Improving LCA Data Accuracy through Digital Twin–Based Soft Sensors: A Comparative Application in Polymer Extrusion

Mirco Piron[a], Enrico Bovo[b], Giovanni Lucchetta[b], Alessandro Manzardo[a]

[a] 1CESQA (Quality and Environmental Research Centre), University of Padova, Department of Civil, Environmental and Architectural Engineering, Via Marzolo 9, 35131 Padova, Italy

[b] Department of Industrial Engineering, University of Padova, via Venezia 1, 35131 Padova, Italy

E-mail: *mirco.piron@unipd.it*

Life Cycle Assessment (LCA) is widely recognized as a robust methodology for evaluating the environmental impacts of products and processes. However, one of its main limitations is associated with the accuracy of inventory data, especially in industrial contexts where operational conditions are dynamic and highly process-specific. In conventional LCA practice, datasets are typically derived from averaged or generic values, which may not adequately capture the real behavior of continuous production systems. To address this gap, innovative approaches for the generation of accurate and timely data are required.

In this work, a methodological framework—previously developed and published [Piron et al., Journal of Cleaner Production, 2025]—was applied. The framework integrates Digital Twin (DT) technology and soft sensors to enhance the quality of data used in LCA inventories. A soft sensor was implemented to estimate the specific energy consumption of a polymer extrusion process in real time, as a function of screw speed, material hardness, and viscosity.

The methodology was applied to a case study involving the extrusion of ten different PVC-based pipe formulations. A comparative analysis was carried out between a conventional LCA data source approach—based on static, averaged values—and dynamically generated, process-specific data obtained through the soft sensor. In this way, the impact of real-time data integration on the reliability and representativeness of LCA results was assessed, with particular emphasis placed on data accuracy rather than impact reduction.

It was found that the dynamic approach enabled a more detailed characterization of energy consumption variability across different materials and operating conditions. As a result, the resolution of the LCA model was improved, and the risk of bias due to oversimplified assumptions was reduced. Although both approaches produced values in the same order of magnitude for Global Warming Potential (GWP100a), the dynamically generated dataset proved to be more robust and traceable, offering added value in process optimization and material selection.

By focusing on improving data accuracy, the integration of digital tools into LCA workflows is shown to support more transparent, site-specific, and responsive sustainability assessments, in line with the goals of Industry 5.0 and current trends in chemical and process engineering.

Keywords: *Digital Twin, Soft Sensor, Life Cycle Assessment, Polymer Extrusion, Environmental Impact*