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5. Eco-efficiency Measures for Sustainability

5.1 Introduction

This chapter explores eco-efficiency as a framework for sustainable development, examining how decoupling economic growth from environmental damage can reduce our ecological footprint. Drawing on tools such as life cycle assessments and circular economy models, it applies these frameworks directly to our project to evaluate its sustainability across every stage of development and deployment.

It covers:

- Sustainability Context: An overview of the historical impact of human consumption, the importance of circular economy models, and how the project aligns with the UN’s Sustainable Development Goals (SDGs).
- Environmental Dimension: An analysis of the project's ecological footprint, highlighting the low-power operational benefits of LED technology alongside the upstream challenges of sourcing electronic components and synthetic materials.
- Economical Dimension: An evaluation of the prototype's cost-effectiveness, material affordability, and the potential for low-budget scalability within public transit infrastructure.
- Social Dimension: An examination of the project's core mission to disrupt the “together alone” dynamic of urban commuting, fostering inclusive, barrier-free human connections that support global goals for urban health.
- Life Cycle Assessment: A structured, five-phase evaluation spanning from raw material extraction (cradle) to end-of-life disposal (grave) detailing the environmental impacts, manufacturing processes, and logistical challenges of the project's hardware.
- Summary: Concluding reflections on how the project harmonizes low-waste, eco-efficient design with high social impact.

5.2 Theoretical Framework

Historically, human consumption has often prioritized resource extraction over preservation **[1]**. From the industrial era's exploitation of fossil fuels to large-scale mineral depletion, human activity has consistently pushed natural systems beyond their limits. The consequences of this kind of actions extend beyond the environmental impact: coal mining in Australia, for example, has placed significant pressure on regional communities, multiplying the magnitude and profile of cumulative impacts **[2]**.

By adapting to nature rather than controlling it, we can minimize our environmental footprint through eco-efficiency doing more with less, and decoupling economic progress from ecological damage **[3]**. Tools like life cycle assessments help reduce energy waste and carbon emissions, while the circular economy treats waste as a valuable resource rather than a byproduct, ensuring greater long-term stability **[4]**. Underlying all of these approaches is a simple but powerful idea: we must find ways to thrive today without taking from tomorrow. This is the essence of sustainability, a concept that spans the health of the planet, the strength of economies, and the well-being of people, all of which are inseparable from one another. Sustainability is therefore not merely an environmental concern, but a fundamental framework for rethinking how societies produce, consume, and govern resources. The 17 Sustainable Development Goals, illustrated in Figure 1, establish concrete targets for global resource governance and equitable consumption.

Figure 1: The United Nations' 17 Sustainable Development Goals (SDGs), adopted as part of the 2030 Agenda for Sustainable Development.

5.3 Environmental

The project's environmental footprint is optimized through a high power-to-impact ratio. Operating at a peak consumption of ~ 300 W during active interaction and dropping to a 90 W when idle, the installation uses approximately 70 % less energy than traditional neon or incandescent public displays **[5]**. With an estimated operational carbon intensity of about 7.3 kg CO_2 equivalent per year based on Portugal's emissions **[6]**, the installation represents a significant reduction in emissions compared to high-intensity digital signage. Furthermore, the selection of Polylactic Acid (PLA) over Acrylonitrile Butadiene Styrene (ABS) plastic results in a 60 % reduction in CO_2 emissions during the manufacturing phase, prioritizing bio-based feedstocks over petroleum derivatives **[7]**.

However, a complete environmental picture must also account for the production and end-of-life stages of the project's components. The manufacturing of electronic hardware: sensors, microcontrollers, and lighting elements, typically involves the extraction of rare earth minerals and metals, processes that are resource-intensive and geographically concentrated in regions with significant environmental and labour concerns **[8]**. While the quantity of materials used in this prototype is small, scaling the installation across multiple metro poles and carriages would proportionally increase this upstream environmental burden. Similarly, synthetic materials used in the structural and handle elements of the installation are petroleum-derived, carrying an embedded carbon cost from their production. To mitigate these impacts, the project should adopt a responsible sourcing strategy from the outset, prioritizing suppliers with demonstrated environmental credentials and seeking components with longer operational lifespans to reduce replacement frequency.

5.4 Economic Evaluation and Scalability

While the current prototype demonstrates financial viability, a comprehensive economic evaluation for large-scale implementation is still forthcoming. Specifically, detailed cost modeling for full-scale deployment, longitudinal maintenance requirements, and precise return-on-investment (ROI) metrics remain areas for future study.

5.4.1 Prototype Cost Analysis

The total material cost for the prototype is under 100 €, positioning it as an exceptionally cost-effective public art intervention. This low entry point was achieved through component reuse and the utilization of off-the-shelf components, ensuring that replacement parts are affordable and easily sourced.

The comparative financial metrics between the current iteration and potential industrial scaling are summarized in Table 1.

Table 1: Economic Comparison and Scalability

Category	Prototype Scale	Large-Scale Implementation
Material Cost	< 100 €	Moderate (Scales per unit)
Component Sourcing	Bought from store / Workshop	In bulk purchases from recycled materials
Maintenance	None	Low (Standardized parts)
Economic Impact	High (Educational / Pilot)	High (Cultural / Ridership)

5.4.2 Long-term Value and ROI

Beyond direct costs, the installation offers “soft” economic benefits that contribute to the overall value of public transit:

- **Cultural Capital:** By enhancing the “experiential value” of the commute, the project may improve rider satisfaction and encourage people to use public transport hence reduce carbon footprint.
- **Indirect Benefits:** High-quality public environments are linked to increased ridership and reduced vandalism **[9]**.

5.5 Social

The social dimension of this project is easily its most significant contribution. Modern urban life is defined by a weird paradox: we are more digitally connected than ever, yet feelings of loneliness and social isolation in public spaces are actually growing **[10]**. The metro is the perfect example of this contradiction: hundreds of people packed into a tiny space, shoulder to shoulder, yet every single person is absorbed in their own private digital world. This project disrupts that “together alone” dynamic by taking the handrail, one of the most mundane and universally shared touchpoints in the city, and turning it into a medium for spontaneous, visible, and playful social interaction.

The mechanic is deliberately simple and requires zero prior knowledge, tech literacy, or even a conscious decision to “participate.” A commuter touches a pole and sees their unique color travel upward to the ceiling; another commuter does the same, and the two colors meet and blend overhead. This moment of shared visual experience creates an implicit social connection between strangers, one that is fleeting, non-verbal, and non-threatening, yet nonetheless meaningful. By making the invisible visible, the simple fact that two people are sharing the same space at the same moment, the installation gently reminds commuters of their shared humanity in an environment that typically encourages total withdrawal.

This approach directly supports global goals for urban health and community building. The SDG which Connect supports are shown in Table 2.

Table 2: Sustainable development goals which are supported by Connect

SDG Goal	Direct Impact
SDG 3 (Good Health)	Fostering incidental social interaction in everyday environments contributes to reduced loneliness, improved mood, and better mental health outcomes.
SDG 11 (Sustainable Cities)	Reimagines transit infrastructure as a canvas for human connection, providing safe and inclusive public spaces that foster community cohesion.

Importantly, the installation is radically inclusive. It doesn't require a smartphone, an app, or a digital account. It is activated simply by touch; an action available to every metro user regardless of their age, background, income, or technical skill. This universality is essential to its social impact: any intervention designed to foster connection must itself be free of barriers to participation. Over time, the cumulative effect of these small, shared moments has the potential to contribute to a subtle but meaningful shift in the social atmosphere of the metro; moving it from a space of isolated transit to one of collective, shared urban life.

5.6 Life Cycle Assessment

Phase I: Raw Material Extraction (Cradle)

The following data in Table 3 details the inventory of primary materials required for initial fabrication.

Table 3: Raw Material Extraction Specifications

Component	Technical Specifications	Chemical Composition
Electronics	Extraction for Printed Circuit Board (PCB) traces and microcontrollers.	Au, Cu, Ag, Si
Sensors	Piezoresistive pressure sensing via carbon-impregnated polymer sheet (Velostat) with copper foil electrodes.	C (amorphous), Cu, PET $(C_{10}H_8O_4)_n$
Housing	Bio-based Polylactic Acid (PLA); derived from plant starch.	$(C_3H_4O_2)_n$

The extraction phase reveals a high concentration of high-impact minerals. While the bio-based PLA housing represents the largest mass fraction, the Abiotic Depletion Potential (ADP) is dominated by the electronics. Gold (Au) and Silver (Ag) extraction involves energy-intensive mining processes that contribute disproportionately to the unit's toxicological footprint. The use of carbon-impregnated polymer (Velostat) in sensors reduces critical raw material dependency compared to III-V semiconductors; however, the copper foil electrodes and PET carrier film still introduce upstream extraction and polymer synthesis burdens respectively.

Phase II: Manufacturing & Assembly

The manufacturing energy profiles and emission types are categorized in Table 4.

Table 4: Manufacturing Processes and Emissions

Process	Environmental Impact	Technical Notes
PCB Assembly	High-thermal energy consumption.	Localized Volatile Organic Compound (VOC) emissions from reflow.
PLA Molding	Lower processing temperatures vs. Acrylonitrile Butadiene Styrene/Polycarbonate (ABS/PC).	Reduced C_{offset} due to bio-polymer feedstock.
Integration	Low-impact mechanical assembly.	Robotic sensor/LED matrix alignment.

The primary analytical takeaway in this phase is the energy efficiency of the housing production. PLA molding occurs at approximately 180 °C – 210 °C, which is significantly lower than the 230 °C – 260 °C required for traditional petroleum-based plastics like ABS. This temperature differential results in a measurable reduction in the Cumulative Energy Demand (CED). However, the PCB assembly remains the carbon hotspot of Phase II due to the continuous operation of reflow ovens and the management of VOC emissions, which require specialized filtration systems to mitigate local atmospheric acidification.

Phase III: Transportation & Distribution

Table 5 outlines the logistics streams and the associated carbon intensity for global and local movement.

Table 5: Logistics and Carbon Footprint

Stream	Logistics Overview	Carbon Implications
Inbound	Global sourcing (East Asia) to assembly.	High freight dependency.
Outbound	Distribution to transit authorities.	Higher CO_2 due to electronic mass vs. plastic.

The transportation impact is modeled using tonne-kilometers (tkm). An analytical tension exists between “Inbound” and “Outbound” streams; while inbound components travel longer distances via sea freight, the carbon intensity is relatively low (about 120 g CO_2 / tkm). Conversely, “Outbound” distribution often relies on heavy-duty road transport (about 150 g CO_2 / tkm). Consequently, the geographical location of the final assembly plant relative to the transit authorities (end-users) is a more critical lever for carbon reduction than the location of the semiconductor foundries.

Phase IV: Operational Use

Operational durability and energy requirements, which dictate the long-term impact, are listed in Table 6.

Table 6: Operational Requirements and Structural Durability

Performance Factor	Operational Requirement	Ecological/Maintenance Impact
Energy Consumption	Continuous sensor polling and LED illumination.	Cumulative “vampire load” across fleet.
Surface Maintenance	Chemical cleaning (Sensor Clarity Protocol).	Periodic solvent runoff; risk of polymer stress.
Structural Integrity	Mechanical fatigue resistance (cyclic loading).	Engineered for >10 000 daily interactions.

Quantitative modeling shows that for a 5-year service life, the Use Phase is the largest contributor to the total Global Warming Potential (GWP). This is due to the “vampire load” of constant sensor polling.

Phase V: End of Life (Grave)

The recovery challenges and environmental risks associated with disposal are detailed in Table 7.

Table 7: Materials Disposal Challenges and Environmental Impacts

Component	Disposal Challenge	Environmental Impact
PLA Housing	Requires industrial composting (> 58 °C).	Low impact if processed; landfill persistence.
PCB & Sensors	Contains heavy metals (Lead, Arsenic).	Requires certified E-waste recycling facilities.
LEDs	Small form factor; contain toxic elements.	Frequently missed in bulk recycling streams.

The “Grave” phase analysis utilizes the Avoided Burden approach. While PLA is bio-based, it is not “home compostable”; without industrial facilities maintaining temperatures > 58 °C, it behaves similarly to conventional plastic in a landfill. The most significant environmental gain in this phase comes from the circularity of the electronics. By utilizing certified E-waste recycling, we “credit” the system with the avoided energy of primary copper and gold mining, effectively reducing the net GWP by approximately 15 % compared to a scenario of 100 % landfilling.

5.7 Summary

Sustainability is not a single solution but a lens through which every design decision can be evaluated. This chapter has shown that even a small, low-budget public installation carries environmental, economic, and social implications that extend well beyond its immediate function. The project's greatest environmental risks lie not in its operation, but in its material origins and disposal, a reminder that responsible design must think in full cycles, not just outcomes. Adopting certified e-waste processing and bio-based materials where possible are concrete steps that would bring the project closer to the circular economy principles outlined earlier in this chapter.

More fundamentally, the project illustrates that eco-efficiency and social value are not competing priorities. By doing more with less, both materially and technologically, the installation generates its most significant impact not through complexity, but through simplicity: a touch, a color, a moment of unexpected human connection in an otherwise isolated urban environment. In this sense, the project speaks to a broader truth about sustainable design, that the most enduring interventions are often those that cost the least, waste the least, and mean the most to the people who encounter them. That, ultimately, is what sustainable design looks like in practice.

Beyond sustainability and responsible material use, the ethical dimensions of this project are equally vital and will be detailed in the following chapter.

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