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5. Eco-efficiency Measures for Sustainability

Introduction

Eco-efficiency is a strategic management concept that focuses on the delivery of competitively priced goods while progressively reducing ecological impacts and resource intensity throughout the life cycle. For the Screen2Green project, this principle serves as a foundational design constraint. This chapter outlines the strategies implemented to ensure the Smart Pot is a sustainable solution, focusing on global goals, optimized resource management such as optimal use of water and the use of local portuguese biodegradable materials.

European Union Sustainable Development Goals

Sustainable engineering aims to address modern challenges by balancing environmental protection with economic viability and social well-being. This project is grounded in the three pillars of sustainability: environmental responsibility, economic performance, and social equity. This idea is aligned with the 17 Sustainable Development Goals (SDGs) established by the United Nations, which provide a global framework for coordinated climate action **[1]**. Addressing climate change requires not only large-scale systemic transformations but also many small improvements, innovative technologies, and incremental design decisions that collectively reduce environmental impacts and support more resilient consumption patterns. The Screen2Green project goals can be seen in Table 1.

Table 1: SDG

SDG	Connection to Screen2Green Project
Goal 3: Good Health	This goal is focused on promotion of well-being. Screen2Green smart pot aims to reconnect with nature people living in small apartments that have no possibility of having their own garden. Contact with nature reduces stress and mental health problems.
Goal 6: Clean Water and Sanitation	Project aims to consume optimal amount of water by implementing automatic watering system connected to life-cycle of the basil plant, therefore using exact amount of water needed to grow
Goal 12: Responsible Consumption	By utilizing local cork and biodegradable filaments for 3D printing manufacturing process, the product promotes a circular economy and discourages the use of non-recyclable industrial plastics
Goal 13: Climate Action	By selecting carbon-negative materials, such as Portuguese cork Project aims to contributes to the reduction of the greenhouse gas emissions associated with the product's life cycle

Environmental

The environmental assessment of the Smart Pot is divided into two distinct categories: the physical product itself and the operational phase involving the user.

Product Impact

The physical construction of the Smart Pot is designed to meet strict European standards. To minimize hazard waste, all electronic components must comply with the RoHS Directive, which restricts the use of toxic substances like lead and mercury **[2]**, all components will be purchased from local Portuguese retailers. Furthermore, the design adheres to the WEEE Directive, prioritizing a modular assembly that allows for easy disassembly. This ensures that the electronics can be separated from the casing at the end of its life, facilitating efficient recycling **[3]**.

User Impact (Water Consumption Optimization)

The usage phase of the Smart Pot addresses a significant environmental and biological issue: the mismanagement of water in indoor gardening. Research indicates that overwatering is the primary cause of plant death in urban households, as excessive moisture leads to root rot and anaerobic soil conditions **[4]**. Inexperienced users frequently provide too much water, which not only wastes resources but ultimately kills the plant.

The Screen2Green Smart Pot solves this problem by utilizing an automated watering system (using solenoid valve connected to ESP32 board) specifically calibrated for the life cycle of Basil. Basil requires regular irrigation to maintain constant growth but is highly susceptible to fungal diseases if the foliage or soil remains overly saturated **[5]**. By employing moisture sensors, the system provides the exact amount of water needed at the correct intervals. This precision optimizes water consumption and ensures the plant's survival, reducing the environmental waste associated with frequently replacing dead plants.

Energy

The energy strategy for the Screen2Green project focuses on minimizing electrical waste through a streamlined power distribution network and the elimination of high-consumption mechanical actuators. By prioritizing local procurement from Mauser Portugal, the system ensures high-quality components with verified technical specifications tailored for the 2026 market **[6]**.

System Power Architecture

The project utilizes a 12VDC 2A power supply as the primary energy source. This voltage is required to actuate the solenoid valve, while a buck converter (step-down) is employed to efficiently reduce the voltage to 5V for the ESP32 microcontroller and associated relay module. The use of a switching buck converter instead of a linear regulator is a critical eco-efficiency decision, as it significantly reduces heat dissipation and maximizes power conversion efficiency **[7]**.

The ESP32 serves as the central control unit, managing the power distribution to the sensors. While the ESP32 has a peak consumption of 1.2W during Wi-Fi transmission, the system is designed to operate primarily in “Deep Sleep” mode. In this state, only the temperature and soil moisture sensors remain active at milliwatt levels, ensuring that the total daily energy footprint remains minimal **[8]**.

Gravity-Fed Irrigation Efficiency

A defining feature of the Screen2Green energy model is the total absence of an electric water pump. Standard automated pots utilize pumps that require high current spikes and frequent maintenance.

Instead, the project employs a gravity-fed system. The water reservoir is designed in an asymmetric bowl-like shape, positioned above the pot to create sufficient hydrostatic pressure.

The solenoid valve is integrated at the lowest point of this reservoir. Energy is only consumed during the short intervals when the relay activates the valve to release water. By utilizing gravity rather than mechanical pumping, the system reduces its peak power requirements by approximately 70% compared to pump-based alternatives **[9]**.

Materials

The material strategy for the Smart Pot combines a traditional Portuguese resource with modern manufacturing techniques to minimize the carbon footprint.

Cork Materials Research

Cork is the primary material for the pot structure. Since the project is based in Porto, using cork is highly efficient because it is sourced locally, which reduces transportation pollution **[10]**.

Cork is effectively recyclable because its processing generates by-products such as granules and powder that are consistently reused to manufacture agglomerates and composite materials. This practice supports a near-zero-waste lifecycle, where almost all cork material is reintegrated into new products rather than discarded **[11]**.

3D Printing Filament Research

Internal parts of the pot are made using 3D printing. The chosen material is PLA (Polylactic Acid), which is a biodegradable plastic made from renewable plants like corn instead of petroleum. Degradation rate is 1 week to 24 months, being the shortest out of all polymers listed. PLA is a sustainable choice because it can be recycled many times without losing its strength **[12]**.

To further improve the sustainability of the printed components, the project explores the use of cork-infused filaments based on recent research. These materials combine polymers such as ASA with cork powder derived from recycled cork waste, allowing natural content to be incorporated directly into 3D printed parts. Studies show that cork can be added in proportions of up to around 15 to 20 percent by weight before the material becomes too brittle for effective processing. This approach not only increases the renewable fraction of the product but also creates parts with a texture and appearance that better match cork-based elements of the design. At the same time, these composites can contribute to lightweight structures and offer some insulating properties, supporting both functional and environmental goals. By selecting recycled polymers together with cork composites, the 3D printed elements remain aligned with the eco-friendly objectives of the Screen2Green project while relying on experimentally validated material behavior **[13]**.

Economical

Economical aspect of sustainability in the Screen2Green smart pot focuses on balancing between economic growth of the company and long-term value provided for the user of the pot. Company aims to provide value both for itself ensuring growth, like throughout selling maintenance services for the pot, but still providing product with long life-span and high quality components like anti-corrosion sensors and locally provided cork. All materials selected for the pot aim to be repairable and replaceable.

Social

Main goal is to fight with phone addiction, improving everyday life. Screen2Green promotes healthy lifestyle rewarding user for outdoor activities, being within screen-time limits and proper regular care of the pot. By providing gardening experience for people living in small apartments, customers can stay calm and away from anxiety connected to a smartphone use.

Regular feedback from the app makes user to stay motivated. Implemented sensors like temperature and soil moisture help inexperienced users to provide for the plant optimal care. System is not fully automated to give possibility of real life contact with the plant, like giving the feedback to feed the vitamins to the plant when needed. App and the pot promotes regular progress keeping the user motivated and awarded after proper behavior.

Life Cycle Analysis

Table 2 estimates the mass and materials for a gravity-fed pot designed for a medium basil plant. The totals are calculated based on a structural weight of approximately 600 grams, plus the electronic components.

Table 2: Inventory

Component	**Category**	**Mass (g)**	**Notes**
PLA 60 %	Structure	300	Main body and water reservoir
Natural Cork 10%	Bottom	50	Cork base to ensure stability and temperature insulation
Solenoid Valve	Hardware	100	Plastic valve with minimum torque required to open, used in gravity watering system
Power Adapter	Hardware	150	External plug-in power supply
ESP and Relay module	Electronics	30	Main control unit
Sensors and wiring	Electronics	40	Soil and temperature sensors

Figure 1 displays the full LCA.

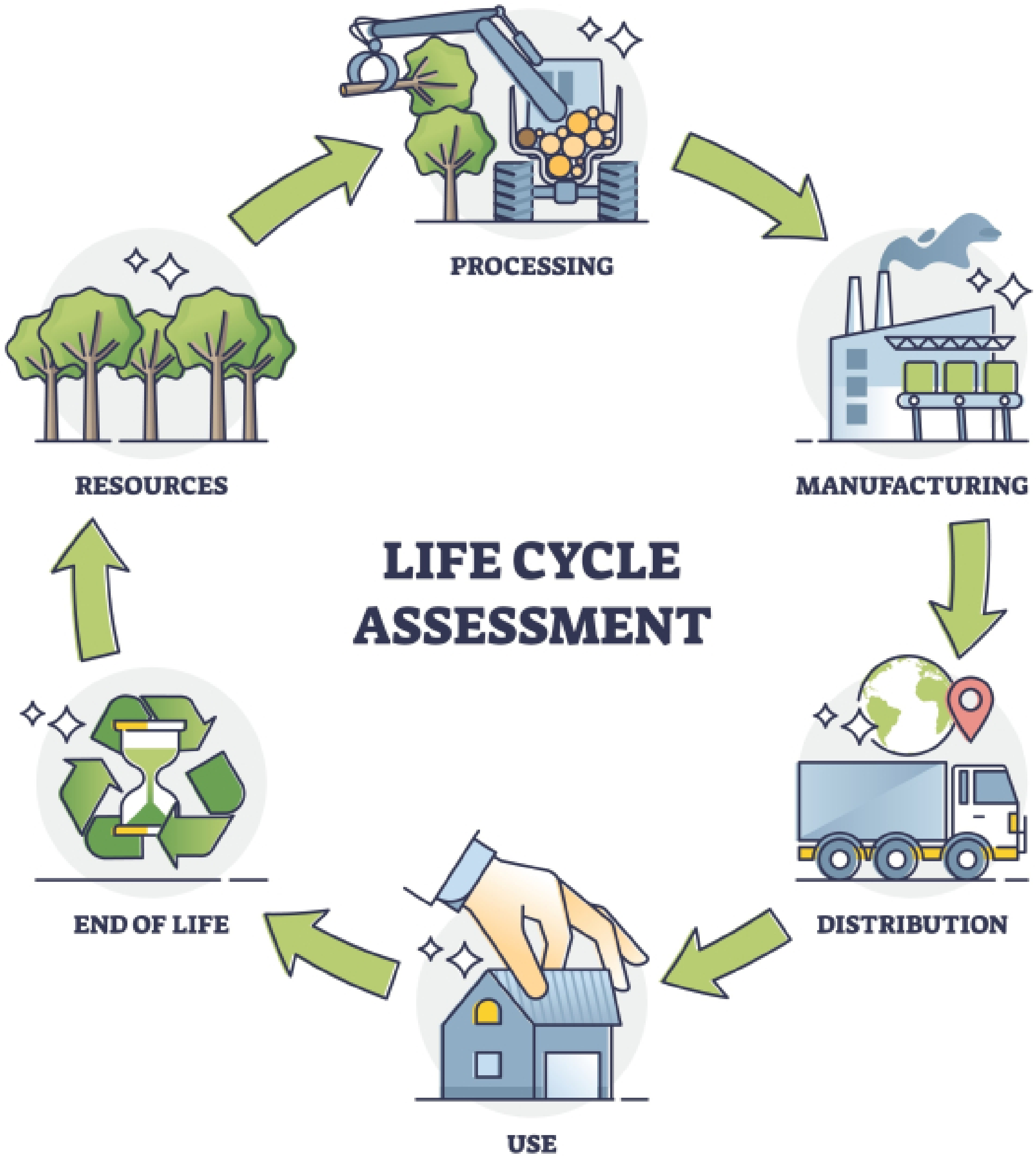

Figure 1: LCA

Resources

- Bio-based Plastics: Polylactic Acid (PLA) derived from corn starch. This choice avoids fossil-fuel-based polymers and reduces the initial carbon footprint.
- Natural Cork: Sourced from Portuguese oak forests. Cork is a carbon-negative material that sequesters approximately 73 kg of CO^2 for every kg produced.
- Sustainable Metals: The solenoid valve and ESP32 use copper and silicon. These are resource-intensive but durable, ensuring the product does not need frequent replacement.

Processing

- PLA Refining: Industrial conversion of raw corn into PLA pellets through milling and fermentation.
- Cork Granulation: Shredding and cleaning natural cork to prepare it for solid base components or filament extrusion.
- Filament Blending: Mixing granulated cork with PLA to create the 30% cork filament. This reduces the total plastic volume by one third.

Manufacturing

- 3D Printing: Structural parts are printed in a Porto facility. This additive process minimizes material waste compared to subtractive manufacturing.
- Renewable Energy: Manufacturing utilizes the Portuguese power grid. It is powered by over 80% renewable sources, resulting in very low manufacturing emissions.
- Toxic-Free Production: PLA and cork printing produce minimal fumes. No toxic chemical baths or heavy industrial melting points are required for the main structure.

Distribution

- Localized Supply Chain: Short transport routes from Alentejo (cork) to Porto (manufacturing). This keeps the “cradle-to-gate” emissions extremely low.
- Lightweight Design: The cork-composite body is significantly lighter than traditional ceramic or heavy plastic. This lowers fuel consumption during final delivery.
- Eco-Packaging: We use recycled cardboard boxes with no plastic fillers. The natural cork base of the pot acts as its own shock absorber during transit.

Use

Features

- Behavioral Detox: The pot serves as a physical mirror for digital habits. Linking plant health to screen time encourages users to reduce phone usage and energy consumption.
- Gravity-Fed System: There is no pump. The system uses a 12VDC solenoid valve and gravity to water the basil. This eliminates a major failure point and reduces energy draw.
- Smart Automation: The ESP32 and soil sensors manage the water tank efficiently. This ensures the plant thrives for 1.5 to 2 weeks without manual effort.

Repair

- Modular Hardware: The solenoid valve, relay module, and sensors are not soldered into the frame. They can be unscrewed and replaced individually.
- Structural Durability: PLA and cork are moisture-resistant. This prevents degradation over years

of use, while modular electronics allow for easy tech upgrades.

End of Life

- Material Separation: The snap-fit design allows users to easily separate the electronics from the bio-based structure at the end of the 2-year lifecycle.
- Composting and Recycling: The natural cork base is 100% compostable. PLA structural parts can be industrially composted or mechanically recycled into new filament.
- Circular Economy: Electronic components like the ESP32 and relay must be sent to WEEE collection points in Porto. This allows for the recovery of precious metals and responsible waste management.

Summary

Provide here the conclusions of this chapter and introduce the next chapter.

This sustainability chapter establishes a comprehensive framework for the Screen2Green Smart Pot by aligning with United Nations Sustainable Development Goals. Environmental impact is minimized through the selection of bio-based Polylactic Acid and carbon-negative Portuguese cork. The mechanical design further prioritizes energy efficiency by utilizing a gravity-fed irrigation system instead of an electric water pump.

A Life Cycle Analysis highlights the benefits of a localized production model in Porto, which significantly reduces transportation-related carbon emissions. The product maintains economic and social value by promoting digital well-being and offering a modular architecture. This structural design facilitates individual component repair and ensures responsible end-of-life management through industrial composting and specialized electronic waste recovery.

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