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Life-LCA: Impacts of a German Human Being in the Old Adulthood Stage

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Abstract: Life-LCA studies, which assess the environmental impacts of human beings, focused so far on the span from conception to 50 years. This case study extends the analysis to an "old adulthood stage", including a retirement (65–75 years) and end-of-life phase (75–80 years), thus complementing the assessment gap in the life cycle of a human being. The Life-LCA method is applied to a fictional study object representing an average German adult using mainly secondary data. Over both life phases, impacts result in 1.2×10^2 t CO_2-eq for climate change, 9×10^{-5} CTUh for human toxicity cancer, 2×10^{-3} CTUh for human toxicity non-cancer, 1.35×10^0 kg Sb-eq for abiotic depletion for elements, and 1.55×10^0 TJ for fossil fuels. Across all impact categories, "transport" is a hotspot, contributing 41% to GWP, followed by "Energy and water" (39%) and "food" (20%). For abiotic depletion for elements, "Electronics" shows a share of 50%. The "retirement phase" causes a higher environmental impact than the "EoL phase" across all impact categories due to restricted mobility with higher age. A study with primary data collection is suggested to check the plausibility of the results.

Keywords: life cycle assessment (LCA); Life-LCA; old adulthood; sustainable lifestyles; sustainable consumption; carbon footprint; personal environmental footprint

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Citation: Bossek, D.; Rudolph, C.; Bach, V.; Finkbeiner, M. Life-LCA: Impacts of a German Human Being in the Old Adulthood Stage. *Sustainability* **2023**, *15*, 11447. https://doi.org/10.3390/su151411447

Academic Editor: Gianpiero Greco

Received: 16 June 2023
Revised: 20 July 2023
Accepted: 21 July 2023
Published: 24 July 2023

1. Introduction

Germany is expecting demographic changes and an aging population in the coming years. In 2021, older adults (65+ years) will make up around a quarter of the total population; by 2050, this share is expected to increase to 28% [1]. Therefore, the role of older adults in consumer markets and their associated environmental impacts are becoming increasingly important. Research shows that spending on food, transportation, personal care, and fashion is decreasing for individuals in the "old adulthood stage" (OAS) while spending on medical expenses is surging [2,3]. This shift in consumption behavior can be attributed to the health and physical limitations that typically affect older adults [2].

In the first Life-LCA case study of a human being, Bossek et al. [4] calculated the environmental impacts of a real-life study object, "Dirk", from his birth to 49 years (his age at the time of performing the analysis). Further, the previously assessed "childhood and youth", "early adulthood", and "middle adulthood" stages were based on primary data collection of individuals [4,5]. The "old adulthood stage" (60 years to the end of life), defined by Goermer et al. [6] was excluded until now.

Therefore, by applying the Life-LCA method [6], this study aims to close this gap by collecting data for the "old adulthood stage". In addition, for the first time in the context of the Life-LCA, a fictional study object representing the average German old adult was chosen mainly using secondary data (e.g., publicly available statistics, pieces of the literature) instead of primary data collection, which was resource- and time-intensive (e.g., monitoring phases up to six months).

Further, to broaden the scope of the Life-LCA application and gain new insights, the impact categories of abiotic depletion for elements (ADP-e), abiotic depletion for fossil fuels (ADP-f), human toxicity cancer (HT cancer), and human toxicity non-cancer (HT non-cancer) are assessed for the first time in the Life-LCA. Additionally, to provide a comparative perspective with prior Life-LCA studies, the impact categories climate change (GWP), acidification (AP), eutrophication (EP), and photochemical ozone creation (POCP) are analyzed to see further if the use of secondary data provides plausible results.

Another motivation for this study was to analyze how environmental impacts change with increasing age, beginning from the statistically average retirement age in Germany (65 years) to extending beyond death to include aspects such as funeral and grave maintenance. To better show these changes in consumption patterns and associated impacts, a subdivision of the life stage into the life phases "retirement age" (65–75 years) and "end of life" (75–80 years) is made. (See Section 2.2 for further explanation.)

In the following sections, the applied materials and methods (see Section 2), Life-LCA results (see Section 3), a discussion with a sensitivity analysis (see Section 4), and a conclusion and outlook (see Section 5) are presented.

2. Materials and Methods

This chapter presents the applied materials and methods, including the goal and scope (see Section 2.1), system boundaries (see Section 2.2), selected impact assessment method (see Section 2.3), and life cycle inventory (see Section 2.4).

2.1. Goal and Scope

This study aims to quantify the environmental impacts of an average German adult in the old adulthood stage by applying the Life-LCA method [6].

The *reporting unit* combines the *reporting individual, period, and flow* for an "Individual Life-LCA". It relies on the individual monitoring and recording their consumption over a defined period and providing these data to the Life-LCA practitioner [6].

However, in this study, a fictional study object is determined to embody the statistically average German adult aged 65 and over. While the term "reporting unit" is typically used in such studies, it is not applicable here due to the subject's fictional nature. Instead, we propose using "reporting unit (average)" to reflect this scenario more accurately. The *reference flow* is set to be all products consumed within the *period* in the "old adulthood stage" (65–80 years). The "old adulthood stage" comprises two subdivisions: the "retirement phase" (65–75 years) and the "end-of-life phase" (75–80 years). (See Section 2.2 for further explanation.)

A "baseline scenario" (BS) provides Life-LCA results of the fictional study object over a one-year period, within the "retirement phase" (see Section 3.2) and the "end-of-life phase" (see Section 3.3). Further, the difference in the annual consumption impacts between these two phases is compared and evaluated (see Section 3.3). As this study uses mainly secondary data, the consumption behavior of the fictional study object strives to represent the statistical average of an older adult in Germany as far as possible. Therefore, no differentiation is made between the sexes, and where appropriate, the median of both sexes is taken. For some of the product categories (see Supplementary Materials (SMs)), the yearly consumption inventory provided in the first Life-LCA case study [4] is based on the 49-year-old entrepreneur Dirk Gratzel and subsequently scaled based on the income and consumption survey conducted by the Federal Statistical Office of Germany (see SMs for an overview of the scaling rates and the selected products) [7].

Further, a sensitivity analysis is carried out for selected product categories (e.g., influence on transportation or different burial options) (see Section 4.2).

2.2. System Boundaries

Two dimensions are assessed: Dimension one, referred to as "the human life cycle", includes changing product consumption behaviors over an individual's life and considers different life stages (childhood and youth stage, early adulthood stage, middle adulthood stage, and old adulthood stage). Dimension two, or "product life cycle", assesses the individual's life cycle of consumed products.

This study focuses on the "old adulthood stage". The Life-LCA method [6] defines the "old adulthood stage" from 60 to death. However, it can be assumed that entering retirement leads to a more significant change in consumption behavior than age does [8]. Therefore, this study quantifies the environmental impacts from the average retirement age in Germany of 65 years to death and beyond [9].

Life stages were first subdivided in a Life-LCA case study, which assessed the environmental impacts of an infant [5] to reduce uncertainty. The same principle is implemented in the presented case study to effectively assess the changing and time-varying consumer behavior and increase the specificity of the results [5]. The two phases of the "old adulthood stage" are defined as follows:

- Retirement phase: 65 to 75 years.
    - The average retirement age in Germany is 64.2 years [9]. Therefore, the "old adulthood stage" is set to start at age 65. It includes ages 65 to 75, as there are apparent differences in physical activity, expenditures, and medical needs compared to individuals over 75 years [10].
- EoL phase: 75 to 80 years.
    - The average death age at which a male dies in Germany is 78. A female individual's average life expectancy is 83 years [11]. Therefore, an average of both life expectancies is used, and the "EoL phase" is defined as the period between 75 and 80 years. All products "consumed" after death (grave maintenance, funeral) are included in the EoL phase; however, they are shown in the new product category "after-life".

As shown in Figure 1, for assessing the Life-LCA of a fictional study object in the "old adulthood stage", the temporal system boundary for dimension one is set to the "retirement phase" and "EoL phase". The system boundaries for dimension two include all services and products consumed during the two life phases considering all impacts from "cradle to grave" (raw material extraction, production, and use and end-of-life phase of the product).

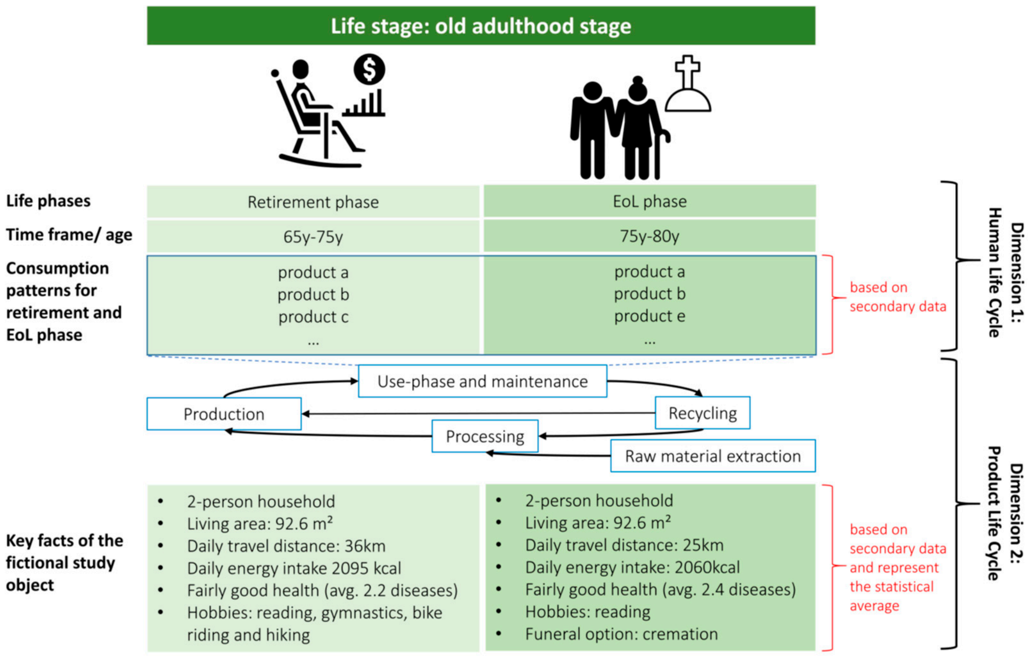


Figure 1. Two-dimensional view in Life-LCA for the "old adulthood stage" based on Goermer et al. [6].

The Life-LCA of the "old adulthood stage" spans over 15 years. Therefore, the results can be determined by adding ten times the one-year results of the "retirement phase" (spanning over ten years) to five times the one-year results of the "EoL phase" (spanning over five years) (see Equation (1)).

$$\text{Life-LCA results of "old adulthood stage"} = 10 \times \text{baseline scenario of "retirement phase"} + 5 \times \text{baseline scenario of the "EoL phase} \quad (1)$$

In addition, as a second scope, the temporal system boundary is set to a one-year period to compare the two phases and scenarios.

Further, the fictional study object's death and funeral are included in the EoL phase. Therefore, an additional "after-life" product category is added. (See Section 2.4.2 for an overview of all product categories.)

Moreover, it is assumed that the fictional study object lives in a 2-person household, as more than 60% of older adults (60+) live in an average household size of 1.7 persons [12]. The consumption of shared products is allocated 1:1 to the fictional study object (e.g., electricity and thermal energy consumption of a 2-person household).

Financial investment, insurance, and products consumed by the children and grandchildren of the fictional study object are excluded. Figure 1 shows the key facts of the fictional study objects for both life phases across the most impactful product categories—transport, energy and water, housing, food, as well as hobbies and leisure.

2.3. Impact Assessment

In order to broaden the scope of the Life-LCA application and generate new insights, the impact categories abiotic resource depletion for elements (ADP-e) and fossil fuels (ADP-f) and human toxicity (HT) cancer and non-cancer are analyzed. Further, for comparability purposes with previous Life-LCA case studies, climate change (GWP), acidification (AP), eutrophication (EP), and photochemical ozone creation (POCP) are assessed and discussed separately (see Section 4.3).

HT cancer and HT non-cancer are chosen as they assess the effects on human health from exposure to toxic substances due to inhalation of air, consumption of food/water, and dermal penetration [13]. However, it must be stated that this impact assessment method has a lower maturity than established ones like GWP [14].

ADP-e and ADP-f refer to the use of abiotic resources (elements) and fossil fuels.

The LCIA method "CML 2001- IA. 2016" is used for the product categories ADP-e, ADP-f, GWP, ADP, EP, and POCP, as it is one of the most applied methods for assessing environmental impacts [15]. The LCIA method 'Environmental Footprint 3.0' [16] is used for the impact category HT cancer and non-cancer.

2.4. Life Cycle Inventory

This chapter outlines the method of data collection and allocations made (see Section 2.4.1). Furthermore, the modeled product clusters with their underlying datasets are presented (see Section 2.4.2).

2.4.1. Data Collection and Allocation

An annual consumption inventory for all product categories is established for the "retirement phase" and the "EoL phase". Each product cluster is allocated to a pre-defined product category (e.g., product cluster "shoes" allocated to the category "clothes and jewelry"). (See Section 2.4.2 for an overview of all product categories.) An Excel sheet is created to collect data and document the yearly consumption of products and their corresponding units. (See SM for an overview of the consumption inventory.)

Where available, data for the consumption inventory are obtained from the secondary literature; otherwise, they are calculated by scaling the annual consumption values of a 49-year-old human being from the first Life-LCA case study [4]. The scaling rates (see SMs for an overview of scaling rates and examples for calculation) are determined considering the expenditure of certain products in different life phases and how they change over time (before 65 years, between 65 and 69 years, and after 69 years). The expenditures for the different product clusters are based on the income and consumption survey of private households by the Federal Statistical Office in Germany [7].

Further allocation procedures and assumptions for selected product categories are presented in the following:

- After-Life

Concerning funeral choices in Germany, cremation is the most popular choice (76%), followed by traditional burial (24%) [17]. Hence, it is assumed that the fictional study object in the "baseline scenario" would choose this method and that the urn would be made of the commonly used material stainless steel [18]. On average, a single cremation process requires approx. 200 kWh of natural gas and 50 kWh of electricity [19]. In a separate sensitivity analysis, the environmental impacts of both funeral choices are compared (see Section 4.2), assuming that the grave surface area is 3 m^2 [20] and that the water demand of a cemetery is 0.1 L per m^2 and day [21]. Further, it is assumed that the grave plot is sold for 25 years [22].

- Energy and water

An RWTH report [23] shows that the average electricity consumption of a 2-person household in the "old adulthood stage" is approx. 3545 kWh/a, whereas the total energy consumption of a 2-person household is assumed to be 18,817 kWh per year [24]. Half of the environmental impacts caused by energy consumption are allocated to the fictional study object.

Moreover, per capita water usage in Germany is approx. 47.085 L p/a [25]. The current breakdown of renewable energy sources for thermal heating in Germany is 86% biomass and -gas, 4.2% solar energy, and 9.8% geothermal energy [26]. Hence, it is assumed that biomass and -gas represent the primary renewable energy sources to meet the thermal energy demand of the fictional study object.

- Food

The annual consumption values for "food" are based on the study by Heuer et al. [27]. The report gives an overview of the average daily food consumption by gender and age group. It is assumed that there are no changes in consumption behavior for "food" between the "retirement phase" and "EoL phase", as the difference in average daily energy intake of an individual between the ages of 65 and 74 years (2095 kcal/day) and 75 and 84 years (2060 kcal/day) is negligibly small [28].

- House

For the product category "house", the living space of the fictional study object is assumed to be 92.6 m^2. This value represents the average living space of an older adult over 65 in Germany (approx. 111 m^2 for homeowners and 69 m^2 for tenant households) [29].

- Transport

From the retirement age onwards, the daily distance traveled by different modes of transport decreases significantly. The main travel purposes for individuals aged 60–69 in Germany are accompanying purposes (5%) (e.g., doctor appointment of a spouse), leisure (28.5%), errands (18.5%) (e.g., short travels to the post office, dry cleaners, car wash), shopping (23.5%), and commute-/work-related travel (21%) [30]. Due to the scope of this case study, all work-related travel and commuting are neglected.

A study by the Federal Ministry of Transport and Digital Infrastructure [30] states that individuals aged 60–69 travel a daily distance of approx. 36 km. For the age group 70–79 years, this value is 25 km. No differentiation is made between the "driver" and "passenger" for the daily traveled distance by motorized private transportation (e.g., privately owned cars). The total daily distance is combined and half is allocated to the fictional study object as all car rides are assumed to be shared with their partner. Furthermore, distances covered by "other transport" methods (e.g., taxi and car-sharing) are allocated to the product cluster "diesel car", as 85% of all German taxis are run by diesel [30,31].

2.4.2. Modeling of Product Clusters

The two common LCA databases GaBi (content version 2022.2) [32] and Ecoinvent 3.5 [33] are used for modeling all product clusters. (See SMs for an overview of data source types and datasets used for modeling a cluster.) In the case of similar datasets in both databases, GaBi is preferred according to the hierarchy of datasets for modeling [4].

Figure 2 shows an overview of the relative shares of data sources for each product category. "Reference materials" are chosen for product clusters where the average material composition is unknown or the product datasets are unavailable in the databases. Where a product is predominantly composed of one material, it is modeled based on that specific material dataset. The term "Proxy, own model" refers to products that are modeled based on their average material composition. Additionally, some proxies are taken from the first Life-LCA case study (referred to as "Proxy, Bossek et al., (2021)") as information from the secondary literature is lacking.

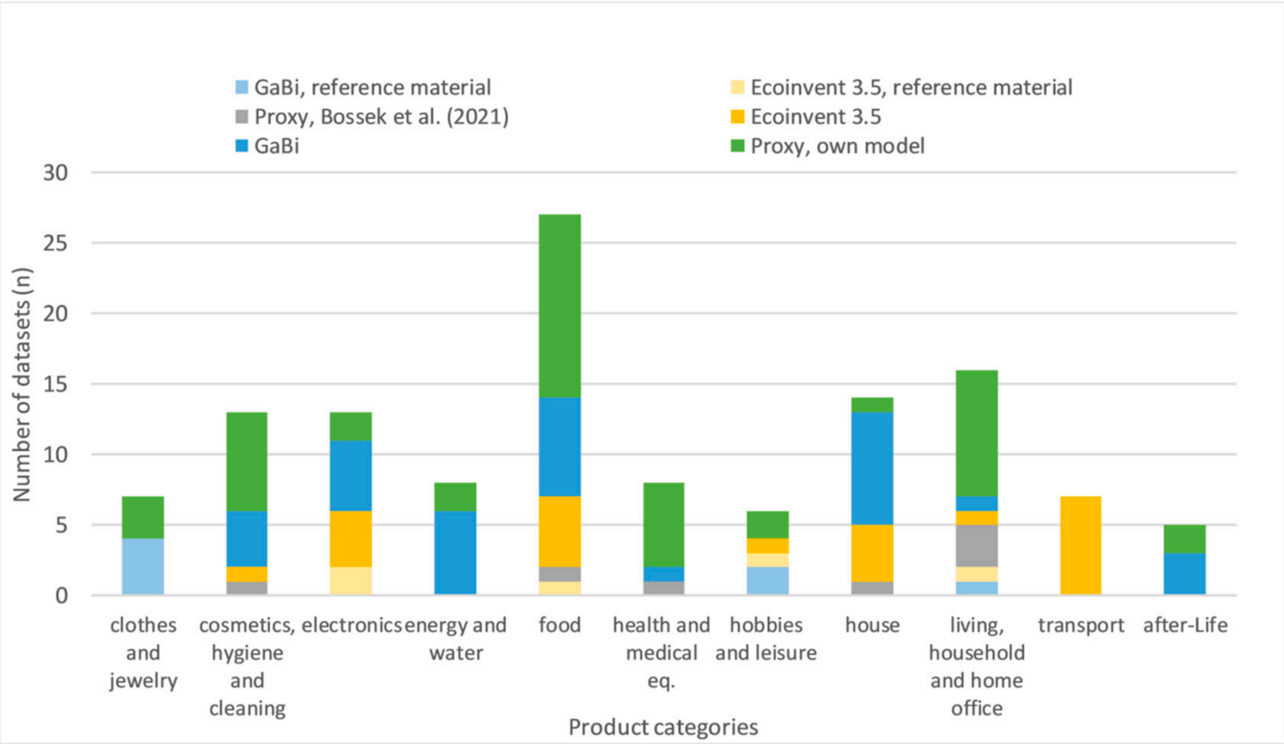


Figure 2. Relative shares of data sources for each product category.

"Proxy, own model" has a significant share, especially for the product categories "food", "health and medical equipment", as well as "living, household, and accessories". The high percentile is because general mixes are modeled for certain food products (e.g., meat is modeled based on the general meat consumption mix in Germany, which consists of beef (17.5%), pork (58%), and poultry (24.5%)). General mixes are created either to simplify future studies or because available secondary data are based on generic values. As yearly food consumption was based on the study of Heuer et al. [28], new products had to be modeled.

A total of 11 product categories are defined based on the first Life-LCA case study [4], which covered 124 product clusters.

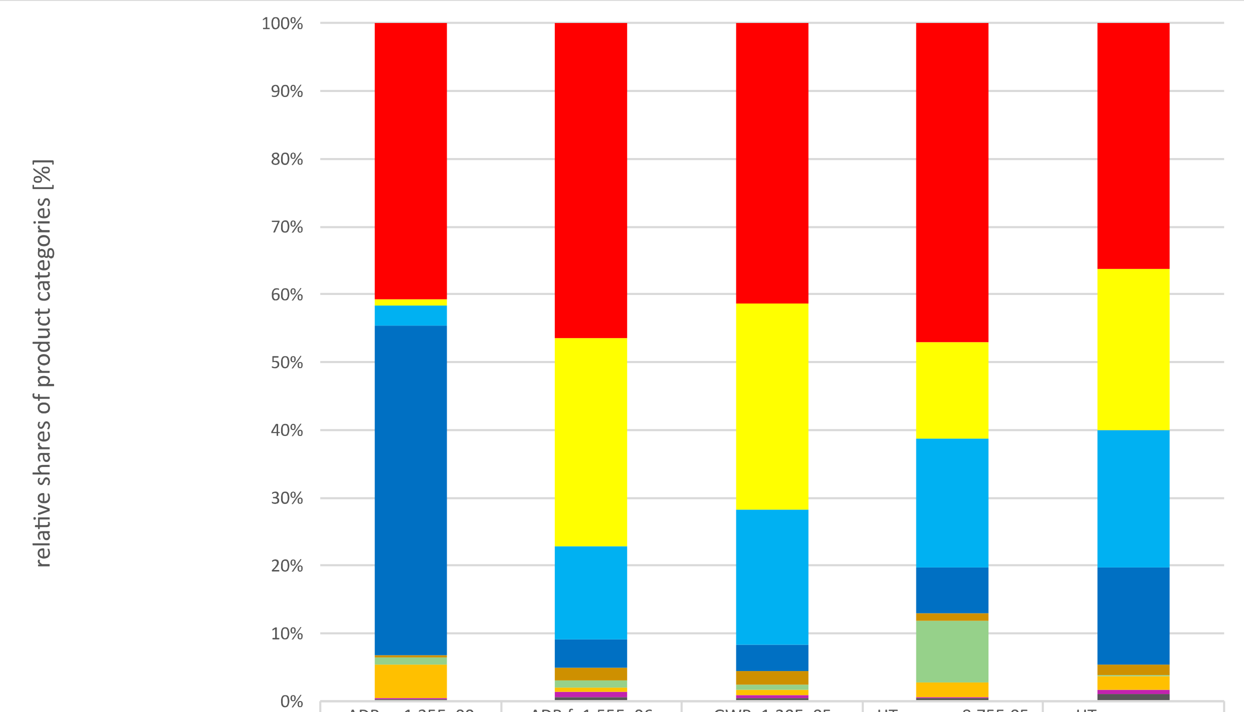
Overall, seven "Proxy, Bossek et al., (2021)" are used. Forty-seven product clusters are newly modeled ("Proxy, own model"). The clusters "clothes", "shoes", "sanitary ware", "furniture", and "tableware" represent the average material composition of the global market. Cereal represents the European mix and consists of wheat, maize, barley, rye, and oat. Finally, the clusters "electricity, conventional energy", "electricity, renewable electricity", "fruit", "meat", and "vegetable" represent the German market.

3. Results

The following chapter presents the results for the impact categories GWP, ADP-e, ADP-f, HT cancer, and HT non-cancer for the "old adulthood stage" (see Section 3.1), the "retirement phase" (see Section 3.2), and the "EoL phase" (see Section 3.3). The results for AP, EP, and POCP can be found in detail in the Supplementary Materials and are briefly discussed in comparison with the results of the first Life-LCA case study in the discussion part (see Section 4.3).

3.1. Life-LCA in the Old Adulthood Stage

Figure 3 shows the Life-LCA results in the "old adulthood stage" over 15 years. The results for GWP add up to 120 t CO_2-eq, for ADP-e to 1.35 kg Sb-eq, for ADP-f to 1.55 TJ, for HT cancer to 0.00009 CTUh, and for HT non-cancer to 0.002 CTUh. For GWP, this equates to an annual impact of 8 t CO_2-eq.



	ADP-e: 1.35E+00 [kg Sb eq.]	ADP-f: 1.55E+06 [MJ]	GWP: 1.20E+05 [kg CO2-eq.]	HT cancer: 8.75E-05 [CTUh]	HT non-cancer: 2.22E-03 [CTUh]
transport	5.49E-01	7.17E+05	4.97E+04	4.11E-05	8.02E-04
energy and water	1.24E-02	4.76E+05	3.68E+04	1.24E-05	5.27E-04
food	3.96E-02	2.13E+05	2.39E+04	1.67E-05	4.50E-04
electronics	6.56E-01	6.57E+04	4.62E+03	5.97E-06	3.19E-04
house	4.82E-03	2.84E+04	2.43E+03	9.03E-07	3.18E-05
hobbies and leisure	1.57E-02	1.58E+04	1.07E+03	7.94E-06	4.83E-06
living, household and home office	6.62E-02	9.92E+03	7.59E+02	1.98E-06	4.39E-05
cosmetics, hygiene and cleaning	2.39E-03	1.20E+04	5.75E+02	1.68E-07	1.28E-05
clothes and jewelry	2.88E-03	7.03E+03	4.34E+02	2.55E-07	2.19E-05
after-life	5.15E-04	2.33E+03	1.76E+02	4.71E-08	2.81E-06
health and medical eq.	2.79E-05	2.20E+02	1.04E+01	4.03E-08	2.19E-07

Figure 3. Life-LCA old adulthood stage (15 years) results and relative shares by product categories.

In total, the fictional study object traveled 166,000 km using different transportation modes and consumed 141 MWh energy and 706 t of water during the entire "old adulthood stage".

The share of transport is a top contributor for all impact categories (41% for GWP and ADP-e, 46% for ADP-f and HT cancer, and 36% for HT non-cancer) due to traveling 166,000 km using public transportation (15%) as well as private vehicles (85%). As shown in Figure 3, the product categories energy and water (30%) and food (20%) also have a significant share for most impact categories.

In contrast to the other impact categories, electronics showcases a significant share for ADP-e, as it is strongly influenced by resource stocks and their extraction rate [34]. Furthermore, the most contributing clusters for each product category are explained in detail for the "retirement and EoL phase" (see Section 3.3).

3.2. Baseline Scenario of the Retirement Phase

The baseline scenario of the "retirement phase" provides results over a one-year period between the ages of 65 and 75 (see Figure 4).

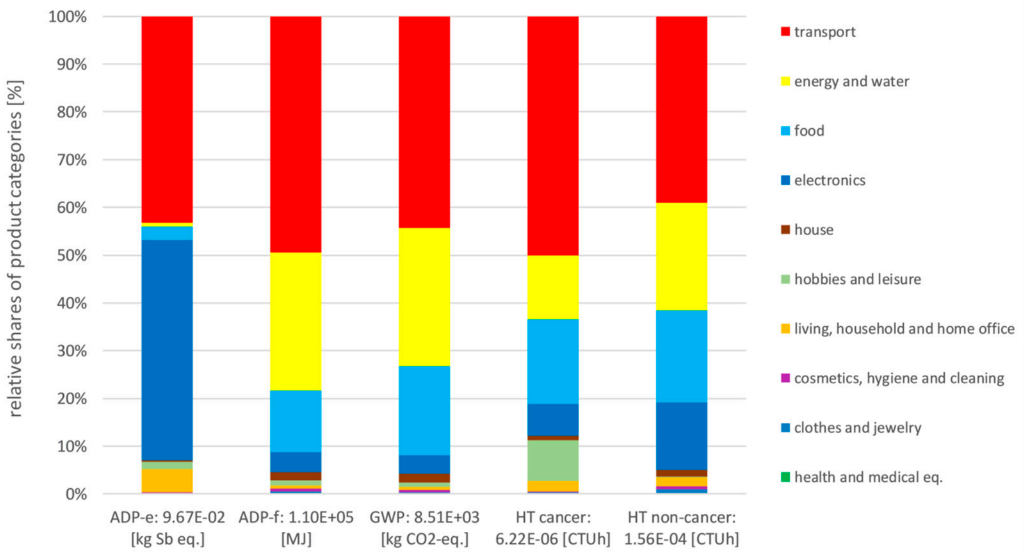


Figure 4. Baseline scenario results of the "retirement phase" on a yearly basis and relative shares of product categories.

Transport is one of the largest contributors across all impact categories. Transport by diesel and petrol cars have a combined relative impact share for ADP-e, ADP-f, GWP, HT cancer, and HT non-cancer of between 96% and 99.5%. It is assumed that the fictional study object travels a total of 12,500 km by various means of transport, 85% by car. Transport by car contributes 20% to the overall kg CO_2-eq emissions.

Energy and water is the second largest contributor to ADP-f (30%), GWP (30%), and HT non-cancer (22%).

Food is also a dominant contributor to GWP (20%), mainly caused by cheese and meat consumption. Both clusters have an impact of 42% on the total kg CO_2-eq emissions for food. Moreover, coffee has among the highest relative impact shares for HT cancer (17%) and HT non-cancer (15%) within the product category "food". Applying fertilizers and pesticides (e.g., zinc and chlorpyrifos pesticides) commonly used during the cultivation of coffee beans is the leading cause. Also, the distribution of coffee (e.g., the transportation of coffee beans to the end user) is responsible for 25% of human toxicity impacts [34].

Moreover, the category "living, household, and accessories" has a small impact on the total ADP-e with a share of only 5% due to the cluster furniture, which has a relative impact share of 76%.

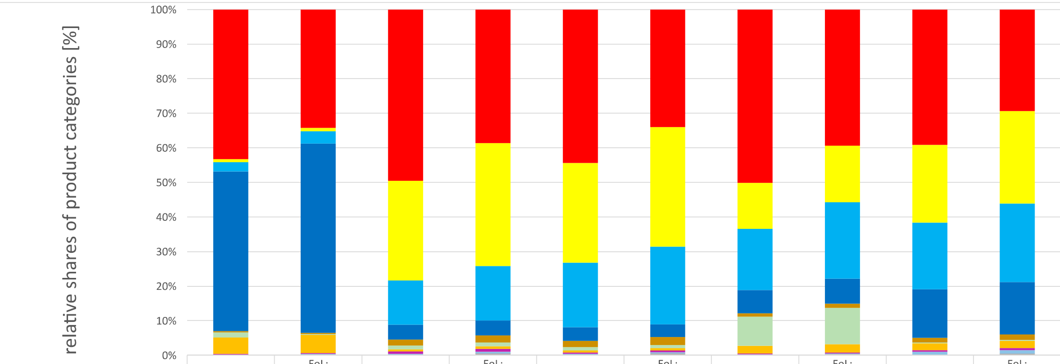
"Electronics" (Computers and notebooks (38%) as well as small electrical appliances (26%)) has a noticeably high impact on ADP-e (46%) due to the use of rare earth metals. Further, electronics, including hard drives, loudspeakers, and headphones, depend on neodymium contributing to ADP-e [35]. Electronics also contributes significantly towards HT non-cancer with a total impact share of 14%, with the clusters of large electrical appliances (35%), computers (21%), and TV (18%) being the main contributors. Electronic products contain harmful substances such as lead, mercury, and certain phthalates and are therefore clustered as hazardous [36].

The category hobbies and leisure has a small impact on HT cancer, with a share of 8%. Gym balls are the leading causes (relative impact share of 95%), as they are commonly made of anti-burst PVC plastic, which contains chemical additives such as phthalates, aliphatics, epoxy, terephthalates, trimellitates, polymerics, and phosphates [37].

The product categories "cosmetics, hygiene and cleaning", "clothes and jewelry", and "health and medical equipment" have a minor impact (0–1%) (see SMs).

3.3. Baseline Scenario of the End-of-Life Phase and Comparison with the Retirement Phase

The baseline scenario of the "EoL phase" provides results over a one-year period of the fictional study object's life between the ages of 75 and 80. Figure 5 visualizes relative shares of each product and impact category and the comparison with the baseline results of the "retirement phase".



	RM: ADP-e: 9.67E-02 [kg Sb eq.]	EoL: ADP-e 7.64E-02 [kg Sb eq.]	RM: ADP-f: 1.10E+05 [MJ]	EoL: ADP-f 8.94E+04 [MJ]	RM: GWP: 8.51E+03 [kg CO2-eq.]	EoL: GWP 7.08E+03 [kg CO2-eq.]	RM: HT cancer: 6.22E-06 [CTUh]	EoL: HT cancer 5.03E-06 [CTUh]	RM: HT non-cancer: 1.56E-04 [CTUh]	EoL: HT non-cancer 1.31E-04 [CTUh]
transport	4.18E-02	2.61E-02	5.44E+04	3.46E+04	3.77E+03	2.40E+03	3.12E-06	1.98E-06	6.09E-05	3.85E-05
energy and water	8.25E-04	8.25E-04	3.17E+04	3.17E+04	2.45E+03	2.45E+03	8.28E-07	8.28E-07	3.51E-05	3.51E-05
food	2.64E-03	2.64E-03	1.42E+04	1.42E+04	1.59E+03	1.59E+03	1.11E-06	1.11E-06	3.00E-05	3.00E-05
electronics	4.47E-02	4.18E-02	4.69E+03	3.76E+03	3.34E+02	2.56E+02	4.15E-07	3.63E-07	2.20E-05	1.98E-05
house	3.21E-04	3.21E-04	1.89E+03	1.89E+03	1.62E+02	1.62E+02	6.02E-08	6.02E-08	2.12E-06	2.12E-06
hobbies and leisure	1.48E-03	1.81E-04	1.10E+03	9.56E+02	7.48E+01	6.51E+01	5.29E-07	5.30E-07	3.30E-07	3.06E-07
living, household and home office	4.60E-03	4.04E-03	6.82E+02	6.19E+02	5.23E+01	4.72E+01	1.36E-07	1.23E-07	3.02E-06	2.73E-06
cosmetics, hygiene and cleaning	1.59E-04	1.59E-04	8.03E+02	8.03E+02	3.83E+01	3.83E+01	1.12E-08	1.12E-08	8.52E-07	8.52E-07
clothes and jewelry	1.93E-04	1.89E-04	4.84E+02	4.37E+02	2.99E+01	2.70E+01	1.76E-08	1.57E-08	1.51E-06	1.35E-06
health and medical eq.	1.45E-06	2.67E-06	1.33E+01	1.74E+01	6.22E-01	8.39E-01	2.06E-09	3.94E-09	1.26E-08	1.85E-08
after-life	0.00E+00	1.03E-04	0.00E+00	4.65E+02	0.00E+00	3.52E+01	0.00E+00	9.42E-09	0.00E+00	5.61E-07

Figure 5. Comparison of the baseline scenarios between the "retirement phase" and "EoL phase" based on relative shares of product categories on a yearly basis.

The results show that in the "EoL phase", "transport" remains one of the largest and most significant contributors across all impact categories. When comparing the baseline scenario results of both phases, it is evident that the "retirement phase" causes a higher environmental impact than the "EoL phase" across all impact categories (see Figure 5). The average yearly GWP in both considered phases is 30% lower than that of an average German adult (11 t CO_2-eq) [38]. In the case of GWP, the total emissions decrease by 17% in the "EoL phase" (see Table 1). The relative impact of transportation by car (diesel and petrol) is >91%. While in the baseline scenario of the "retirement phase", 110,600 km is driven by car, the traveled distance is reduced by 38% in the "EoL phase". Consequently, transport impacts are lower in the "EoL phase".

Table 1. Changes in the GWP results on a yearly basis for the baseline scenario of the retirement and EoL phase.

Product Category	Retirement Phase GWP [kg CO_2-eq]	EoL Phase GWP [kg CO_2-eq]	Changes in %
clothes and jewelry	29.90	27	−9.7%
cosmetics, hygiene, and cleaning	38.30	38	0%
electronics	334	256	−23.4%
energy and water	2450	2450	0%
food	1590	1590	0%
after-life	0	35	0.4%
health and medical equipment	0.62	0.84	34.9%
hobbies and leisure	75	65	−13%
house	162	162	0%
living, household, and home office	52	47	−9.8%
transport	3770	2400	−36.3%
sum	**8502**	**7072**	**−16.8%**

Besides transport, changes in GWP between the two phases for other product categories are small.

For the product categories "electronics", "health and medical equipment", "hobbies and leisure", "living, household and accessories", and "clothes and jewelry", changes in consumption for selected product clusters are assumed. As shown in Table 1, for example, the product cluster clothes decreases by 13% and shoes by 10% in the "EoL phase" compared to the "retirement phase". For electronics, the reduction ranges from 7% (housing infrastructure) to 80% (audio and hifi). These changes have a small impact on the overall results. For GWP, clothes and jewelry result in an impact of 30 kg CO_2-eq in the "retirement phase" and 27 kg CO_2-eq in the "EoL phase", which equates to a reduction of approx. 10% for this specific product category (see Table 1). However, regarding total GWP, the changes in consumption of clothes and jewelry only result in an overall reduction of 0.04%. For the product category electronics, the decrease in GWP in the "EoL phase" equates to only 0–1%.

The product category after-life part of the "EoL phase" consists of three product clusters: urn, casket, and cremation process. "After-life" impacts the five chosen categories little, as the share remains below $\leq$0.5%. In the case of GWP, "after-life" adds an impact of 35.2 kg CO_2-eq and increases the overall GWP of the "retirement phase" by 0.4%. Furthermore, the product cluster urn is the main contributor with a relative share of 92% towards ADP-e due to stainless steel.

4. Discussion

This chapter presents the case study results (see Section 4.1), its limitations, challenges, and future perspectives (see Section 4.2), a sensitivity analysis (see Section 4.3) and presents a comparison of the results with the optimized scenario of the first Life-LCA case study (see Section 4.4).

4.1. General Discussion of the Results

Comparing the results of the "retirement phase" and "EoL phase" shows that consumer behavior changes per life phase. Especially for the product category "transport", the changes significantly impact the overall Life-LCA results within the "old adulthood stage". Therefore, splitting the life stage into two separate phases was essential to determine the most accurate results.

Further, while the "after-life" product category broadens the system boundary and contributes to a more holistic understanding of the "old adulthood stage", it was found to have inconsequential impacts on all evaluated impact categories. These results suggest that Life-LCA studies of the "old adulthood stage" could feasibly exclude the "after-life" category, thereby streamlining the process. Moreover, refining the necessary product categories for analysis, particularly in studies primarily using secondary data, can further simplify the study while reducing the demands of data collection and modeling. For instance, considering the results within a German context, a simplified assessment could solely focus on the product categories of transport, energy and water, and food. These categories account for approx. 80–90% of the environmental impacts across all considered impact categories, except for ADP-e, where electronic products predominantly contribute to the impacts.

However, it is crucial to consider the influence of specific regional consumption patterns. A product category with a minor impact in one region may have a significant impact in another. For instance, in the transportation category, private vehicle use might have a more substantial environmental footprint in countries with less developed public transportation systems compared to countries with efficient public transit. Similarly, in the food category, a shift towards a plant-based diet might have a more pronounced environmental impact in countries where meat consumption is high compared to countries with lower meat consumption rates. Therefore, tailoring Life-LCA studies to reflect local consumption patterns is critical for ensuring accuracy and relevance.

Also, the results show that alterations in consumption habits may result in the redistribution of burdens among the considered impact categories, indicating that optimization measures should consider more than just GWP. For example, replacing meat with plant-based foods could reduce GWP but may unintentionally increase burdens in other impact categories such as EP.

Moreover, the chosen consumption values for "energy and water" represent the statistical average in Germany but do not differentiate between ages. For this reason, assumptions were established (e.g., that the fictional study object lives in a two-person household) to reduce uncertainty when obtaining the energy consumption values.

As mentioned in Section 2.4.2, only GaBi and Ecoinvent databases were used as sources for the modeling of product clusters. The LCA reports, and case studies are not chosen as sources, as in the previous Life-LCA case studies [4,5]. Therefore, result conversions did not occur, and associated uncertainties could be reduced. Additionally, this study does not apply any strict allocation rules. For some product categories (e.g., electricity and thermal energy consumption of a two-person household), a ratio of 1:1 was allocated to the fictional study object. Therefore, long-lasting and shared products (e.g., house, television) with a high burden per product unit show low impacts. Nevertheless, an adequate allocation of burdens in the two-person household is generally missing for most product categories (e.g., allocation of car rides if only one family member runs errands such as grocery shopping).

4.2. Case Study Challenges, Limitations, and Future Perspectives

The major limitation and challenge of the study is that it is mainly based on secondary data. In some cases, the necessary secondary data were unavailable (e.g., average consumption values of products within "living, household, and accessories"), and consumed quantities of specific products had to be obtained from different sources. For instance, for some product categories (see SMs), data were taken from the yearly consumption inventory provided in the first Life-LCA case study [4] based on the 49-year-old entrepreneur Dirk Gratzel and were subsequently scaled based on the income and consumption survey conducted by the Federal Statistical Office of Germany (see SMs for an overview of the scaling rates and the selected products) [7]. Therefore, the values provided for these product categories do not represent the average adult in Germany. Further, the same uncertainties apply to selected products as in the previous Life-LCA case study.

Nevertheless, this study has demonstrated that secondary data collection is more efficient and resource-saving compared to primary data collection. It eliminates the need for familiarization of a study object with the goal and scope of the study, long monitoring phases, ongoing supervision during data collection (e.g., feedback sessions), and primary data evaluation. Furthermore, it suggests the potential value of creating a centralized database with average consumption rates, for example, the average distance traveled per transport means and life stage, as implemented in this study. Such a database would enhance both the precision and efficiency of environmental impact studies and broaden the Life-LCA methodology's application. Readily accessible data could reduce resources spent on primary data collection, simplify comprehensive cradle-to-grave assessments, and ultimately lead to a more nuanced understanding of environmental impacts.

However, while creating a centralized database would bring numerous advantages, it would also present its challenges, notably ensuring the data remain up-to-date to accurately reflect the changes in consumption patterns across different life stages. This could be particularly challenging given the dynamic nature of consumer behaviors, which can shift due to technological advancements, societal changes, policy interventions, and economic factors. On a broader scale, this would require cooperation and coordination among various national and international entities to gather and share the necessary data. In general, the presented approach based on secondary data can serve as a blueprint for similar studies in other countries or regions, not only focusing on studies with similar socio-economic and demographic contexts. Primary data collection should be conducted additionally for specific product categories where existing data are insufficient or lacking. It is also suggested to evaluate the impact of regional discrepancies (e.g., metropole vs. rural areas) as the region in which a person lives also impacts consumer behavior, living space, and energy consumption [39].

Further, existing research often bases macro-scale impact studies of human consumption patterns on Life Cycle Assessments (LCAs) for specific products. The results from these LCAs are then extrapolated to represent overall consumption patterns through various scaling techniques [40,41]. However, most of these studies primarily investigate the impacts of citizens' lifestyles [42,43], with a predominant focus on greenhouse gas emissions using input–output analysis [44,45], or they concentrate on a different regional context or broader scope (e.g., Europe instead of Germany) [40,46]. They overlook the specific product clusters and consumption patterns associated with different stages of the human life cycle, such as the "old adulthood stage" included in this case study.

Another limitation is that gender was not considered, even though it can be an influencing factor affecting the overall consumption pattern and Life-LCA results. (See Section 4.3 for a gender sensitivity analysis on "transport".) Therefore, it is suggested that future studies should carry out a Life-LCA for both genders in all considered product categories to assess and compare the differences in results.

While the presented case study is partly empirical, focusing on data drawn from national statistics and the first Life-LCA case study, the theoretical persuasion lies in extending the system boundaries of the Life-LCA method to cover an unexamined life stage and introducing additional impact categories. Further, the Life-LCA method got adapted with a subdivision into two separate life phases and introduced a new product category, "after life". This can be viewed as a practical contribution to the theory of Life-LCA, expanding its application to make a comprehensive cradle-to-grave assessment for future studies possible.

Moreover, by using the insights from this study and previous Life-LCA case studies, it is now possible to examine unexplored life phases such as adolescence and early childhood or conduct a more detailed analysis of the early adulthood stage (which was estimated using data from a 49-year-old study subject, Dirk, from the initial Life-LCA study) to carry out a comprehensive cradle-to-grave case study. It is suggested to base this comprehensive study on a German context, as all previous case studies were conducted in this regional background. Therefore, the existing datasets and consumption inventories from the previous Life-LCA case studies can be utilized.

Nevertheless, the application of the Life-LCA method and the general framework for assessing a human being's environmental impacts through the LCA is not limited to

Germany. Exploring new regions could reveal interesting new challenges as consumption patterns and environmental impacts differ based on local socio-economic factors, cultural differences, and policy measures. Each region's unique characteristics would require adapted data collection methods, modeling of specific product clusters, and redefining dimension one, the human life cycle, adding complexity to the research.

Furthermore, by setting benchmarks for the environmental impacts of humans across various regions, targeted intervention strategies could be developed for product categories where reduction measures would have the greatest impact. Such information would be particularly useful for policymakers as well as interesting for the general public.

Beyond the typical scenario of linear, healthy aging until death assumed in this study, it is suggested to explore other potential life events that could significantly alter consumption patterns and environmental impacts. Health crises, for example, could lead to hospitalization or necessitate a shift to a care home resulting in changes in consumption behaviors, such as transport or food choices and, therefore, environmental implications. An interdisciplinary approach encompassing gerontology, LCA, and health sciences, among others could provide a holistic view of the environmental implications of life events in the "old adulthood stage".

4.3. Sensitivity Analysis

In the following, the results of the sensitivity analysis for selected product categories and clusters are presented.

- "After-life": traditional burial vs. cremation

In the baseline scenario, the fictional study object is assumed to be cremated after his death, as cremation is Germany's most popular funeral choice, followed by the traditional burial [18]. Thus, product clusters for a traditional burial were modeled, which include "grave maintenance, gardening" and "grave maintenance, irrigation". Results show that a cremation causes a GWP of 35.2 kg CO_2-eq in the EoL phase, while a traditional burial has 22.5 kg CO_2-eq. This equates to a 56% higher impact of cremation than a traditional burial due to the "cremation process" itself, specifically the use of fossil fuels and the high energy needs. Cremation has an overall GWP of 0.15% in the total Life-LCA result for the old adulthood stage, while traditional burial only impacts around 0.1%. Land use, an impact category not yet considered, could potentially present significant impacts in the case of traditional burials compared to cremation.

- "After-life": alternative urn materials

Due to the underlying dataset of "stainless steel" in the "baseline scenario", the product cluster "urn" is the main contributor with a share of 90% of the total ADP-e for the product category "after-life". Alternatively, urns can be made from other materials with lower impact. Thus, the urn was modeled with ceramic and stone. If the urn was to be made from ceramics, it would only have an ADP-e impact with a share of 30%, and the product category "after-life" would have a total ADP-e impact of 0.012 g Sb-eq (on a yearly basis) in the "EoL phase".

Moreover, if the urn was made from stone, "after-life" would only have an ADP-e impact of 0.009 g Sb-eq. Nevertheless, in all cases, the overall contribution of "after-life" towards the total ADP-e in the "EoL phase" is negligibly small (0–1%). Therefore, if the fictional study object was preserved in an urn, the choice of different material compositions of the product would make an insignificant change towards the total environmental impact.

- "Electronics": impact of consumption reduction

Compared to other product categories in the baseline scenario, "electronics" has a contribution of 49% to the total ADP-e impact. When reducing the overall consumption by 30%, the impact reduces by 15% (from 1.35 kg Sb-eq to 1.15 kg Sb-eq). These results showcase the importance of reducing the consumption of electronic devices.

- "Energy and water": conventional energy vs. renewable energy

The energy consumption of the fictional study object is based on the current electricity and thermal energy mix in Germany. In the "baseline scenario", it is assumed that 47% of electricity consumption (778.28 kWh) derives from renewable energy, while 53% (874.12 kWh) stems from conventional energy sources [47]. However, if the current yearly electricity demand for the fictional study object (1652.39 kWh) in Germany was entirely covered by conventional energy, energy impacts would increase their GWP by 21%, amounting to an overall contribution of 35% (44.7 t CO_2-eq) towards the total GWP in the "baseline scenario" of the Life-LCA. In contrast, if the current electricity demand for the fictional study object was covered only by renewable energy, "energy and water" could decrease their GWP by 24% compared to the "baseline scenario". Consequently, "energy and water" would only contribute 25% towards the total GWP. Furthermore, if 100% of the thermal energy consumption was based on renewable energy carriers, the GWP of "energy and water" could also decrease by 24% compared to the "baseline scenario".

In a further step, if both electricity and thermal energy demands were covered by renewable energy, then "energy and water" would only have a GWP of 12.9 t CO_2-eq. The impact can be reduced by 65% for "energy andwater", and the total GWP in the Life-LCA could decrease by 20%.

- "Transport": public transport vs. car transport

If the fictional study object travelled all distances by public transport (local train) instead of petrol and diesel car, GWP for "transport" would decrease by 73%. The GWP would have an impact of 84.3 t CO_2-eq, which is 30% lower than the "baseline scenario". However, there are constraints and limitations to only using public modes of transportation in Germany. Especially in rural regions, the infrastructure for trains and buses is insufficient. Many communities have inadequate connections to the nearest small or midsized cities, and there is a clear need to improve access to public transportation [48]. Approx. 90% of all households own at least one car, and more than 60% of all trips are made by private car [49]. The current infrastructure significantly limits achieving climate goals in the transportation sector, as the urban form and transportation systems are among the primary obstacles to achieving decarbonization within this sector [50].

- "Transport": influence of gender

Furthermore, gender can influence the Life-LCA result. For example, women aged 60–69 travel on average 30% less km than men [30]. Therefore, if the fictional subject object was male, the GWP for "transport" would be 59 t CO_2-eq. In contrast, if the subject was female, the impact would be 38 t CO_2-eq, representing a reduction of approx. 35% compared to the male subject. As a result, a fictional female study subject would have a total GWP of 16% lower than a male subject during the "old adulthood stage" (spanning 15 years).

4.4. Comparison of GWP, AP, EP, and POCP Impacts of the Old Adulthood Stage with the Optimized Scenario Results of the First Life-LCA Case Study and Plausibility Check

The combined average CO_2-eq emissions on a yearly basis for the two life phases under consideration in the old adulthood stage is 7.75 tons, around 20% lower than Dirk's emissions in the optimized scenario (9.5 tons), mainly due to restricted mobility with ongoing age. In comparison with the optimized scenario, all considered impact categories (GWP, AP, EP, and POCP) in the old adulthood stage have lower impacts, except for "food" and "health and medical equipment" (see supplementary materials). The combined average impacts for AP add up to 33 kg SO_2-eq, for EP to 15 kg PO_4-eq, and for POCP to 2.7 kg C_2H_4-eq.

For AP and POCP, the results from the old adulthood stage are 50%, and for EP, they are 35% lower. The relative shares for all product categories show similarly across all considered impact categories. Hence, the difference in the optimized scenario from the first Life-LCA case study will be briefly explained using GWP as an example.

The consumption values for food in the old adulthood stage are based on the average dietary intake of a German who does not follow any particular diet and are twice as high as in the optimized scenario as Dirk adheres to a vegan diet. As a result, the average values still account for meat and dairy products, significant contributors to CO_2-eq emissions.

As age progresses, health and medical equipment's impacts for GWP increase by about 15% in the end-of-life phase. Further, Dirk's living area is twice as large, leading to a 30% higher energy consumption. Additionally, more furniture is present, which increases "living, household, and home office" by approx. 75%.

Dirk owns about twice as many clothes as the average in the old adulthood stage resulting in double the impacts. There is also a substantial reduction (−85%) in "hobbies and leisure" in the old adulthood stage since Dirks's dog was included in the first Life-LCA case study. His hobbies, such as hunting or tennis, are also captured and increased overall emissions.

Transport in the average old adulthood stage scenario is reduced by only 10% for GWP. Although Dirk travels five times as many kilometers as the average, the values almost equalize since he mainly uses public transportation.

The observations suggest that the comparison results and the 20% lower impacts in the old adulthood stage relative to Dirk's results are plausible. However, conducting an additional study with real-life individuals from both life phases and primary data collection would further validate these findings and corroborate the effectiveness of secondary data use in such studies.

5. Conclusions and Outlooks

In the context of the Life-LCA, the impact categories ADP-e, ADP-f, HT cancer, and HT non-cancer were selected for the first time showing valuable insights. Any measures for reduction should consider different impact categories to prevent trade-offs. Further, the Life-LCA database was expanded by modeling specific datasets for the old adulthood stage, adding value and data quality and offering a solid foundation for future case studies. For the first time, secondary data and a fictional study object were used to apply the Life-LCA approach, reducing the assessment's resources and time effort. However, a study with primary data instead of secondary data could be conducted to check the plausibility of the results. Moreover, to further reduce uncertainties, the previously defined "old adulthood stage" was divided into two subdivisions (retirement and EoL phase), enabling a more accurate Life-LCA. A new product category, "after life", expanded the Life-LCA system boundaries. This enhances the practical contribution to the theory of Life-LCA, expanding its application to make a comprehensive cradle-to-grave assessment for future studies possible.

The results underscore the significance of the transport sector across all impact categories in the Life-LCA, indicating the importance of environmentally friendly transport alternatives. In addition, the results showed that the older a person gets, the smaller their footprint becomes, attributable mainly to the individual's restricted mobility. Future research on different influencing factors that affect the overall consumption patterns of an individual (e.g., gender and regional discrepancies) is suggested to face new challenges since regional and socio-economic conditions influence the variations in consumption behaviors and environmental impacts. The unique features of each region would necessitate custom data collection methods and the redefinition of the human life cycle model of dimension one, adding another level of intricacy to the research. In addition, establishing a central database of average data on consumption rates (e.g., yearly traveled distance by diesel car or clothes consumption in kg) and having pre-modeled product mixes (e.g., meat, cereal) for each life stage are recommended to facilitate future modeling efforts and allow for an easier benchmarking.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su151411447/s1. The Supplementary Materials provide LCIA results (1), the consumption inventory (2), data source type and dataset used for product cluster modeling (3), scaling rates (4), and LCIA results II (5).

Author Contributions: Conceptualization, D.B., C.R., V.B. and M.F.; data curation, D.B. and C.R.; investigation, D.B. and C.R.; methodology, D.B. and C.R.; supervision, V.B. and M.F.; writing—original draft, D.B. and C.R.; writing—review and editing, V.B. and M.F. All authors have read and agreed to the published version of the manuscript.

Funding: We acknowledge the support of the Open Access Publication Fund of the TU Berlin.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available in the article and Supplementary Materials.

Conflicts of Interest: The authors declare no conflict of interest.

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