



A method for assessing circularity, environmental and social sustainability of manufacturing systems

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GCSM

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on Sustainable Manufacturing



CISAMS

Integrated Circularity and
Sustainability Assessment of
Manufacturing Systems



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The Three Dimensions of Integrated Sustainability

1

Circularity

Focuses on **resource loops**, waste minimization, and reuse

2

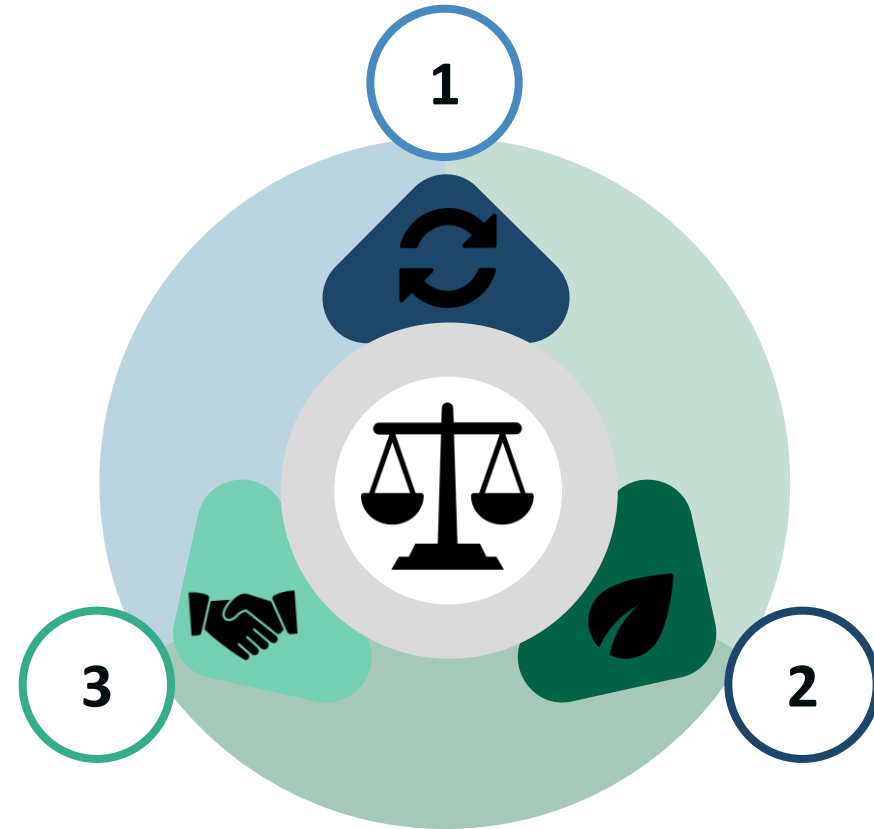
Environmental Sustainability

Emphasizes **carbon footprint**, emissions, pollution, and resource depletion

3

Social Sustainability

Covers **labour conditions**, equity, health & safety, and governance



Why combine Circularity, Environmental & Social dimensions?

CISAMS: What is missing in current literature?



No integrated approach to combine circularity, environmental & social indicators in manufacturing



Limited expert validation or prioritization in existing frameworks



Circular and social metrics remain fragmented, especially compared to standardized economic one

Unified Framework

Combining CE, environmental and social dimensions together

Expert-driven prioritization

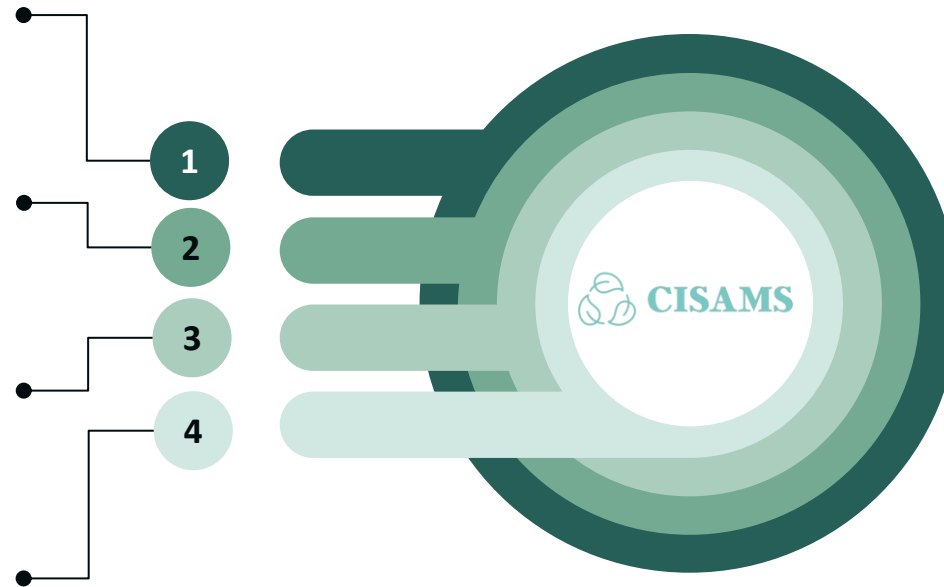
Using Bayesian Best-Worst Method (BWM)

Manufacturing-specific

Standardization for indicator categories

Social Sustainability

Redefined: includes workforce, supply chain, and community impact



Methodological Framework for Integrated Sustainability Assessment



Reviewed academic literature to identify **relevant indicators** specific to **circularity, environmental, and social sustainability in manufacturing.**

Indicators were filtered for **relevance, feasibility, and clarity**, then grouped into **12 circularity, 12 environmental, and 7 social sustainability categories.**



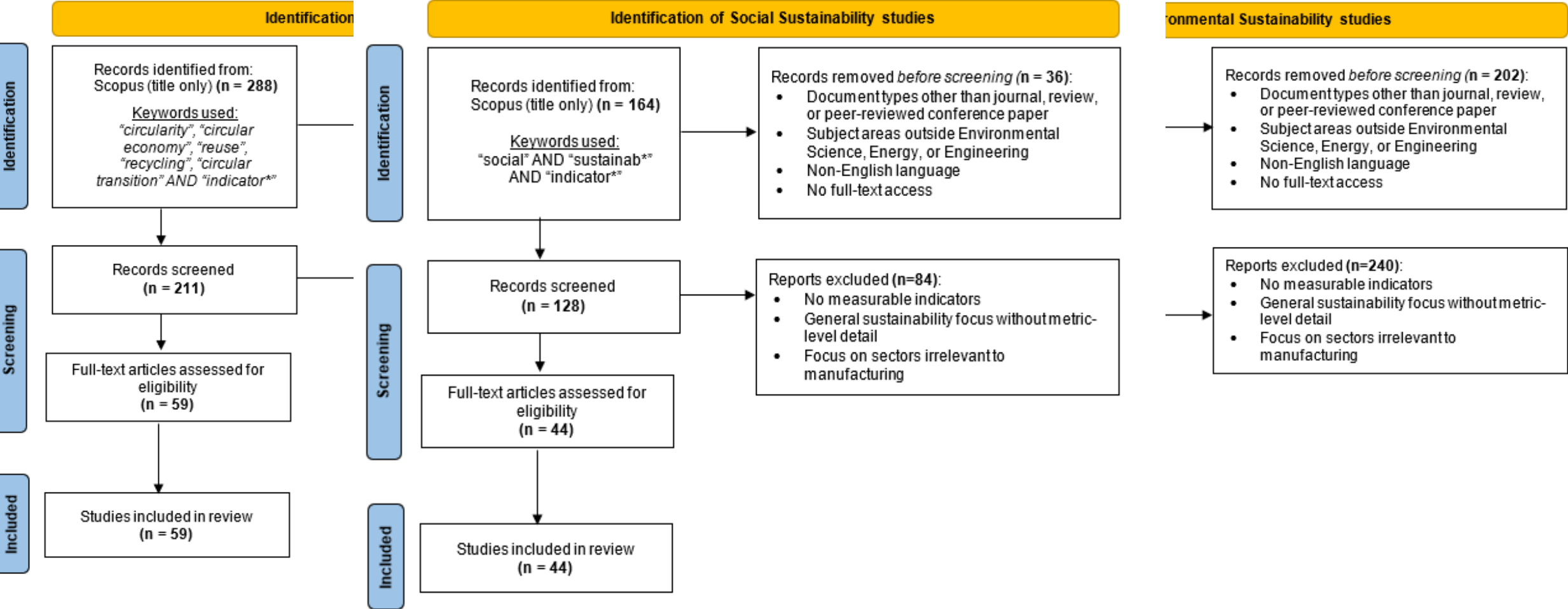
Applied the **Bayesian Best-Worst Method (BWM)** to capture expert input and assign relative weights to each category, using a probabilistic aggregation approach.

The weighted categories formed the basis of a **multi-criteria framework** to assess the sustainability performance of different manufacturing alternatives.

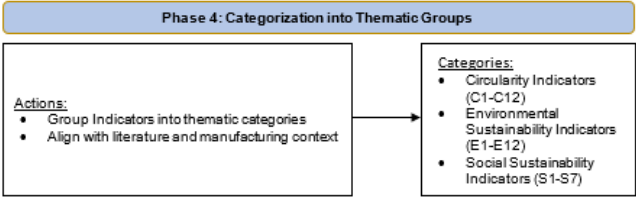
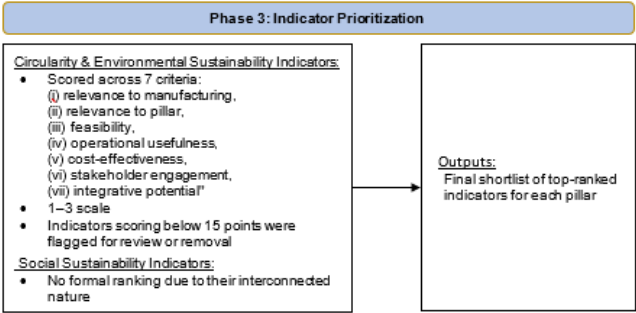
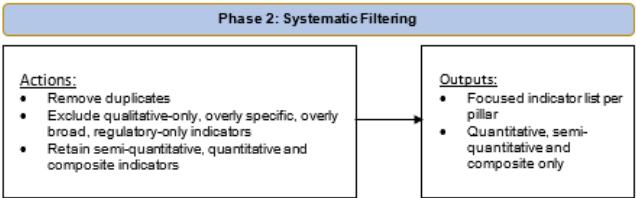
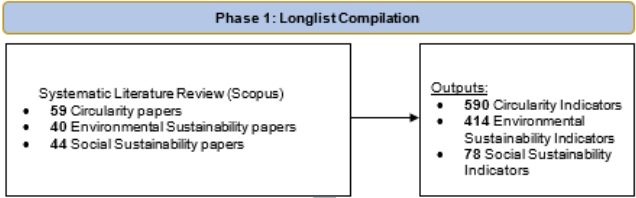


Used the **PROMETHEE-II** method to generate a complete ranking of alternatives, revealing **trade-offs** across circularity, environmental, and social dimensions.

Review Protocol for Identifying Circularity, Environmental and Social Sustainability Studies



Workflow for Identifying and Structuring Sustainability Indicators



Categorization of Indicators Across Sustainability Dimensions

Circularity		Environmental Sustainability		Social Sustainability	
Cat.	Description	Cat.	Description	Cat.	Description
C1	System-Level Circularity	E1	Acidification	S1	Employment
C2	Product Design & Adaptability	E2	Air Quality	S2	Labor Standards
C3	Economic & Value Metrics	E3	Climate Change	S3	Fair Compensation
C4	End-of-Life Management	E4	Env. - Economic Trade-Offs	S4	Ethical Practices
C5	Production Process Efficiency	E5	System-Level Env. Metrics	S5	Health & Safety
C6	Raw Material Composition	E6	Eutrophication	S6	Governance
C7	Durability & Longevity	E7	Ozone & Radiation Impact	S7	Impacts on Society
C8	Remanufacturing & Refurbishing	E8	Packaging	-	-
C9	Resource Efficiency	E9	Material Sustainability	-	-
C10	Waste Flow & Management	E10	Resource Use & Depletion	-	-
C11	Recovery, Reuse & Reutilization	E11	Toxicity	-	-
C12	Recyclability & Recycling	E12	Water Management	-	-

Survey Methodology for Expert-Driven Prioritization

General Survey Research Objective

To derive reliable expert weights for the 31 indicator categories across circularity, environmental, and social dimensions, enabling balanced and standardized assessments in manufacturing

Specific Survey Research Objectives



Gather **expert opinions** across academia, industry, and policy



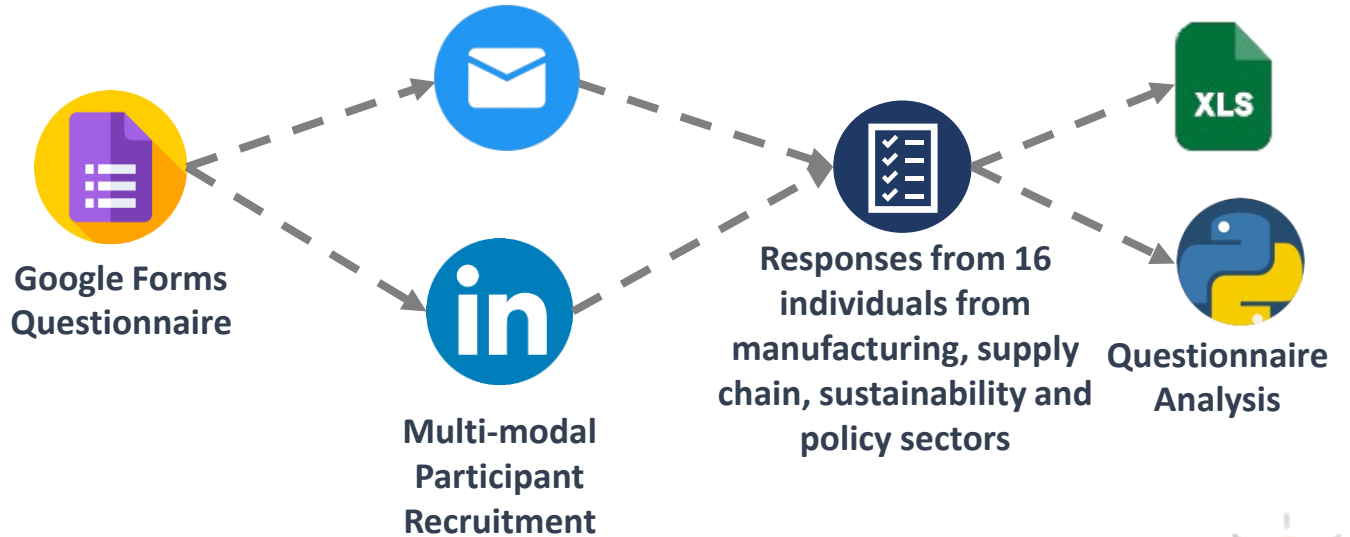
Prioritize indicator categories and generate **relative weights** using the **Bayesian Best-Worst Method (BWM)**



Ensure **consistency** in expert responses through **reliability checks**



Translate **final weights** into a **multi-criteria decision-making model (PROMETHEE-II)**, enabling **performance comparison** across sustainability dimensions



Rationale behind Methodological Choices



The **Bayesian BWM** was adopted for its ability to **model uncertainty** in expert judgments, **tolerate inconsistencies**, and **generate probabilistically aggregated weights**. Compared to the classical BWM, its probabilistic structure enhances robustness, especially with **small sample sizes** or **incomplete comparisons**.



PROMETHEE-II was chosen over other MCDM methods for its capacity to handle **conflicting criteria** without requiring **normalization or compensability**. Its outranking logic supports more **realistic trade-off analysis**, while its full-ranking output offers **clearer decision support** than partial-ranking methods like ELECTRE.

Multi-Criteria Evaluation of Tyre Recycling Alternatives: A case study

Five industrial pathways for EoL tyre valorization, assessed using Circularity, Environmental, and Social indicators

A3: Moulded objects

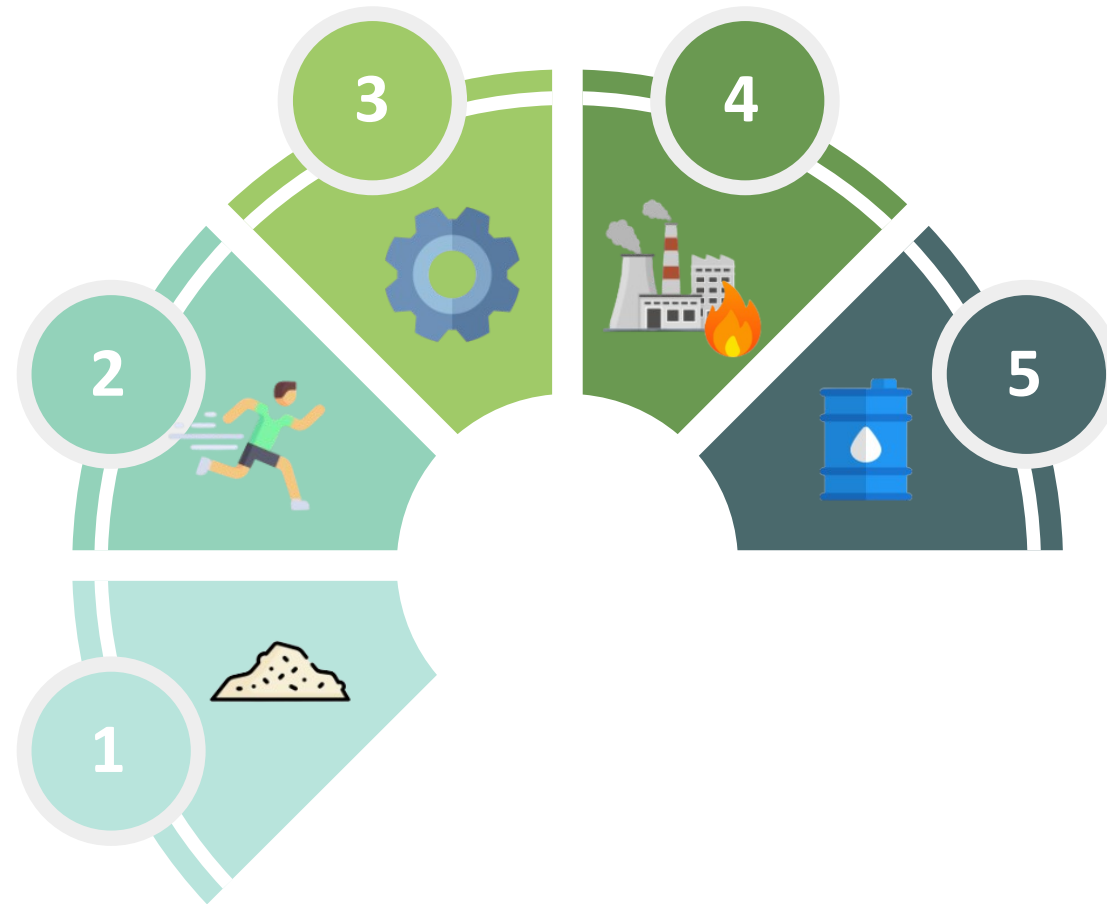
Tyres undergo mechanical devulcanization to be reshaped into moulded goods like mats or industrial parts.

A2: Athletic surfaces

Similar granulation process, but rubber granules are repurposed into running tracks, playgrounds, or sports flooring.

A1. Turf granulation

Tyres are mechanically shredded into granules used as infill material in synthetic turf systems.



A4: Tyre-derived fuel

Tyres are combusted in cement kilns or industrial boilers to recover energy.

A5: Pyrolysis

Tyres are thermochemically decomposed in the absence of oxygen to extract fuel oil, gas, and carbon black.

BWM-Derived Weights for the three Indicator Categories

Research Implications

Best-Worst Method Derived Weights

Table 1. Weights for the C, E and S categories as obtained by MCMC BWM analysis on questionnaire data.

C	Weight(C)	E	Weight(E)	S	Weight(S)
C1	0.1155	E1	0.0724	S1	0.1502
C2	0.0958	E2	0.1047	S2	0.1710
C3	0.0885	E3	0.1109	S3	0.1593
C4	0.0937	E4	0.0749	S4	0.1662
C5	0.0916	E5	0.1070	S5	0.1564
C6	0.0700	E6	0.0629	S6	0.0820
C7	0.0678	E7	0.0623	S7	0.1148
C8	0.0797	E8	0.0494	-	-
C9	0.0673	E9	0.0872	-	-
C10	0.0646	E10	0.0814	-	-
C11	0.0834	E11	0.0954	-	-
C12	0.0820	E12	0.0915	-	-

Method & Data Source

Seven expert decision-makers (1 outlier removed) provided pairwise comparisons for each pillar. Weights were calculated using the **Bayesian Best–Worst Method (BWM)**.

Key Insights

- Highest-weighted categories: **C1 (Circularity), E3 (Environmental Sustainability), S2 (Social)**
- Indicates **priority emphasis** on system-level circularity, climate change, and labour standards before ranking alternatives with PROMETHEE-II.
- These weights directly informed the PROMETHEE-II ranking of alternatives presented next.

Best-Performing Alternatives: Circularity, Environmental, & Social

Top 3 performers for each sustainability dimension

Table 2. Ranking of alternatives from PROMETHEE-II analysis of the case study payoff data

Alt (C)	C Flow	Alt (E)	E Flow	Alt (S)	S Flow
A3	0.711	A3	0.301	A2	0.368
A2	0.433	A1	0.246	A1	0.368
A1	-0.206	A2	0.185	A3	0.129
A5	-0.246	A5	-0.276	A5	-0.412
A4	-0.692	A4	-0.456	A4	-0.453



A1: Turf Granulation



A2: Athletic Surfaces



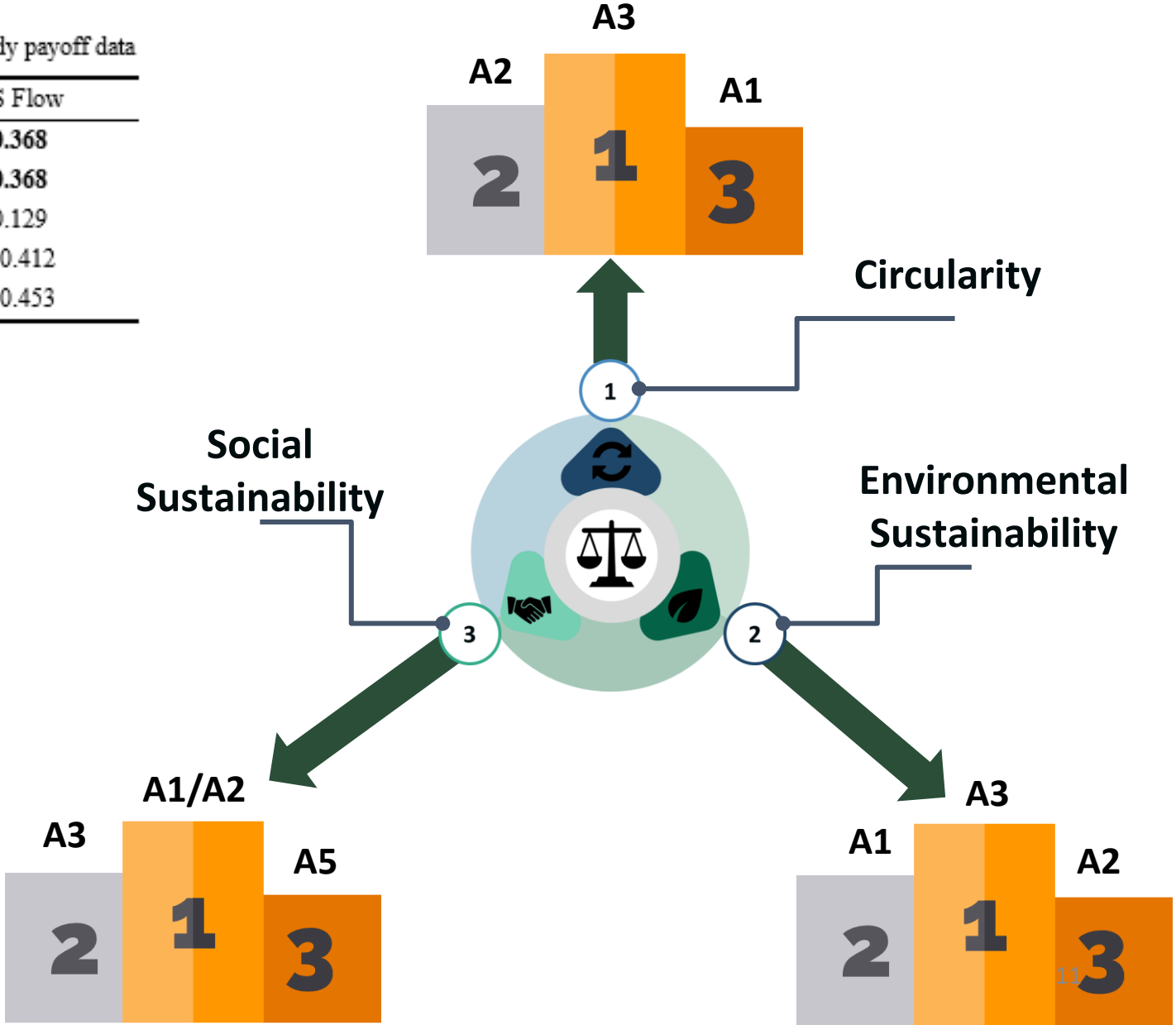
A3: Moulded Objects



A4: Tyre-derived fuel



A5: Pyrolysis



Conclusions, Implications & Future Work

Main Findings

PROMETHEE-II analysis revealed **distinct trade-offs among sustainability pillars**, confirming that alternatives vary in performance and **no single option dominates** across all criteria

Moulded Objects (A3) achieved the highest **Circularity and Environmental Sustainability** scores, showing strong material reuse and low environmental burden

Turf Granulation (A1) and **Athletic Surfaces (A2)** performed best in **Social Sustainability**, reflecting higher employment potential and local economic benefits

Decision-makers should apply the integrated C–E–S framework to **balance these trade-offs**, using **stakeholder-specific weights** to reflect local priorities.

- **Pilot the method** in real manufacturing settings and different regions/sectors
- Re-run BWM with broader panels to **test generalizability** and reduce subjectivity

- **Develop a fully unified decision-support system** that embeds C-E-S criteria into a single MCDA model, enabling simultaneous trade-off analysis and composite scoring
- Explore **hybrid weighting** (Bayesian BWM + data-driven/entropy/CRITIC) to enhance robustness and manage uncertainty

Implications & Future Work



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Thank you!

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