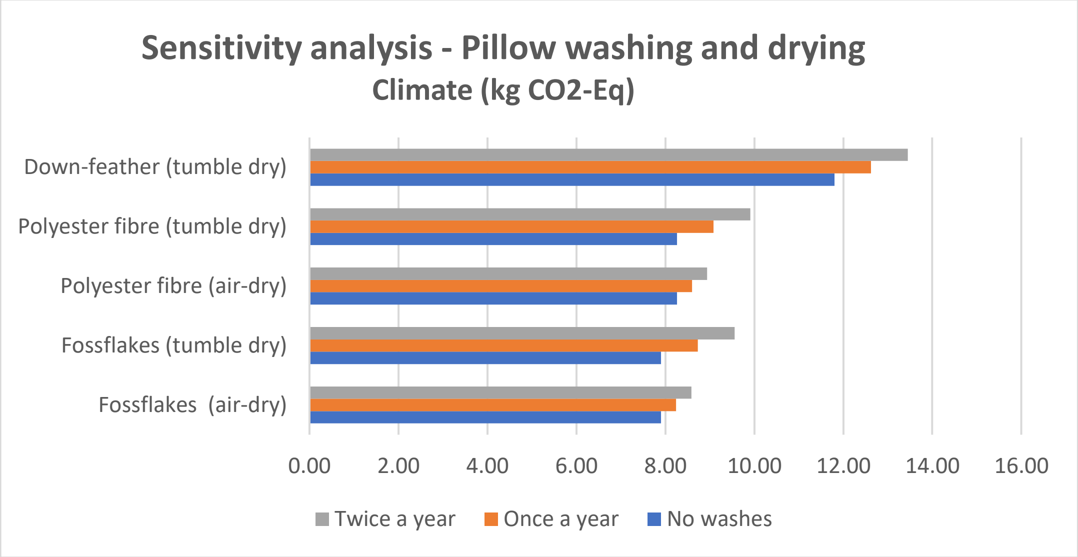

Figure 18: Full life cycle environmental impact of each pillow with the added impacts of various scenarios of washing and drying - comparing air-drying with tumble-drying and yearly laundry with twice-yearly.

From Figure 18, we observe that for pillows with similar environmental impacts, such as Fossflakes and polyester fibre pillows, the frequency and method of washing and drying can significantly influence which pillow has the lower impact in terms of climate change, given how close their total impacts are. However, when comparing down-feather pillows to Fossflakes or polyester fibre pillows, the method of washing and drying does not change the overall result; down-feather pillows consistently show the highest climate impact. This remains true even in the 'worst case scenario' of washing and tumble drying a Fossflakes or polyester fibre pillow twice a year (totaling four times over its lifespan) versus the 'best case scenario' of not washing or drying the down-feather pillow at all.

The sensitivity analysis clearly shows that the frequency and method of washing and drying are important factors in determining a pillow's total environmental impact. However, these factors depend on the user's preference rather than the type of pillow. Thus, when comparing the three different pillow types, the washing and drying methods become less significant. It is important to note, still, that while we cannot draw definitive conclusions about the environmental impacts of the three pillow types based solely on the frequency and method of washing and drying, Fossflakes and polyester fibre pillows do offer the user the option to reduce their environmental impact. This is due to their ability to be effectively air-dried, unlike down-feather pillows, which require tumble drying. This flexibility allows for a more environmentally friendly laundering option for users who choose to wash their pillows frequently.

5.2 Further investigation of limitations

The sensitivity analysis primarily focused on testing how variations in existing parameters - such as distribution methods, pillow weight, and use phase - affect the study's results. In contrast, this section examines the potential impact of factors not initially considered or beyond the scope of the main analysis. These include different markets/geographies for the used datasets, ancillary processes for non-core materials, and alternative end-of-life scenarios like landfill or system expansion for energy recovery. By investigating these additional aspects, we aim to understand how these unexamined variables could influence the outcomes, providing a more comprehensive evaluation of the study's limitations and ensuring the robustness of the conclusions.

5.2.1 Impact of Regional Variability in Production Locations

This section looks at how different production locations can affect the environmental footprint of pillow manufacturing. We use region-specific data for electricity, water, heat, gas, and waste management to see how changing the production location impacts the results of our Life Cycle Assessment (LCA). This helps us understand the role of geographic differences in our findings.

We focus on the part of the pillow's life cycle that takes place at the manufacturer's factory processes, particularly the final filling processing and subsequent assembly of the pillow, as these are the main areas where the pillow manufacturer itself directly impacts the environment. This analysis shows the differences that come from simply being in different locations, due to variations in electric grid mixes, water and gas sourcing, and waste handling. For the specifics on which datasets where recontextualized to different geographies in the pillow's modelling, see appendix F under respectively the 'Fill Processing' and 'Pillow Assembly' processes for Fossflakes and the polyester fibre pillow and the combined 'Fill Processing and Pillow Assembly' for the down-feather pillow.

To make the comparison clear, we continue by examining two specific geographies: a general global average (GLO) and Denmark. Denmark is relevant because it is the location of Fossflakes' production and ranks high on environmental performance due to its significant use of renewable energy. Comparing this to the environmental standards of the global average, which represents a broader and less sustainable range of practices, this approach allows us to investigate the extremes and better understand the potential impact of location-specific factors on the environmental performance of different pillow types.

	Climate (kg CO2-Eq)		Water (m3)		Land (m2*a crop-Eq)	
Pillow type	GLO	DK	GLO	DK	GLO	DK
Fossflakes	9.0E-01	3.7E-01	4.0E-03	3.4E-03	9.0E-03	3.9E-02
Polyester fibre	5.9E-01	1.7E-01	3.3E-03	2.9E-03	7.9E-03	3.6E-02
Down-feather	8.2E-01	3.2E-01	2.3E-03	2.2E-03	7.2E-03	2.1E-02

Table 20: The difference in impact of having the pillow factory production using GLO or DK markets as datasets for water, energy and waste treatment.

Pillow type	Climate (kg CO2-Eq)	Water (m3)	Land (m2*a crop-Eq)
Fossflakes*	6.7%	0.1%	-2.6%
Polyester fibre**	-5.0%	-0.1%	2.6%
Down-feather**	-4.3%	0.0%	0.1%

*Table 21: The change in impact from the pillow's original location to another location. With respect to each pillows total impact (and standard scenario DK or general). * = deviation from DK scenario; ** = deviation from general/GLO scenario.*

The investigation shows that production geography significantly affects climate impact, with the Fossflakes pillow experiencing a 6.7% increase when comparing global production to Denmark, while polyester fibre and down-feather pillows see reductions of -5.0% and -4.3%, respectively. However, water and land use impacts remain minimal, with changes typically below ±0.1% for water and around 2-3% for land use. This suggests that while energy sourcing (electric grid mix) strongly influences climate impact, other factors like water and land use are less affected by regional differences.

5.2.2 Ancillary Processes: Transportation of Non-Core Materials

This subsection examines the environmental impact of transporting ancillary or non-core materials, such as packaging and labels, which are often overlooked in the primary analysis. By assessing the transport distances and modes for these materials from various locations, we aim to quantify their contribution to the overall environmental footprint. Understanding the role of these ancillary processes helps to ensure a more complete evaluation of the environmental impacts associated with pillow production.

Import of yarn:

Something that is already modelled simply via the datasets used for 'textile, cotton' is the transportation of the needed yarn. We here wish to test the limitation of the study by investigating its impact and assessing whether not knowing more about this part of the pillow's life cycle, i.e. in this case downstream transportation distances, can have a significant impact on the pillow's total impact.

Transport mode	Distance	Unit
transport, freight, light commercial vehicle	24.6	km
transport, freight, lorry, unspecified	385.7	km
transport, freight, sea, container ship	1143.9	km

Table 22: Average import/export of yarn to and from the yarn manufacturer. Retrieved from the dataset 'market for yarn, cotton - GLO' (Ecoinvent)

Transport of yarn	Weight (kg)	Climate (kg CO2-Eq)	Water (m3)	Land (m2*a crop-Eq)
market for yarn, cotton - GLO (only transport)	0.13	1.6E-02	3.6E-05	5.7E-04

Table 23: The impact of transporting 130 g of yarn (needed for the pillow shell), based on the 'market for yarn, cotton - GLO' dataset (see previous table for detail on distance and mode).

Pillow type	Climate (kg CO2-Eq)	Water (m3)	Land (m2*a crop-Eq)
Fossflakes	-0.2%	0.0%	-0.1%
Polyester fibre	-0.2%	0.0%	-0.1%
Down-feather	-0.1%	0.0%	0.0%

Table 24: The contribution of transporting 130 g of yarn to each pillow's full life cycle impact.

The investigation shows that yarn transportation has a negligible impact on the overall environmental footprint of the pillows. Even when transport distances were increased significantly, the effect remained under -0.2% across all impact categories. Therefore, detailed transportation data for yarn is not critical to the study's conclusions.

Import of distribution packaging:

The transportation details of the packaging materials are not shown in full due to the complexity of the mixed transport modes and locations used in modelling. However, documentation for these datasets can be found by referencing the market datasets used: '*market for corrugated board box* – RoW' and '*market for packaging film, low density polyethylene – GLO*'. Each pillow uses approximately 110g of PE plastic and 116g of cardboard, and the impact of transporting these materials is aggregated based on the transport modes and distances within the datasets. Table 25 presents the overall environmental impact from transporting these materials.

Scenario	Climate (kg CO2-Eq)	Water (m3)	Land (m2*a crop-Eq)
Normal transport dist.	1.74E-02	4.87E-05	8.07E-04

Table 25: The impact of the average import/transportation of the distribution packaging materials that is needed for the pillows - cardboard and packaging film – calculated using market datasets from Ecoinvent for each material.

Pillow type	Climate (kg CO2-Eq)	Water (m3)	Land (m2*a crop-Eq)
Fossflakes	-0.22%	-0.01%	-0.07%
Polyester fibre	-0.21%	-0.01%	-0.07%
Down-feather	-0.15%	-0.01%	-0.01%

Table 26: The contribution of transporting the packaging to each pillow's full life cycle impact.

The investigation reveals that the transportation of packaging materials, including cardboard and PE film, has an insignificant impact on the overall environmental footprint of the pillows, with variations in climate impact, water use, and land use all remaining below -0.22% across categories. Therefore, the transport of packaging materials contributes negligibly to the total life cycle impact of the pillows.

5.2.3 Alternative EoL: 100% Landfilling of Pillows

In this section, we explore the environmental impact of an alternative end-of-life scenario where all pillows are disposed of in landfills rather than through incineration or recycling. The analysis focuses on the effects this change has on key environmental indicators, such as greenhouse gas emissions, water use, and land use, allowing us to assess the potential environmental trade-offs between different waste management methods. Table 27 and Table 28 provide a comparison of the impacts between landfill and incineration for each pillow type.

	Climate (kg CO2-Eq)		Water (m3)		Land (m2*a crop-Eq)	
Pillow type	Landfill	Incin.*	Landfill	Incin.*	Landfill	Incin.*
Fossflakes	2.0E-01	2.0E+00	4.3E-05	1.6E-03	2.7E-03	6.5E-04
Polyester fibre	1.8E-01	1.5E+00	4.4E-05	1.3E-03	2.7E-03	6.1E-04
Down-feather	6.4E-01	4.7E-01	7.0E-05	1.4E-03	2.8E-03	1.0E-03

Table 27: The impact of disposing the pillow, depending whether its 100% landfill or the original incineration scenario (*)

Pillow type	Climate (kg CO2-Eq)	Water (m3)	Land (m2*a crop-Eq)
Fossflakes	-23%	-0.2%	0.2%
Polyester fibre	-16%	-0.2%	0.2%
Down-feather	1%	-0.1%	0.0%

Table 28: The difference in impact when shifting from incinerating to landfilling the pillow. With respect to each pillows total impact.

Shifting to 100% landfilling for end-of-life disposal has a mixed impact. While the climate impact decreases significantly for the Fossflakes and polyester fibre pillows (-23% and -16%, respectively), this is due to the delayed decomposition of plastics in landfills, which means emissions are spread over many years. However, landfilling can have hidden negative effects, particularly in other impact categories like water and soil pollution, such as marine eutrophication and human toxicity potential. For the down-feather pillow, the climate impact remains relatively stable (+1%), with only minor changes in water and land use impacts. While the immediate climate benefits of landfilling plastics are evident, the long-term environmental risks must also be considered.

5.2.4 System Expansion: Energy Recovery

When disposing of pillows by incineration in a waste-to-energy (W2E) plant, it is important to evaluate the energy recovered from each type of pillow. Incineration reduces waste volume and converts organic materials into carbon dioxide (CO_2) and water, releasing heat that can be used for electricity and heat production. Although incineration may seem more polluting than landfill disposal, it mitigates long-term impacts like methane emissions and groundwater contamination from landfills.

The energy output from incineration depends on the material's overall composition, including factors like carbon and hydrogen content, which contribute to the calorific value, or energy released during combustion. Plastics like polyethylene (PE) and polyethylene terephthalate (PET) are known for high energy recovery due to their high calorific value.

For down-feather pillows, specific data on energy production from incineration were unavailable. Consequently, average values for municipal solid waste from the Ecoinvent datasets were used as a proxy. Down-feathers, primarily composed of keratin, have around 60% carbon by weight (based on a study on bird waste, mainly chickens [30]), which is higher than the average carbon content in typical municipal solid waste [31], but equal to or lower than that of most plastics - PE is around 80 wt% (*wt% = weight percent*) and PET is around 63 wt% [32]. This carbon content suggests that down-feathers could provide moderate energy recovery; however, this is a cautious indication. The actual energy output may vary due to other influencing factors, such as moisture content, the presence of nitrogen, and specific combustion conditions in the incineration plant. While carbon percentage offers some insight into potential energy recovery, it is not definitive, and further research is needed to provide a more accurate evaluation of down-feather incineration.

Table 29 below presents the energy factors, representing the net energy production per kilogram of material, including both electric and thermal energy outputs from the incineration of each material. These values are sourced from Ecoinvent datasets.

Material	Process	Energy factors [MJ/kg]
Cotton shell	Electric	-1.78
	Thermal	-3.58
PE	Electric	-5.55
	Thermal	-10.69
PET	Electric	-2.97
	Thermal	-5.81
Down-feather	Electric	-1.39
	Thermal	-2.85

Table 29: Energy recoverable from the incineration of pillow materials.

To model the energy recovery from pillow incineration, we used these energy factors to calculate the net energy output based on the specific composition of each pillow type, continuing the assumption that 98% of each pillow is incinerated. That means the specific material that accounts for the energy recovery is 127.4 grams for the shell and 686 grams of the filling. The impact from energy recovery is then modelled using the datasets '*market for electricity, high voltage - DK'* for electric energy and '*market group for heat, district or industrial, natural gas - RER*' for thermal energy. These datasets were selected to simulate Northern European energy grids, aligning with the assumption that the end-of-life of the pillow occurs in the same region. For further details, please refer to Appendix F section F.7.

Although pillows are typically incinerated as whole items, we modelled each material component separately (PE, PET, down-feather, and cotton shell) to account for their distinct combustion characteristics and the subsequent avoided impacts due to energy recovery. This approach assumes that materials burn independently within the industrial furnaces of incineration plants, which is considered a reasonable assumption for a discarded pillow.

Overall (Cradle to Grave with Energy Recovery) - Affect [%]	Climate (kg CO2-Eq)	Water (m3)	Land (m2*a crop-Eq)
Fossflakes	-7.4%	-0.5%	-3.8%
Polyester fibre	-4.6%	-0.3%	-2.5%
Down-feather	-1.7%	-0.1%	-0.1%

Table 30: The impact of energy recovery on environmental impact. The negative percentage shows the avoided or 'positive' environmental impact when energy recovery is included in the life cycle assessment.

Table 30 shows that across all three impact categories the most benefit is recovered from the Fossflakes pillow and the least from the down-feather pillow. Climate impact is the main beneficiary, with only a very small impact on water and land use.

Energy recovery of each pillow		Climate (kg CO2-Eq)	Water (m3)	Land (m2*a crop-Eq)
FOSSFLAKES	Cradle to Grave	7.90	0.78	1.13
	Energy recovery	-0.59	0.00	-0.04
Polyester fibre	Cradle to Grave	8.26	0.78	1.10
	Energy recovery	-0.38	0.00	-0.03
Down-feather	Cradle to Grave	11.80	0.91	11.26
	Energy recovery (municpal waste)	-0.21	0.00	-0.01

Table 31: Environmental impact of pillows and energy recovered during incineration.

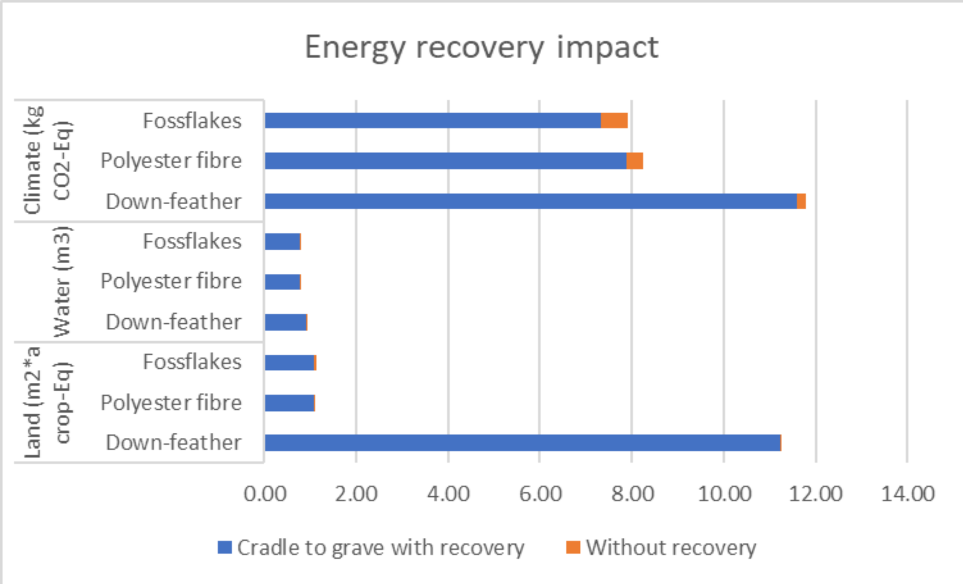

Figure 19: A relative comparison of the overall cradle to grave environmental impact of the pillows net of energy recovery.

Considering incineration in a waste-to-energy plant, the environmental benefit of energy recovery from each pillow is still relevant and, in some cases, can influence the determination of which pillow is most sustainable - particularly when comparing the polyester fibre pillow and Fossflakes, as these two are close in overall environmental impact. This consideration becomes especially pertinent depending on the availability of different types of waste treatment facilities.

However, Figure 19 indicates that while energy recovery has benefits, these are not substantial enough to significantly alter the overall environmental impact of any of the pillows. It is important to note that these findings are subject to uncertainty inherent in the data used for modelling energy recovery and emissions. Factors such as variability in incineration efficiency, regional differences in energy grids, and assumptions made regarding material combustion could introduce variability in the results. As a result, while the trends observed in Figure 19 are robust, the exact magnitudes of impact reductions should be interpreted with caution.

For future studies, obtaining specific empirical data on the waste and energy recovery effects of incinerating down-feather, alongside landfill data for comparison, would be optimal. Such data would reduce the uncertainty and strengthen the conclusions of the analysis. This sensitivity analysis supports the overall finding that energy recovery does not dramatically shift the environmental ranking of the pillows, even though it remains a relevant factor to consider in assessing their sustainability.

5.3 Key Observations

1. **Fossflakes Pillow**:

- **Best Overall Performance**: The Fossflakes pillow consistently ranks as the least impactful across most of the impact categories assessed. Aside from the impact categories noted in the main results, it performs best in categories such as terrestrial acidification (16%), freshwater ecotoxicity (84%), and fine particulate matter formation (31%).
- **Potential Trade-offs**: Although the Fossflakes pillow generally has a lower environmental impact, it still has higher impacts in categories such as ionizing radiation (56%) and mineral resource scarcity (77%). These areas suggest that while the pillow performs well overall, there are specific environmental trade-offs that should be considered in the context of resource use and long-term environmental performance.

2. **Polyester Fibre Pillow**:
    - **Moderate Performance**: The Polyester fibre pillow ranks second in most impact categories, often closely following the Fossflakes pillow. It shows comparable results to Fossflakes in categories like freshwater ecotoxicity (84%) and human carcinogenic toxicity (100%), but slightly higher impacts in others such as terrestrial acidification (18%) and mineral resource scarcity (88%).
    - **Balanced Trade-offs**: The polyester fibre pillow demonstrates a balance between environmental impacts and practical performance. It is a viable alternative to Fossflakes for those who prioritize lower costs or specific functional attributes, but with slightly higher environmental impacts in certain areas.
3. **Down-Feather Pillow**:
    - **Highest Environmental Impact**: The down-feather pillow exhibits the highest impact across almost all categories, including terrestrial acidification (100%), freshwater eutrophication (100%), and human carcinogenic toxicity (100%). These results highlight the significant environmental burden associated with the production and disposal of down-feathers, particularly due to the intensive agricultural practices involved in raising ducks and geese, as well as the processing of down-feathers.
    - **Critical Hot-Spots**: The down-feather pillow's performance emphasizes the environmental cost of natural fill materials. The impact in categories such as freshwater eutrophication and terrestrial ecotoxicity (88%) points to the considerable effects of land and water resource usage, which are much higher than those for synthetic alternatives.

Conclusion:

The Fossflakes pillow emerges as the most environmentally friendly option across the majority of impact categories, making it the preferable choice from an environmental perspective. The polyester fibre pillow, while generally more impactful than Fossflakes, still represents a moderate option with balanced environmental performance. In contrast, the down-feather pillow, despite its natural composition, is associated with significantly higher environmental impacts, particularly in categories related to land and water use, toxicity, and resource scarcity.

These findings underline the importance of evaluating the full life cycle impacts of pillow materials. While natural materials like down and feather are commonly perceived as more environmentally preferable, this analysis demonstrates that they can have higher environmental costs compared to synthetic alternatives. For stakeholders looking to minimize environmental impact, the choice of pillow fill material is crucial, with Fossflakes offering a clear advantage in this study.

5.4 Consistency Check

A consistency check was carried out to ensure that the different systems were modeled in a uniform way throughout the study. By setting similar system boundaries, data sources, and assumptions for each pillow type, we maintained a standardized approach in our analysis. This helps ensure that any differences in environmental impacts are due to the actual performance of the pillow fillings themselves, rather than differences in how the models were built or the data used.

To support this consistency, we used the same datasets and methods wherever possible, and any differences were clearly documented and explained. The use of reliable databases like Agribalyse and Ecoinvent, along with openLCA software, helped keep the modeling consistent across all systems.

Overall, this consistency check was important to make sure that our comparisons are fair and accurately reflect the true environmental performance of each pillow type.

5.5 Animal welfare

Life Cycle Assessments (LCAs), as defined by the ISO 14044 and ISO 14040 standards, focus on quantifying environmental impacts but do not typically consider ethical factors such as animal welfare. In the production of down-feather pillows, there can be a significant range in how ducks and geese are treated—from humane conditions with sustainable farming practices to harmful methods like live plucking or force-feeding. These differences not only impact animal welfare but can also influence environmental outcomes. Practices that ensure higher animal welfare may result in higher environmental impacts in certain categories, such as land use and resource consumption, compared to intensive farming with poorer welfare standards.

5.6 Social responsibility

While LCAs focus on environmental aspects, social responsibility is crucial for a comprehensive understanding of sustainability. This includes labour conditions, community impacts, and the broader social implications of production and disposal. The global supply chain for pillows involves diverse stakeholders, from factory workers producing synthetic fillings to farmers cultivating cotton. Social responsibility considerations include fair wages, safe working environments, and minimizing negative impacts on communities.

Furthermore, the end-of-life disposal of pillows affects waste management workers and local communities, highlighting the need for responsible waste practices. Manufacturers can enhance social responsibility by enforcing ethical standards and utilizing certifications like Fair Trade, SA8000, and OEKO-TEX® STANDARD 100 (as previously stated for Fossflakes), which ensure safe working conditions and reduce harmful substances. Although OEKO-TEX® STANDARD 100 primarily focuses on consumer safety, it indirectly supports social responsibility by promoting transparency and safer working environments [22].

Incorporating social aspects into product life cycle assessments can encourage more sustainable and ethically responsible production practices, aligning with the broader goals of sustainable development.

5.7 Product longevity

Durable products that maintain their quality and function over time can significantly reduce the frequency of replacement, thereby diminishing the cumulative demand for raw materials and the associated impacts from production, distribution, and disposal. Due to lack of relevant data, this study assumes the three pillows have an equal lifetime of two years.

Assessing the lifespan of the three pillows and incorporating the findings into LCA calculations would provide more accurate predictions of their overall environmental impact. This would also serve to inform consumers and manufacturers about the benefits of investing in durable goods, potentially leading to a reduction in waste and a move towards more sustainable consumption patterns.

Finding a comprehensive and standardised assessment method to assess pillow lifetime is essential for the industry to establish product benchmarks and guide consumer choices. It would encourage manufacturers to design for durability and consumers to make informed decisions based on product longevity.

In 2023, Fossflakes embarked on a project to create a suitable methodology. While this work is still in its infancy, it has highlighted the need to consider a range of factors, including changes in support, appearance, texture, and comfort, as well as the typical lifespan of pillows among users. Given these complexities, Fossflakes sees significant value in collaborating with other pillow manufacturers to refine this process.

5.8 Review Feedback and Critical review

The critical review of this LCA report was conducted to ensure adherence to ISO 14044 (2006) and ISO/TS 14071 (2014) standards. It involved an independent evaluation of the study's methodology, data, and conclusions to ensure consistency with industry practices and high-quality reporting. The process, conducted between April 2024 and October 2024, comprised three iterations:

1. **Version 1 (April 2024)**:
   The initial draft was submitted, and the review panel highlighted missing descriptions of production systems, transparency in Appendix A data, and transport calculations. Structural suggestions were also provided to improve readability.
2. **Version 2 (May 2024)**:
   Fossflakes addressed these comments, primarily by clarifying production data, improving documentation, and adding a new section on limitations. The reviewers then conducted a more comprehensive review, providing 135 comments on this version.
3. **Version 3 (August 2024)**:
   The panel's final review focused on how the reviewers' comments were addressed. Key revisions to the report included:
   - Expanded sensitivity analyses: Investigated assumptions such as pillow weight and size, laundering impacts, and other key variables.
   - New section, "Further Investigation of Limitations": Added to address omitted factors and clarify constraints in the analysis.
   - Enhanced documentation and argumentation around the functional unit: Detailed assumptions, limitations, and sourcing considerations for each pillow type, such as the expected lifetime of pillows and the sourcing of bird-related data.
   - Integration of background modelling and calculations: Further incorporated into the main report (e.g., in the LCI section), balancing additional detail with maintaining readability and clarity. Sensitive data was retained in Appendix F (supplied separately to the review panel) to ensure confidentiality.

The final version was approved as a complete and ISO-compliant LCA study. These revisions shaped the report's structure and content, including the use of appendices for supplementary rationale and data, expanded sensitivity analyses, and detailed sub-studies.

The critical review process significantly improved the clarity, quality, and transparency of the report, ensuring it provides a robust foundation for public comparative assertions.

6 Conclusions

The results of the LCA point towards several important conclusions:

1. **Environmental impacts vary by material**
   The LCA highlights significant differences in performance across all impact categories when comparing pillows filled with Fossflakes, polyester, and down-feather materials. These impacts demonstrate the importance of material choice in determining a pillow's environmental footprint.

2. **Fossflakes and polyester perform better than down-feather**
   Fossflakes and polyester-fibre filled pillows exhibit better environmental performance than down-feather pillows across most impact categories. This suggests that synthetic fills can be viable alternatives to down-feather in terms of environmental sustainability.

3. **Re-evaluating perceptions of down-feather sustainability**
   Contrary to the widespread belief that down-feather fillings are inherently more environmentally sustainable due to their natural origin, down-feather pillows have a higher environmental impact in key areas compared to synthetic alternatives like Fossflakes and polyester.
   This finding challenges existing perceptions and underscores the necessity of evaluating products based on comprehensive environmental impact assessments rather than assumptions about natural versus synthetic materials.

4. **Importance of considering the entire life cycle**
   The study underscores the value of evaluating products through a cradle-to-grave perspective, taking all materials into account from raw material extraction to end-of-life disposal. This comprehensive approach is crucial for understanding the full environmental implications of consumer products.

5. **Cotton shell's significant impact**
   Regardless of the type of filling, the cotton shell is a significant contributor to the environmental impact of pillows, especially in terms of water use. This highlights the need for environmental consideration of all components of a pillow, not just the filling.

6. **Role of consumer choices in sustainability**
   The LCA illuminates the impact that consumer choices—such as opting for pillows made from certain materials, extending the life of pillows through proper care, and

responsibly disposing of pillows—can have on environmental footprints.

7. **Need for further research and data**
   The study identified areas for further research, including the need for more comprehensive data on pillow lifetime and the frequency of pillow laundering.

8. **Potential for industry improvement**
   The LCA suggests that there is significant potential for improvement within the pillow manufacturing industry, particularly in adopting materials with a lower environmental impact, enhancing product durability, and increasing transparency regarding environmental impacts.

7 Recommendations and Perspectives

To unlock the full potential for environmental sustainability in the pillow industry, it is vital for manufacturers, consumers, and retailers alike to come together in a shared effort. Below we suggest how each player can contribute to reducing the environmental footprint of pillows.

7.1 For Pillow Manufacturers

1. **Innovate on materials**
   Evaluate lower environmental impact materials for both pillow fillings and shells, considering their environmental impacts across the life cycle.

2. **Extend longevity**
   Prioritise the durability of pillows, extending their life span through high-quality, resilient materials, reducing the frequency of pillow replacements needed and the environmental impact per year of use.

3. **Offer recycling**
   Facilitate the recycling of pillows at end-of-life. This includes designing pillows with recyclable, compostable or reusable materials and setting up recycling programmes to ensure consumers can contribute to circularity.

4. **Provide transparent information**
   Provide clear, accessible information about the environmental impacts of products, such as labelling pillows with their environmental footprint. Consider certification under life cycle environmental standards such as EU Ecolabel, Nordic Swan Ecolabel and Cradle to Cradle to provide assurance to consumers about the environmental performance of products. Collaborate on developing standard tests, e.g. pillow

performance and longevity, and share value chain data and learnings with an ‘open source’ mindset.

5. **Educate consumers**
   Make sure consumers know how to care for and dispose of pillows to minimise their environmental impact.

7.2 For Retailers

1. **Promote environmental transparency**
   Provide clear, comprehensive information about the environmental impacts of pillows. Transparency can help consumers make informed decisions.

2. **Curate a lower-impact product range**
   Select and promote pillows with lower environmental impacts across their life cycles, helping to shift market demand towards products that are not only comfortable but also have a reduced environmental footprint.

3. **Educate consumers**
   Use marketing materials, in-store displays, and online resources to educate consumers about the importance of considering the entire life cycle of products and extending the life of pillows through proper care and maintenance.

4. **Support responsible disposal**
   Encourage and facilitate the responsible disposal of old pillows, such as recycling programs or partnerships with recycling centres.

5. **Engage with suppliers**
   Collaborate with suppliers to improve the environmental performance of pillows. This could involve encouraging the use of recycled materials, optimising manufacturing processes for energy and water efficiency, less waste during production and adopting distribution and packaging solutions with a smaller environmental impact.

7.3 For consumers

1. **Make informed choices**
   When purchasing pillows, consider the environmental impact of different materials as indicated by LCA findings. Opt for materials that have lower impacts on climate change, water, and land use.

2. **Reduce the need for replacement**
   Extend the life of pillows through proper care and maintenance, following manufacturer guidelines for washing and drying. This decreases the need for frequent replacements, thus reducing the environmental footprint.

3. **Dispose with care**
   At the end of a pillow's usable life, seek out sustainable disposal options. This may include recycling programs, donation for reuse if sanitary, or other environmentally friendly disposal methods recommended by local waste management services.

4. **Support sustainable practices**
   Support brands and manufacturers that prioritize sustainability in their products and practices, including those that provide transparency about their environmental impacts and participate in recycling or take-back programs.

5. **Advocate for change**
   Consumers can play a role in advocating for more sustainable industry practices through their purchasing choices and by engaging in dialogue with manufacturers and retailers about the importance of environmental sustainability in home textiles.

Through such efforts and choices, each of us holds the power to mitigate climate change, preserve natural resources and protect biodiversity. By uniting our actions, we can transform the pillow industry - and our world - for the better.

8 Conflict of Interest

This study was conducted by Fossflakes, the manufacturer of one of the pillows investigated. While Fossflakes is the author of this study, every effort has been made to ensure objectivity and transparency throughout the research process. To mitigate potential bias, the study was subject to third-party verification by independent reviewers with expertise in LCA and the pillow industry. Additionally, transparency in the methodology and data used has been prioritized, with all assumptions and modelling choices clearly documented and justified. This approach helps ensure that the results and conclusions drawn from this study are based on robust, impartial analysis.

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<u>Appendix A</u> : Rationale and Background Data for Pillow Size and Weight Metrics

This appendix provides the background data used to support the selection of specific pillow metrics for the functional unit of this study. It includes comparative data on the weights of polyester fibre and down-feather pillows and explains the focus on the 50x70 cm pillow size, highlighting its relevance in the European market

The choice of the 50x70 cm medium pillow size, along with the focus on distribution and disposal in Northern Europe, was initially based on Fossflakes' product range and its popularity in this region. The assumption was that this size is representative of the broader European market, given its prevalence among European pillow suppliers. To validate this assumption and ensure the study's relevance, additional data were collected and analysed to provide context and support the decision.

Pillows examined - Weight of fill and shell

Pillow weight data were primarily sourced from Jysk's websites, as Jysk is one of the few retailers that provides detailed information on both shell and fill weights for pillows [5]. With over 3,400 physical stores in more than 25 countries and online presence in 48 countries, Jysk was considered a reliable source to reflect broader market trends. Most other retailers only provided either the fill weight or the total weight or did not provide detailed specifications at all.

Pillow type	Name of product	Fill	Shell	Total	Height	Shell-type	Website	Fill power
Fossflakes	Fiberpute 50x70 Fossflakes ROYAL NORDIC	700	130	830	15	bomullscambric	jysk.no	-
Polyester fibre	Fiberpute 50x70 KVITEKOLL	600	75	675	13	polyestermikrofiber	jysk.no	-
	Fiberpute 50x70 Varnamo VANGSEN	550	90	640	15	polyester, mikrofiber	jysk.no	-
	Fiberpute 50x70 GLOPTIND	700	80	780	6	polyester (100% resirkulert), mikrofiber	jysk.no	-
	Fiberpute 50x70 TRONFJELLET	750	90	840	17	bomullscambric	jysk.no	-
	Fiberpute 50x70x3 KRONBORG BEERENBERG	550	100	650	10	bomullscambric	jysk.no	-
	Fiberpute 50x70 KRONBORG OKSHORNET	800	80	880	15	bomullscambric	jysk.no	-
	Pillow with synthetic filling 50x70 VIKANES	600	115	715	16	polyester, microfiber	jysk.pl	-
	Pillow with synthetic filling 50x70 VEOFJELLET	600	113	713	14	polyester, microfiber	jysk.pl	-
	Pillow with synthetic filling 50x70 ULVIK	600	100	700	16	polyester, microfiber	jysk.pl	-
	Pillow with synthetic filling 50x70 Høie NATURE	600	100	700	14	bomullscambric	jysk.pl	-
	Pillow with synthetic filling 50x70 KNUTSEGGEN	650	100	750	17	bomullscambric	jysk.pl	-
	Pillow with synthetic filling 50x70 KRONBORG BRURI	800	80	880	16	bomullscambric	jysk.pl	-
Down-feather	Andefjærspute 50x70x3 NOTODDEN	810	150	960	15	bomullscambric	jysk.no	-
	Moskusandedunspute 50x70 Høie GEILO	600	200	800	15	bomullscambric	jysk.no	750/400
	Andedunspute 50x70 KRONBORG BEITO	850	73	923	17	bomull	jysk.no	350/250
	Andedunspute 50x70 Høie TRYM	600	70	670	13	bomullscambric	jysk.no	500
	Moskusandedunspute 50x70 Norsk Dun JOTUNHEIMEN	600	120	720	13	bomullscambric	jysk.no	400
	Goose down pillow 50x70 KRONBORG OKKEN	670	204	874	15	100% cotton, jacquard	jysk.pl	750/375
	Pillow with duck feathers 50x70 GALDEBERGET	850	195	1045	15	bomullscambric	jysk.bg	300/125
	Pillow with duck feathers 50x70x5 NONSNIBBA	1220	180	1400	15	cotton	jysk.bg	-
	Duck feather pillow 50x70/75x3 HIMMELTINDEN	900	250	1150	15	bomullscambric	jysk.uk	-

**RED text = not applicable data for the comparison. Other shell material.*

Table 32: Display of the data collection for assessing other pillow fill and shell weights within the same category; cotton shell, size of 50x70cm, medium height.

The range of pillows included in this analysis was chosen to provide a broad view of the market while focusing on the most commonly available types that meet the criteria of having a cotton shell and medium firmness. However, the selection does not include every pillow type or size available, which may impact the representativeness of the averages used in the study. The variability in pillow weights across the sample indicates that there is no single "standard" pillow weight, but rather a range that reflects different qualities, consumer preferences and manufacturing practices.

Size and location

The maps below illustrate the types of pillows that Fossflakes distributes across Europe, primarily through Jysk. While complete data for all countries were not accessible, various online sources were used to infer the most popular pillow sizes in different regions. These sources were employed to fill data gaps and are assumed to accurately reflect regional demand.

As indicated in the maps, the 50x70 cm size is among the most popular options across many European countries. Some sources suggest that the 50x70 cm pillow is commonly referred to as the standard EU size, while others identify the 65x65 cm size as the "Euro" pillow.

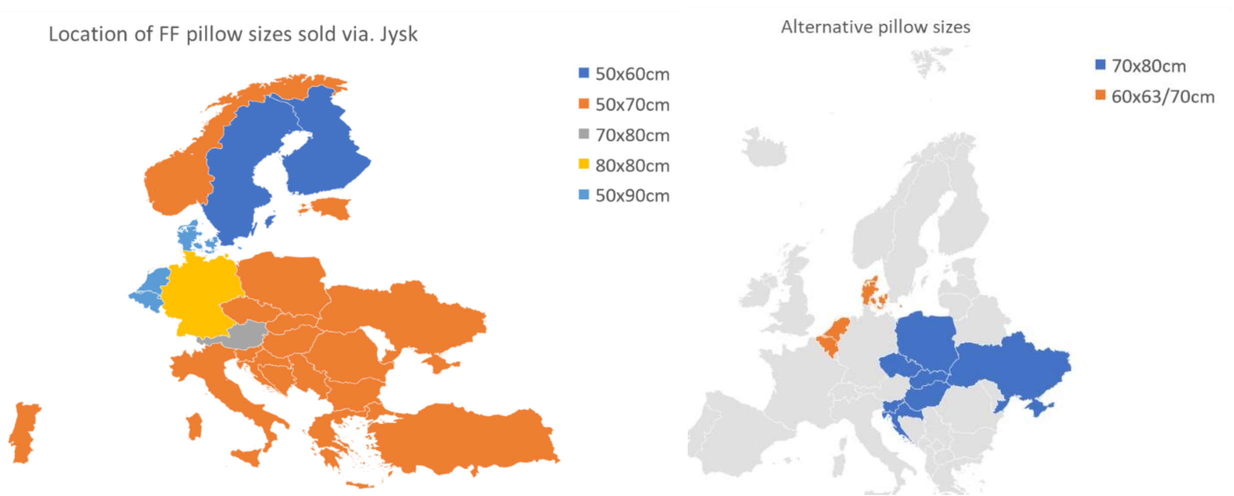

Figure 20: The two maps show the different pillow sizes sold by Jysk in various countries. Some countries have more than one type (alternative sizes).

The two maps in Figure 20 show the different pillow sizes sold in various countries. However, note some countries use several sizes and these standards are not the strictest. For example, in Ukraine, both the 50x70 cm and 70x80 cm pillow sizes are sold, indicating a preference for multiple sizes within the market.

Lifetime of pillows

Determining the lifetime of a sleeping pillow is challenging due to the lack of specific public research or standardized tests on the subject. Opinions on pillow longevity vary widely, with factors such as hygiene concerns (e.g. fungi and bacteria[7]) and material fatigue (e.g., wear and tear) playing a role in when a pillow is considered "used up".

A review of publicly available information, including a sample of top Google search results for "lifetime of pillows," reveals that most sources recommend a lifespan of 1-3 years for pillows, regardless of type. Notably, a few outliers suggest longer lifetimes for down-feather pillows, with claims of durability lasting 5-10 years or more. However, such claims typically come from down-feather suppliers and may reflect optimal conditions rather than average use. See Table 33 below for more detail and sources.

[7] A. A. Woodcock, N. Steel, C. Moore, S. Howard, A. Custovic and D. & Denning, "Fungal contamination of bedding," *Allergy,* vol. 61, pp. 140-142, 2006.

Lifetime (statement)	Source
"Most pillows need replacing every 18 months - 3 years"	https://tielleloveluxury.co.uk/blogs/blog/how-long-do-pillows-last-heres-how-to-know-when-to-replace-them
"Most experts recommend replacing pillows every 1 to 2 years. Doing so helps to ensure that you're using pillows that are supportive, clean, and free of allergens. It is also important to care for the pillows you use to ensure their longevity."	https://www.sleepfoundation.org/best-pillows/how-often-should-you-replace-your-pillows
"Down and Feather: Since these pillows can be washed regularly (we recommend every 6 months) and the fill is so durable, they easily can last 5-10 years, or more. Synthetic: A good rule of thumb with synthetic is 1-2 years depending on the quality of materials and usage."	https://www.pacificcoast.com/blog/gift-guides/how-long-do-pillows-last.html
"Polyester or Down Alternative: Pillows using polyester fiber or a synthetic down alternative are the most common and cost-effective type of pillow available. They generally last 1 to 2 years. Down or Feather: Pillows made with down, feathers, or a combination of these natural materials generally last 1 to 3 years."	https://sleepdoctor.com/pillow-information/when-should-you-replace-your-pillow/
"If you're looking for a ballpark figure, Judith Palmer, director of product and merchandising for pillows and cushions at Purple, says that pillows last, on average, approximately two years. However, the lifespan of a pillow depends on several factors and how often the pillow is used."	https://www.realsimple.com/how-long-do-pillows-last-8583915
"Pillows should be changed every two years and duvets every five. 82% of people do not know this and most keep their bedding for longer. The average Briton keeps a pillow for 3.2 years and a duvet for 7.6 years. 57% of people only replace their bedding when it starts to wear out."	https://www.dailymail.co.uk/health/article-2579149/How-clean-YOUR-bedding-The-average-Briton-keeps-pillow-YEAR-longer-causing-neck-damage-dust-mite-infestations.html

Table 33: Statements on lifetime of pillows, retrieved from arbitrary websites.

Given this variability and the absence of conclusive data, a conservative estimate of 2 years has been chosen as the baseline lifetime for all pillow types in this study. This aligns with the majority of recommendations while providing a consistent and reasonable basis for the life cycle assessment. This choice ensures fairness and avoids favouring any one pillow type.

To improve the robustness of future studies, standardizing the criteria for pillow lifetimes - both in terms of hygienic and structural durability - would provide a clearer foundation for evaluating environmental impacts. Fossflakes recognizes the value of such efforts and views this as a priority area for future research and collaboration within the industry.

Appendix B : Assumptions and Data Validation for Down-Feather Pillow

To ensure accurate representation of the life cycle impacts in modelling the down-feather pillow, several data sources were critically evaluated. The primary datasets were sourced from the Ecoinvent and Agribalyse databases, known for their comprehensive environmental data on agricultural and industrial processes.

Weight Assumptions for Ducks and Geese:

The average weight assumption of 3 kg per bird (both ducks and geese) and the yield of 1 kg of usable down-feather per 10 birds (100 grams per bird) used in this study are based on expert input and a thorough review of relevant literature. These weights are reflective of common commercial breeds typically used in down production.

For ducks, weights generally range between 2.95 kg and 3.5 kg, as reported by various sources. The RSPCA notes that ducks can weigh between 3.1 and 3.5 kg[8], depending on the breed and rearing conditions. Another source from the Department of Primary Industries, New South Wales, Australia, identifies a common commercial duck weight of approximately 2.95 kg[9].

Geese, on the other hand, show a wider range of weights. A study on Polish geese reports a typical weight range of 3 to 7.5 kg, influenced by species and environmental conditions[10]. Larger commercial breeds of geese can weigh up to 10 kg, as highlighted by guidelines from Teagasc[11], an Irish agricultural and food development authority.

Plumage Yield and Down Content:

The data on plumage yield and down content is primarily based on a study by Kozák (2011)[12], which provides a comprehensive overview of feather formation, moulting, and down production in geese. According to this study, the plumage of birds generally constitutes about 5-7% of their total body weight. For geese, this results in a feather yield of approximately 90 to 220 grams, depending on the slaughter age and species. Of this total feather weight, about 20-30% consists of down, with the remainder being covert feathers. For ducks, the feather

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[8] Duck farming - Welfare of farmed ducks | RSPCA - RSPCA - rspca.org.uk. (n.d.). Retrieved from https://www.rspca.org.uk/adviceandwelfare/farm/ducks

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[10] Lewko, L., Skotarczak, E., Moliński, K., & Gornowicz, E. (2022). Analysis of slaughter traits in geese depending on breed, sex and length of rearing period. *Poultry Science*, *102*(6), 102281. https://doi.org/10.1016/j.psj.2022.102281

[11] Teagasc. (n.d.). Free-Range goose Production - TEAGASC | Agriculture and Food Development Authority. https://www.teagasc.ie/rural-economy/rural-development/diversification/free-range-goose-production/

[12] Kozak, J. (2011). An Overview of Feathers Formation, Moults and Down Production in Geese. Asian-Australasian Journal of Animal Sciences. 24. 10.5713/ajas.2011.10325. (PDF) An Overview of Feathers Formation, Moults and Down Production in Geese (researchgate.net)

yield is typically lower, around 70-90 grams, including down. This variability in yield is influenced by several factors, including breed, age, and environmental conditions.

Conclusion:

Assuming a 3 kg bird weight and a yield of 0.1 kg (100 grams) of down-feather per bird is a fair and balanced approach for this study. The bird weight is intentionally conservative, sitting on the lower end of the spectrum for both ducks and smaller breeds of geese. This is to avoid making relatively uncertain assumptions that could inadvertently favour the Fossflakes pillow, given that Fossflakes is the company conducting the study and must exercise additional caution with these kinds of decisions. A higher bird weight, with a larger meat-to-feather ratio, would increase the environmental impact of the down-feather pillows raw material extraction phase (e.g. raising the birds), through economic allocation, making this conservative estimate appropriate.

Additionally, choosing a weight closer to 3 kg aligns with the predominant market data, where ducks are far more commonly raised than geese. From 2009 to 2013, approximately 2.7 billion ducks and 653 million geese were raised for meat[13], highlighting the greater prevalence of ducks in the market. In summary, the chosen bird weight and down-feather yield figures provide a reasonable and balanced basis for the life cycle assessment within the scope of this study. While uncertainties such as regional variations in bird sizes and rearing practices may influence these values, this approach supports a fair and transparent comparison across different pillow types.

[13] *The Sustainable and Humane Practices of the Down and Feather Industry: A Global Assessment of Industry Statistics and Practices* by Harry Schmitz, Ph.D., commissioned by the International Down and Feather Bureau (IDFB). https://idfb.net/fileadmin/idfb/public/10_IDFB_White_Paper_6.07.16.pdf

Appendix C : Impact Assessment Method - ReCiPe

Developed by Goedkoop et al. (2008)[14] and updated subsequently by Huijbregts et al. (2016)[15], the ReCiPe method was created by a collaboration between RIVM, Radboud University Nijmegen, Leiden University, and PRé Consultants. The method aims to standardize and harmonize life cycle impact assessment (LCIA) methodologies, providing consistent and comprehensive environmental impact profiles.

ReCiPe translates the vast array of emissions and resource extractions during a product's life cycle into a concise set of environmental impact scores using characterization factors.

- **Midpoint Factors:** Calculate impacts at an intermediate point in the impact pathway where environmental mechanisms are consistent across pollutants, offering lower uncertainty.
- **Endpoint Factors:** Directly relate to damage on protection areas like human health and ecosystem quality, providing insights that are more aligned with actual environmental impacts but with higher uncertainty.

Within the Midpoint factors there are three different perspectives which are available in ReCiPe 2016:

- **Individualist:** The individualistic perspective prioritizes short-term interests, acknowledges undisputed impact types, and demonstrates technological optimism regarding human adaptation. Climate change time horizon: 20 years.
- **Hierarchist:** The hierarchist perspective relies on scientific consensus regarding time frames and the plausibility of impact mechanisms.
  Climate change time horizon: 100 years.
- **Egalitarian:** The egalitarian perspective is the most precautionary, considering the longest time frames and all available impact pathways.
  Climate change time horizon: 1000 years.

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[14] Goedkoop, M., Heijungs, R., Huijbregts, M., Schryver, A. D., Struijs, J., & Zelm, R. V. (2008). *ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level*. Report I: Characterisation. RIVM, Radboud University Nijmegen, Leiden University, and PRé Consultants. Retrieved from https://www.rivm.nl/sites/default/files/2018-11/ReCiPe_main_report_final_27-02-2009_web.pdf

[15] Huijbregts, M. A. J., Steinmann, Z. J. N., Elshout, P. M. F., Stam, G., Verones, F., Vieira, M., Hollander, A., & van Zelm, R. (2016). *ReCiPe 2016: A harmonized life cycle impact assessment method at midpoint and endpoint level. Report I: Characterization*. National Institute for Public Health and the Environment (RIVM). Retrieved from https://www.rivm.nl/documenten/recipe-2016-method

Note that the time horizon used for climate change, was shown for comparison and to understand the differences between the perspectives. For this LCA study, the ReCiPe Midpoint (Hierarchy) approach was used.

In summary, the ReCiPe Midpoint (Hierarchy) approach offers a scientifically robust, globally applicable method for evaluating environmental impacts in LCA studies. It standardizes impact assessment across various categories, making it a crucial tool for researchers and practitioners focused on reducing environmental footprints and supporting sustainability-oriented decision-making.

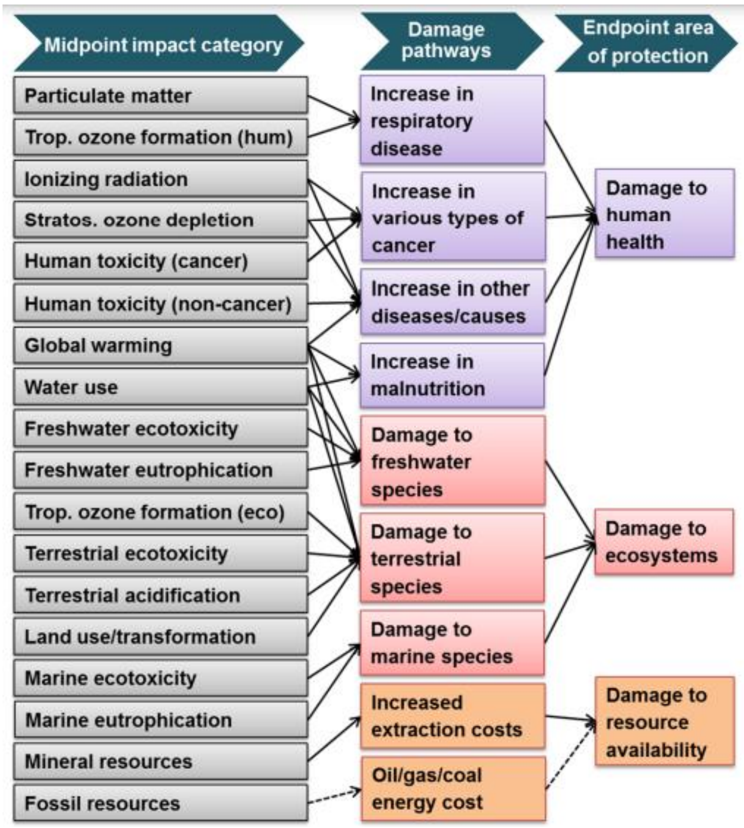

Table 34: Overview of impact categories in ReCiPe.

The above figure shows an "overview of the impact categories that are covered in the ReCiPe2016 methodology and their relation to the areas of protection". The figure was retrieved from the RIVM website[16].

[16] https://www.rivm.nl/en/life-cycle-assessment-lca/recipe

Appendix D : Data Quality Assessment Using the Pedigree Matrix

For the uncertainty analysis, the data quality of system flows was evaluated using the pedigree matrix approach[17]. The pedigree matrix is a tool that helps assess the reliability, completeness, temporal correlation, geographical correlation, and further technological correlation of the data used in life cycle assessments (LCA). Each data quality indicator is rated on a scale from 1 to 5, with 1 representing high-quality data and 5 indicating low-quality or highly uncertain data.

Data Quality Indicators	1	2	3	4	5
Reliability	Verified data based on measurements	Verified data partly based on assumptions or non-verified data based on measurements	Non-verified data partly based on qualified estimates	Qualified estimate (e.g., by industrial expert)	Non-qualified estimates
Completeness	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from > 50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from only some sites (<< 50%) relevant for the market considered or > 50% of sites but from shorter periods	Representative data from only one site relevant for the market considered or some sites but from shorter periods	Representativeness unknown or data from a small number of sites and from shorter periods
Temporal correlation	Less than 3 years of difference to the time period of the data set	Less than 6 years of difference to the time period of the data set	Less than 10 years of difference to the time period of the data set	Less than 15 years of difference to the time period of the data set	Age of data unknown or more than 15 years of difference to the time period of the data set
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown or distinctly different area (e.g., North America instead of Middle East, OECD-Europe instead of Russia)
Further technological correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study (i.e., identical technology) but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials	Data on related processes on laboratory scale or from different technology

Figure 21: Ecoinvent Data Quality System. Pedigree matrix.

The matrix provided in Figure 20 illustrates the grading system used to evaluate the different data quality indicators. These grades are then converted into uncertainty factors, which quantify the potential error or variance in the data, allowing for a more nuanced understanding of the overall uncertainty in the LCA results. For instance, a lower rating in reliability would imply a lower uncertainty factor, indicating that the data are more dependable. Conversely, a higher rating suggests greater uncertainty and a less robust data source.

[17] M. A. J. Huijbregts, G. Norris, R. Bretz, A. Ciroth, B. Maurice, B. V. Bahr and A. S. H. D. Beaufort, "Framework for modelling data uncertainty in life cycle inventories," The International Journal of Life Cycle Assessment, vol. 6, no. 3, pp. 127-132, 2001.

Uncertainty factors	1	2	3	4	5
Reliability	1.0	1.05	1.1	1.2	1.5
Completeness	1.0	1.02	1.05	1.1	1.2
Temporal correlation	1.0	1.03	1.1	1.2	1.5
Geographical correlation	1.0	1.01	1.02	1.05	1.1
Further technological correlation	1.0	1.05	1.2	1.5	2

Table 35: The weighting of uncertainties for the various Data Quality Ratings (1-5).

In this study, the pedigree matrix was applied to all significant data flows within the LCA to thoroughly assess data quality and identify potential uncertainties. This method facilitated the identification of key data quality issues that could impact the results, allowing for a systematic evaluation of how these uncertainties might affect the overall conclusions. By using the pedigree matrix to assess uncertainty, we gained insights into the robustness of our findings and highlighted areas where data quality could be enhanced for future research.

Although specific uncertainty quantifications were not conducted, the uncertainty factors derived from the pedigree matrix informed our understanding of the potential variability in the results. This approach ensures that the conclusions consider a range of possible outcomes related to data quality variations, rather than relying solely on average data values.

Appendix E : Critical Review Statement

Checklist on the compliance to the ISO 14040-44 standards of the Final report

Scope of the critical review

The reviewers had the task of assessing whether:

1) the methods used to carry out the LCA are consistent with the international standards ISO 14040 (2006) and ISO 14044 (2006),
2) the methods used to carry out the LCA are scientifically and technically valid,
3) the data used are appropriate and reasonable in relation to the goal of the study,
4) the interpretations reflect the limitations identified and the goal of the study, and
5) the study report is transparent and consistent.

Although a detailed review of individual dataset files and LCA models in the software was beyond the scope of this review, all modelling steps, calculations, and decisions are thoroughly documented in the appendix to ensure full transparency and context for the data.

The critical review panel was chosen to ensure the required LCA competence and expertise in the scientific and technical aspects of the studied product system.

Review process

The critical review process took place in the last stage of the LCA study. The review was based on ISO 14044 (2006) and ISO/TS 14071 (2014). The review process took place between April 2024 and October 2024.

The process involved two rounds of review and commenting on LCA work resulting in the final LCA report. In the first review – April 2024 – the reviewers commented on a preliminary LCA report providing comments of a general nature with main missing items. The comments were processed by the practitioner into a 2nd version of the LCA report dated May 2024. The reviewers examined the second version of the report returning 135 comments in total.

The last comment round was performed with a specific focus on how comments from the 2nd round were addressed and integrated into the final LCA report dated August 2024.

The final report as an entity including appendices was evaluated by the review panel to represent a complete LCA study with the remark listed under "Specific remarks"

Specific remarks

It was suggested by the LCA review panel to put a larger amount of the primary data collection and calculations into the actual LCA report rather than appendices, to enhance its readability as a stand-alone document.

While Fossflakes partially implemented this suggestion the company also prioritized safeguarding the confidentiality of sensitive information by keeping detailed modelling and background calculations in the appendices. This approach aligns with the methodology of the only comparable industry LCA—the International Down and Feather Bureau (IDFB) report *Life Cycle Assessment of Down Fill Material*—in the absence of standardized LCA reporting guidelines in the bedding and fill industry.

The review panel accepts this approach, as data is present and correct in the LCA report together with the appendices as a complete entity. Compliance with ISO 14040 and 14044 is achieved by providing full access to the review panel, as permitted for confidential data under these standards. However, for a comprehensive understanding of the exact modelling processes, inputs, and detailed assumptions, the reader would need access to both the report and all appendices.

General description

This study aims at performing a comparative LCA of three types of pillows:

1. A pillow from Fossflakes with the specific Fossflakes filling.
2. A comparable pillow with polyester fibre filling.
3. A comparable pillow with down-feather filling.

The assessment is performed with an identical shell based on the typical sold product from Fossflakes.

The assessment is performed as a cradle-to-grave study covering the entire life cycle of the pillows. Data for the non-Fossflakes solutions are covered partly using primary data from the competing solutions. The competing solutions are described and modelled fairly.

Two main points of allocation are present:

1. A specific economic allocation is performed to distribute the environmental burden between meat and down/feather as sellable output from duck production.
2. Allocation of energy consumption within the Fossflakes production is allocated by energy usage of machinery, expert judgment, and energy/water bills, followed by an overhead distribution by occupied production floor space.

For background datasets, allocation followed those in the Ecoinvent database.

The impact assessment is carried out using the ReCiPe 2016v1.03 (H) methodology.

The study makes use of primary inventory data provided by Fossflakes and Dykon combined with a combination of literature values.

Because of the system boundaries the use stage was not included in the model.

Modelling of the end-of-life stages was mostly based on secondary data from the Ecoinvent database, properly selected to align with the scope of the project. It could be concluded that the data used are adequate and in accordance with the goal and scope of this study here. In cases where the data was of a lower quality, sensitivity assessment was carried out.

The study includes data quality assessment and sensitivity analyses. The robustness of results is well discussed and contextualized to decision-making. Comparative conclusions are based on minimum significance levels, meaning that conclusions on best performance are drawn when clear differences among alternatives can be seen.

Overall, the critical review found the quality of the chosen methodology and its application in the final analysis to be adequate for the purposes of the study and in accordance with the ISO 14040 and ISO 14044 standards, including the specific remark mentioned above.

The reporting of the study and its results is transparent.

This critical review checklist has been prepared to enable the results of a critical review to conform precisely to the guidelines of the ISO 14040-44 Standards. The checklist compilation was performed by the critical reviewers.

This checklist consists of 3 sections.

- Section 1 of the checklist corresponds to section 5.1 of ISO 14044, and addresses general reporting requirements, applicable to all LCA studies.
- Section 2 pertains to additional reporting requirements that apply in cases where the results of the LCA are to be communicated to any "third party" – that is, to any interested person or organization other than the commissioner or the practitioner of the study.
- Section 3 contains the special requirements that come into play when the third-party communication makes what the ISO standards refer to as a "*comparative assertion*", which is intended to be disclosed to the public. A comparative assertion is defined (see 3.5 of ISO 14044) as an "*environmental claim regarding the superiority or equivalence of one product versus a competing product that performs the same function.*"

SECTION 1: General Reporting Requirements and Considerations

The columns (or the boxes) at the left are checked to indicate "yes" and left un-checked to indicate that the requirement does not appear to have been met.

Requirements		**Review comments**	**Authors responses**	**Issue resolved? (Y/N)**
X	Are the results and conclusions of the LCA completely and accurately reported without bias to the intended audience?			
X	Are the results, data, methods, assumptions, and limitations transparent and presented in sufficient detail to allow the reader to comprehend the complexities and trade-offs inherent in the LCA?			
X	Does the report allow the results and interpretation to be used in a manner consistent with the goals of the study?			

SECTION 2: Requirements when results will be communicated to third parties (parties other than the commissioners and the practitioners of the LCA)

Requirements	**Review comments**	**Authors' responses**	**Issue resolved? (Y/N)**
a) General aspects: ☒LCA commissioner, practitioner of LCA (internal or external); ☒ date of report; ☒ statement that the study has been conducted according to the requirements of 14044.			
b) Goal of the study: ☒ reasons for carrying out the study; ☒ intended applications; ☒ target audiences; ☒statement whether the study intends to support comparative assertions intended to be disclosed to the public.			
c) Scope of the study: 1) function: ☒ statement of performance characteristics; ☒ any omission of additional functions in comparisons; 2) functional unit: ☒ consistency with goal and scope; ☒ definition; ☒ result of performance measurement; 3) system boundaries: ☒ omissions of life cycle stages, processes or data needs; ☒ quantification of energy and material inputs and outputs; ☒ assumptions about electricity production; 4) cut-off criteria for initial inclusion of inputs and outputs: ☒ description of cut-off criteria and assumptions; ☒ effect of selection on results; ☒ inclusion of mass, energy and environmental cut-off criteria.			
d) Life cycle inventory analysis: ☒ data collection procedures; ☒ qualitative and quantitative description of unit processes; ☒ sources of published literature; ☒ calculation procedures; validation of data: ☒ data quality assessment; ☒ treatment of missing data; ☒ sensitivity analysis for refining the system boundary; allocation principles and procedures: ☒ documentation and justification of allocation procedures;			

☒ uniform application of allocation procedures.			
e) Life cycle impact assessment: ☒ LCIA procedures, calculations and results of the study; ☒ limitations of the LCIA results relative to the defined goal and scope of the LCA; ☒ relationship of LCIA results to the defined goal and scope, see clause 4.2 of 14044; ☒ relationship of the LCIA results to the LCI results, see clause 4.4 of 14044; ☒ impact categories and category indicators considered, including a rationale for their selection and a reference to their source; ☒ description of or reference to all characterization models, characterization factors and methods used, including all assumptions and limitations; ☒ description of or reference to all value-choices used in relation to impact categories, characterization models & factors, normalization, grouping, weighting and, elsewhere in the LCIA, a justification for their use and their influence on the results, conclusions and recommendations; ☒ statement that the LCIA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins or risks; Are any new impact categories, category indicators, or characterization models used as part of the LCIA? ☒ NO (Proceed to part f) Life Cycle Interpretation) ☐ YES (IF YES, complete the checklist items below) ☐ description and justification of the definition and description of any new impact categories, category indicators or characterization models used for the LCIA; ☐ statement and justification of any grouping of the impact categories; ☐ any further procedures that transform the indicator results and a justification of the selected references, weighting factors, etc.; ☐ any analysis of the indicator results, for example sensitivity and uncertainty analysis or the use of environmental data, including any implication for the results; ☐ data and indicator results reached prior to any normalization, grouping or weighting shall be made available together with the normalized, grouped or weighted results.			
f) Life cycle interpretation: ☒ results; ☒ assumptions and limitations associated with the interpretation of results, both methodology and data related; ☒ data quality assessment; ☒ full transparency in terms of value-choices, rationales and expert judgments;			
g) Critical review:			

☒ name and affiliation of reviewers; ☒ critical review report; ☒ responses to comments/recommendations.			

SECTION 3: Requirements for Comparative Assertions intended to be disclosed to the public

The columns (or the boxes) at the left are checked to indicate "yes" and left un-checked to indicate that the requirement does appear to have been met.

Requirements		**Review comments**	**Authors responses**	**Issue resolved? (Y/N)**
X	Analysis of material and energy flows to justify their inclusion or exclusion			
X	Assessment of the precision, completeness and representativeness of data used			
X	Description of the equivalence of the systems being compared in accordance with 4.2.3.6 of 14044;			
X	Description of the critical review process			
X	Evaluation of the completeness of the LCIA			
X	Statement as to whether or not international acceptance exists for the selected category indicators and a justification for their use			
X	Explanation for the scientific and technical validity and environmental relevance of the category indicators used in the study			
X	Results of the uncertainty and sensitivity analyses			
X	Evaluation of the significance of the differences found			
X	Is Grouping included in the LCA? ☒ NO (Checklist is complete) ☐ YES (IF YES, complete the checklist items below) ☐ procedure and results used for grouping; ☐ statement that conclusions and recommendations derived from grouping are based on value choices; ☐ justification of the cut-off criteria used for normalization and grouping (these can be personal, organizational or national value-choices); ☐ statement that "ISO 14044 does not specify any specific methodology or support the underlying value-choices used to group the impact categories"; ☐ statement that "The value-choices and judgments within the grouping procedures are the sole responsibilities of the commissioner of the study (e.g. government, community, organization, etc.)".			

<u>Appendix F</u> : Life Cycle Inventory Data and Modelling

Appendix F contains the inventory data and modeling details for the different pillows and their components, as developed in the LCA software OpenLCA. It includes descriptions of the data collection process, primary data development, assumptions made, methods used in Life Cycle Inventory (LCI) development, and the databases utilized. Additionally, it provides an overview of the calculations and rationale behind key methodological choices.

Confidentiality

This appendix is confidential and supplied separately for the critical review panel and Fossflakes employees. It contains sensitive information about Fossflakes' operations and is not to be disclosed publicly without further evaluation and necessary edits to protect proprietary data.

For further questions or clarification about the data and methods used in this study, inquiries can be directed to Fossflakes. Requests will be reviewed on a case-by-case basis to determine what additional information can be shared.