Extended Abstract
6th PLATE 2025 Conference
Aalborg, Denmark, 2-4 July 2025

Exploring Lifetime Modeling Approaches in Life Cycle Assessment of Textiles and Footwear

Agata Costanzo[a, b], Marco Frey[a], Monia Niero[a]
a) Sant'Anna School of Advanced Studies, Interdisciplinary Center on Sustainability and Climate, Pisa, Italy
b) University of Padova, Department of Industrial Engineering, Padova, Italy

Keywords: Lifetime Modeling; Functional Unit (FU); LCA; Durability; Consumer Behavior.

Introduction

The European Union is prioritizing the development of sustainable production and consumption regulations (European Parliament, 2024), with the textile and footwear sector identified as a key focus due to its challenges, including those posed by fast fashion (Faraca G. et al., 2023). In this regard, the upcoming Product Environmental Footprint Category Rules for Apparel and Footwear will define guidelines for evaluating the potential environmental impacts of products in a comparable way.

In this context, Life Cycle Assessment (LCA) plays a crucial role. Indeed, a key factor in ensuring comparability of LCA studies is the functional unit (FU), which aims to define the product's specific function, quantify related flows, and assess the environmental profile. From an operational perspective, FU can be defined by answering four questions: What? How much? How well? How long? (European Parliament, 2024) When considering textiles and footwear products, the last two questions are challenging to represent, as they intrinsically depend on variables such as consumer behavior, product durability, and fashion trends (Laitala & Klepp, 2020). Consumer habits such as usage frequency, care practices, and disposal preferences significantly affect product lifespan. Similarly, the quality and durability of materials determine how long a product can last. Furthermore, rapidly changing fashion trends can shorten products' lifespan, as consumers may discard items that are no longer in style, even if still functional. To capture these aspects, Klepp et al. (2020) proposed to measure garment lifespan in terms of years, number of wears, cleaning cycles, and users. Consequently, the ideal FU should combine all these factors.

However, there is a lack of sufficient knowledge to effectively operationalize this approach and capture these highly variable aspects in LCA modeling. Consequently, this study aims to explore how product lifespan has been modeled in LCA studies of textile and footwear products to initiate a discussion on the most suited approach.

Methods

A literature search was conducted on Scopus, considering publications available up to November 2024, using the combination of keywords reported in Table 1. Our focus was on studies explicitly addressing LCA of textiles and footwear products, which included considerations on product lifetime.

Lifetime	Life Cycle Assessment	Product Category
life service		
service life	Environmental impact	Apparel
service of life	Environmental assessment	Footwear
duration of service	Environmental impact assessment	Textile
lifetime	Life cycle analysis	Cloth
lifespan	Life cycle assessment	Garment
product life	LCA	

Table 1: keywords and terms of literature search

The search yielded 104 articles, 17 of which deemed relevant based on explicit criteria: (i) inclusion of LCA for textiles or footwear, (ii) consideration of lifetime modeling, and (iii) accessibility of methodological details. Selected articles were categorized based on product(s) studied, system boundaries, FU, lifetime modeling approach, and lifetime estimation methods.

Preliminary results

The reviewed studies covered a wide range of products, primarily clothing items, with some studies addressing multiple products simultaneously. T-shirts were the most analyzed product (Amasawa et al., 2023; Farrant et al., 2010; Kjaer et al., 2016; Meng et al., 2024; Meyer et al., 2011; Periyasamy et al., 2017; Proske & Finkbeiner, 2020; Temizel-Sekeryan & Hicks, 2021), followed by trousers (Amasawa et al., 2023; Farrant et al., 2010; Kambanou et al., 2024; Luo et al., 2022; Periyasamy et al., 2017; Zamani et al., 2017) and jackets (André, 2024; Steinberger et al., 2009). Other products, such as shoes (Ferreira et al., 2020), shoe soles (Caraceni et al., 2024), socks (Meyer et al., 2011), dresses (Zamani et al., 2017), and sweaters (Wiedemann et al., 2020), were only reported once. We also included two non-apparel product studies that we deemed relevant: bedsheets (De Saxce et al., 2012) and silver-enabled textiles (Hicks & Theis, 2017). The studies operate within different system boundaries with cradle-to-grave being the most common (13 studies), followed by cradle-to-use (2) and reuse-focused modeling (2).

Concerning FU and lifetime modeling, various approaches were identified:

i) **Number of care cycles** - This approach estimates lifespan based on the number of washes, using values from literature and surveys. For example, t-shirts were modeled with a lifespan of 100 laundering cycles (Hicks et al., 2015; Temizel-Sekeryan & Hicks, 2021), while for jeans, two approaches were followed, one considering average yearly washing cycles (Periyasamy et al., 2017), and the other assuming various frequency and washing scenarios (Luo et al., 2022).

ii) **Combination of the number of wears and care cycles** - Here FU is defined as a function of the number of times a product is worn, often set to a single wear. In this context, care cycles scan product lifetime since they occur with a defined frequency. For example, Steinberger et al. (2009) modeled the lifecycle of a cotton t-shirt and a polyester jacket, considering as FU “100 days of a garment being worn”, which includes variable care cycles for the t-shirt (one every two wearings) and the jacket (three times a season). Zamani et al. (2017) and Sandin et al. (2019), when evaluating several garment types, considered FU of “one average use”.

iii) **Years of use** - In this method, lifetime is measured in years rather than specific usage cycles (Amasawa et al., 2023; André, 2024; Ferreira et al., 2020). Unlike previous approaches, here the use phase consists of many stages, where clothing is either worn, cleaned, or stored.

iv) **Durability-based lifetime estimation** - This approach models lifespan based on the product's intrinsic properties. De Saxce et al. (2012) and Caraceni et al. (2024) applied this method to bed sheets and footwear soles respectively, by conducting mechanical tests to establish durability parameters. This approach focuses on the product’s inherent characteristics (material quality, construction, and design), to estimate its potential lifespan and may be relevant, where durability and performance are key factors. However, it may not fully capture the impact of consumer behavior and usage patterns.

Conclusions

This study explores how the concept of product lifetime has been integrated into LCA studies for textile and footwear products. The complexity of this topic has so far prevented the development of a comprehensive model capable of simultaneously representing the number of wears, service lifespan, and durability features.

While there is substantial literature on consumer behavior, offering valuable data for LCA studies, approaches that define lifespan based on product durability remain underexplored. These durability-based models have the potential to evaluate products' lifespan by leveraging their intrinsic properties and product performance. Moreover, incorporating durability into LCA studies could facilitate the inclusion of product quality metrics, a critical issue for the apparel and footwear sector.

Future research should focus on harmonizing these models by integrating durability metrics with consumer data and developing standardized methodologies for lifetime modeling that improve accuracy and applicability in the textile and footwear sector. A proposal for recommendations will be formulated based on the type of products, FU, and goal of the LCA study.

References

Amasawa, E., Brydges, T., Henninger, C. E., & Kimita, K. (2023). Can rental platforms contribute to more sustainable fashion consumption? Evidence from a mixed-method study. *Cleaner and Responsible Consumption*, *8*(January), 100103. https://doi.org/10.1016/j.clrc.2023.100103

André, H. (2024). Opening the black box of the use phase in circular economy life cycle assessments: Environmental performance of shell jacket reuse. *Journal of Industrial Ecology*, *28*(3), 542–555. https://doi.org/10.1111/jiec.13475

Caraceni, F., Cordara, M., Caelli, C., Brondi, C., Airoldi, F., & Ballarino, A. (2024). Functional Unit definition in a circular economy perspective: Implication for LCA normalisation for a footwear outsole. *Procedia CIRP*, *122*, 737–742. https://doi.org/10.1016/j.procir.2024.01.103

De Saxce, M., Pesnel, S., & Perwuelz, A. (2012). LCA of bed sheets - Some relevant parameters for lifetime assessment. *Journal of Cleaner Production*, *37*, 221–228. https://doi.org/10.1016/j.jclepro.2012.07.012

European Parliament. (2024). *REGULATION (EU) 2024/1781 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL. Establishing a framework for the setting of ecodesign requirements for sustainable products, amending Directive (EU) 2020/1828 and Regulation (EU) 2023/1542 and repealing Directive 2.*

Faraca G., Spiliotopoulos C., Ranea Palma A., Pérez-Camacho M.N., A. F., Bernad Beltran D., Lag Brotons A., Delre A., Pérez Arriba Z., Arcipowska A., La Placa M.G., Wolf O., Sanye Mengual E., Amadei A., Maury T., Ardente F., & Mathieux F. (2023). *Ecodesign for Sustainable Products Regulation - preliminary study on new product priorities*.

Farrant, L., Olsen, S. I., & Wangel, A. (2010). Environmental benefits from reusing clothes. *International Journal of Life Cycle Assessment*, *15*(7), 726–736. https://doi.org/10.1007/s11367-010-0197-y

Ferreira, M. J., Vera V., P., & Costa, P. (2020). LIFE GREENSHOES4ALL – FOOTWEAR ENVIRONMENTAL FOOTPRINT. *8th International Conference on Advanced Materials and Systems (ICAMS)*, 297–302. http://dx.doi.org/10.24264/icams-2020.IV.6

Hicks, A. L., Gilbertson, L. M., Yamani, J. S., Theis, T. L., & Zimmerman, J. B. (2015). Life Cycle Payback Estimates of Nanosilver Enabled Textiles under Different Silver Loading, Release, and Laundering Scenarios Informed by Literature Review. *Environmental Science and Technology*, *49*(13), 7529–7542. https://doi.org/10.1021/acs.est.5b01176

Hicks, A. L., & Theis, T. L. (2017). A comparative life cycle assessment of commercially available household silver-enabled polyester textiles. *International Journal of Life Cycle Assessment*, *22*(2), 256–265. https://doi.org/10.1007/s11367-016-1145-2

Kambanou, M. L., Matschewsky, J., & Carlson, A. (2024). Business models and product designs that prolong the lifetime of construction workwear: Success, failure and environmental impacts. *Resources, Conservation and Recycling*, *206*(April), 107602. https://doi.org/10.1016/j.resconrec.2024.107602

Kjaer, L. L., Pagoropoulos, A., Schmidt, J. H., & McAloone, T. C. (2016). Challenges when evaluating Product/Service-Systems through Life Cycle Assessment. *Journal of Cleaner Production*, *120*, 95–104. https://doi.org/10.1016/j.jclepro.2016.01.048

Klepp, I. G., Laitala, K., & Wiedemann, S. (2020). Clothing lifespans: What should be measured and how. *Sustainability (Switzerland)*, *12*(15), 1–21. https://doi.org/10.3390/su12156219

Laitala, K., & Klepp, I. G. (2020). What affects garment lifespans? International clothing practices based on a wardrobe survey in China, Germany, Japan, the UK, and the USA. *Sustainability (Switzerland)*, *12*(21), 1–47. https://doi.org/10.3390/su12219151

Luo, Y., Wu, X., & Ding, X. (2022). Carbon and water footprints assessment of cotton jeans using the method based on modularity: A full life cycle perspective. *Journal of Cleaner Production*, *332*(December 2021), 130042. https://doi.org/10.1016/j.jclepro.2021.130042

Meng, F., Brandão, M., & Cullen, J. M. (2024). Replacing Plastics with Alternatives Is Worse for Greenhouse Gas Emissions in Most Cases. *Environmental Science and Technology*, *58*(6), 2716–2727. https://doi.org/10.1021/acs.est.3c05191

Meyer, D. E., Curran, M. A., & Gonzalez, M. A. (2011). An examination of silver nanoparticles in socks using screening-level life cycle assessment. *Journal of Nanoparticle Research*, *13*(1), 147–156. https://doi.org/10.1007/s11051-010-0013-4

Periyasamy, A. P., Wiener, J., & Militky, J. (2017). Life-cycle assessment of denim. In *Sustainability in Denim*. Elsevier Ltd. https://doi.org/10.1016/B978-0-08-102043-2.00004-6

Proske, M., & Finkbeiner, M. (2020). Obsolescence in LCA–methodological challenges and solution approaches. *International Journal of Life Cycle Assessment*, *25*(3), 495–507. https://doi.org/10.1007/s11367-019-01710-x

Sandin, G., Roos, S., Spak, B., Zamani, B., & Peters, G. (2019). *Environmental assessment of Swedish clothing consumption* (Issue September). https://doi.org/10.13140/RG.2.2.30502.27205

Steinberger, J. K., Friot, D., Jolliet, O., & Erkman, S. (2009). A spatially explicit life cycle inventory of the global textile chain. *International Journal of Life Cycle Assessment*, *14*(5), 443–455. https://doi.org/10.1007/s11367-009-0078-4

Temizel-Sekeryan, S., & Hicks, A. L. (2021). Cradle-to-grave environmental impact assessment of silver enabled t-shirts: Do nano-specific impacts exceed non nano-specific emissions? *NanoImpact*, *22*(February), 100319. https://doi.org/10.1016/j.impact.2021.100319

Wiedemann, S. G., Biggs, L., Nebel, B., Bauch, K., Laitala, K., Klepp, I. G., Swan, P. G., & Watson, K. (2020). Environmental impacts associated with the production, use, and end-of-life of a woollen garment. *International Journal of Life Cycle Assessment*, *25*(8), 1486–1499. https://doi.org/10.1007/s11367-020-01766-0

Zamani, B., Sandin, G., & Peters, G. M. (2017). Life cycle assessment of clothing libraries: can collaborative consumption reduce the environmental impact of fast fashion? *Journal of Cleaner Production*, *162*, 1368–1375. https://doi.org/10.1016/j.jclepro.2017.06.128