MADE FOR PLANET · PCF SERVICE

Product Carbon Footprint Engine

Methodology specification v1.0 — fashion, footwear and packaging

Aligned with ISO 14067:2018, ISO 14040/14044, GHG Protocol Product Life Cycle Standard and WBCSD PACT Methodology v3.0. EU PEF Circular Footprint Formula available as an end-of-life option.

Mission Sustainability, Gandhinagar · 26 September 2026 · Engine 1.0.0 · Factor library 2026.09-mfp.1

Status chip	Meaning in this document and in the engine's factor library
VERIFIED	Read from the publisher's own document.
PIN	Read from a faithful secondary copy (checksummed mirror, citing paper, public API). Pin to the primary document before any external claim.
CONTESTED	Published, but sources disagree materially or the scope is non-standard. Sensitivity analysis is mandatory.
COMPUTED	Derived by the engine from exact chemistry or a stated formula.

1. What the engine does, and the rule it will not break

The engine calculates the **climate change impact (GWP100) of one declared unit of product** — a T-shirt, a pair of shoes, a box — using attributional, process-based life cycle assessment. It reports a cradle-to-gate figure in the PACT v3 data model and, when asked, a cradle-to-grave figure covering distribution, use and end-of-life.

The rule: the engine never invents a number. Every value it uses is (a) supplied by the company, (b) a cited factor from the library, or (c) exact chemistry. If an input is missing, the calculation stops and returns every missing item at once. Every default the engine does apply is written to an assumptions register that travels with the result.

This is the honest reading of "no assumptions". ISO 14067 and ISO 14044 do not forbid assumptions — allocation, cut-offs and background data are unavoidable — they forbid **undisclosed** ones. The engine therefore makes every assumption explicit, scored and reversible.

Out of scope for v1

- Impact categories other than climate change (water, land, toxicity). PEF-style multi-impact scoring needs licensed EF 3.1 datasets.
- Consequential LCA, avoided-emission claims, offsets and carbon credits. None of these may be netted into a PCF under ISO 14067 or PACT v3.
- Comparative public claims. These need an ISO 14067 critical review by an independent panel.

2. Standards alignment

Requirement	Source rule	Engine implementation
Scope of a PCF for B2B exchange	PACT v3 §3.2.3: cradle-to-gate, stages 1–3 (materials, production, inbound logistics). Outbound logistics reported separately.	`cradle_to_gate` = raw_materials + production + inbound_transport + packaging. Distribution only in `cradle_to_grave`. **VERIFIED**
Cut-off	PACT v3 §3.3.1.2: excluded processes < 3 % of emissions in aggregate (was 5 % in v2); report the share.	`exclusions[]` need an estimate and evidence; ≥ 3 % raises a non-conformance warning. **VERIFIED**
Allocation	ISO 14044 hierarchy; PACT v3 §3.3.1.4: avoid by subdivision, else economic if value ratio > 5, else physical.	Facility data allocated automatically by the PACT ratio test; method written to the register. **VERIFIED**
GWP	PACT v3 §3.2.2 and ISO 14067: latest IPCC AR, 100-yr.	AR6: CO_2 1, CH_4 fossil 29.8, CH_4 non-fossil 27.0, N_2O 273. **PIN** (GHG Protocol reproduction of AR6 Table 7.15)
Biogenic carbon	ISO 14067: report separately. PACT v3 §3.3.2.4: two totals, excl. and incl. uptake; uptake optional if bio-C < 5 %.	Both totals always reported; uptake and emissions from carbon mass balance. **VERIFIED**
Land-use change	PACT v3: dLUC and sLUC included, reported as a separate field.	Split out where the source publishes the share (natural rubber 79 %). Otherwise flagged.
Aircraft	PACT v3 §3.3.2.1: exclude radiative forcing; optional separate field.	Air freight factor without RF; `aircraftGhgEmissions` reported.
Packaging	PACT v3 §3.3.1.1: include; report separately.	`packaging[]` stage; `packagingGhgEmissions` field.

Requirement	Source rule	Engine implementation
Data quality	PACT v3 §4.2: technological, geographical, temporal representativeness, 1 (best)–5; mandatory from 2027.	Scored per line; emission-weighted aggregate (§6).
Primary data share	PACT v3 §4.2: report; computed on absolute emissions excl. uptake.	Two figures: strict (activity and factor primary) and activity-based (§6).
Recycling / end-of-life	GHG Protocol: recycled-content (cut-off) or closed-loop. PEF: Circular Footprint Formula.	`eol_method`: `cutoff` (default, PACT exchange) or `cff`.
Uncertainty & sensitivity	GHG Protocol Ch.10 (qualitative minimum); ISO 14067 sensitivity on significant choices.	Pedigree Monte Carlo + automatic factor-choice sensitivity.

3. Goal and scope inputs

Field	Required	Why
`product.mass_kg`	yes	Mass balance check; PACT `productMassPerDeclaredUnit`.
`product.declared_unit`, `declared_unit_amount`	yes (default 1 piece)	PACT declared unit. A functional unit is added for cradle-to-grave.
`study.boundary`	yes	`cradle_to_gate` or `cradle_to_grave`.
`study.reporting_year`	yes	Temporal representativeness of every factor.
`study.reference_period`	recommended	PACT `referencePeriodStart/End` (activity data period).
`study.gwp_set`	default AR6	Characterisation of gas-split factors and direct emissions.
`study.eol_method`	default cutoff	Recycling allocation approach.
`exclusions[]`	if anything is left out	Proves the < 3 % cut-off.

4. Inventory model and equations

4.1 Materials

Each bill-of-materials line gives the net quantity in the product, the process loss fraction up to the gate, the recycled content R1 and the country of origin. Losses are mass balance, not a guess: the company states them, and the engine accounts for both the extra material and the treatment of the scrap.

```
m_gross = m_net / (1 − L)                              L = loss fraction up to the gate
EF_cut-off = (1 − R1) · E_v + R1 · E_rec               E_v virgin, E_rec recycled-feedstock factor
GHG_material = m_gross · EF
GHG_losses   = Σ_route (m_gross − m_net) · s_route · EF_route
```

A supplier-specific factor (EPD, supplier PCF received through PACT exchange, or measured data) replaces the library factor for that line and counts as primary data. It must carry value, unit, year, geography, source and whether it was third-party verified.

Materials whose factor is a methodological choice — bovine leather, where the share of cattle farming allocated to the hide moves the result between 17 and 110 kg CO_2e/m^2 — have **no default**. The user must name the factor, and the sensitivity table always shows the other choice.

4.2 Processes and allocation

Energy can be given per declared unit or as facility totals for the reference period. Facility totals are allocated to the reference output and scaled to one declared unit:

```
value ratio = max(price_i) / min(price_i)
share_ref = (m_ref · p_ref) / Σ (m_i · p_i)    if ratio > 5      (economic, PACT v3 §3.3.1.4)
share_ref = m_ref / Σ m_i                       otherwise         (physical: mass)
E_per_DU  = E_facility · share_ref · (kg reference output per DU) / m_ref
```

Electricity uses the grid of the country of consumption unless a supplier or contractual factor is supplied. Fuels are recharacterised from their published $CO_2/CH_4/N_2O$ split to the study's GWP set and well-to-tank emissions are added:

```
EF_fuel = CO₂ + CH₄ · GWP_CH4,fossil + N₂O · GWP_N2O + WTT
e.g. industrial coal, AR6: 0.31915 + 0.00003679·29.8 + 0.0000086·273 + 0.05629 = 0.37888 kgCO₂e/kWh
```

Metered energy (`measured: true`) is treated as exact activity data. Anything not metered must carry an activity uncertainty (`activity_gsd`); the engine will not treat an estimate as a measurement. Refrigerant leakage is multiplied by the IPCC GWP of the gas.

4.3 Transport

```
GHG = (m / 1000) · d · EF_mode        t·km basis, well-to-wheel (TTW + WTT)
```

The mass on each leg is stated explicitly (gross material mass inbound, product plus packaging outbound). Air freight is modelled without radiative forcing and reported in the aircraft field, as PACT v3 and ISO 14067 require.

4.4 Use phase (cradle-to-grave only)

Lifetime energy per declared unit times the grid factor of the country of use. The scenario source is mandatory (`use_phase.basis`) — for apparel, PEFCR Apparel & Footwear v3.1 §6.4 Tables 39–42 is the policy-aligned reference. The engine ships no washing defaults because those values could not be verified from the PEFCR text for this release.

4.5 End of life (cradle-to-grave only)

Cut-off (default). Recycling carries only collection and transport; the recycled material leaves the system burden-free and no credit is given. Landfill uses published factors (including methane from degradable carbon). Incineration emits the product's fossil carbon as CO_2 by mass balance, with 100 % oxidation (IPCC 2006 default for MSW incineration); biogenic CO_2 is reported separately; no energy credit is taken.

Circular Footprint Formula (PEF, optional). For a material with recycled content R1 and end-of-life recycling R2 and energy recovery R3:

```
Material : (1 − R1)·E_v + R1·(A·E_rec + (1 − A)·E_v·Qs_in/Qp) + (1 − A)·R2·(E_recEoL − E*_v·Qs_out/Qp)
Energy   : (1 − B)·R3·(E_ER − LHV·X_ER,heat·E_SE,heat − LHV·X_ER,elec·E_SE,elec)
Disposal : (1 − R2 − R3)·E_D
Defaults : B = 0;  A = 0.2 paper, metals, glass;  A = 0.5 plastics.  Qs/Qp, LHV and X_ER must be supplied.
```

A-values for textiles and all Qs/Qp ratios could not be read from PEF Annex C for this release, so the engine requires them as inputs. Because PACT v3 exchanges cut-off based PCFs, a CFF result is flagged as informational for PACT purposes.

4.6 Carbon accounting

Carbon content is computed from polymer repeat units with IUPAC atomic weights — polyethylene $(C_2H_4)_n$ 0.8563, polypropylene 0.8563, PET $(C_{10}H_8O_4)_n$ 0.6250, polyamide 6 0.6369, cellulose $(C_6H_{10}O_5)_n$ 0.4445, polyisoprene 0.8816 kg C/kg COMPUTED. Paper and board use IPCC 2006 Vol.5 Table 2.4 (90 % dry matter, 46 % C of dry, 1 % fossil) VERIFIED.

```
CO₂/C = 44.009 / 12.011 = 3.664
Biogenic uptake        = − Σ C_bio · m_gross · 3.664              (all biogenic inputs)
Biogenic CO₂ emitted   =   Σ C_bio · m_incinerated · 3.664
PCF incl. uptake       =   PCF excl. uptake + uptake + biogenic CO₂ emitted
Fossil CO₂, incineration = C_fossil · m_incinerated · 3.664
```

Biogenic carbon landfilled or sent to recycling is reported as stored or exported. Methane from landfilled biogenic carbon is counted in the PCF and reported as biogenic non-CO_2, which is how PACT v3 structures it.

5. Emission-factor library

5.1 Selection hierarchy

1. Supplier-specific, third-party verified (EPD, verified PCF via PACT exchange).
2. Supplier-specific, unverified (measured data, supplier declarations).
3. National government datasets (CEA for Indian electricity; UK DESNZ conversion factors).
4. Industry association eco-profiles (PlasticsEurope, European Aluminium, worldsteel).
5. Peer-reviewed or institutional LCA studies (ifeu, Textile Exchange, Science of the Total Environment).
6. Proxy from a similar material — only with a technological score of 3 or worse, which the DQR and the uncertainty then carry.

ecoinvent, the reference background database, costs several thousand euros a year per licence. The library is built so each entry can be swapped for an ecoinvent or EF 3.1 process later without changing the engine.

5.2 Factors in library 2026.09-mfp.1 (selected)

Material / activity	Value	Unit	Source	Year	Status
Conventional cotton fibre (incl. LUC)	2.7	$kgCO_2e/kg$	ifeu 2022	2022	PIN
Organic cotton fibre (incl. LUC)	2.3	$kgCO_2e/kg$	ifeu 2022	2022	PIN
Conventional / organic cotton (alternative)	1.808 / 0.978	$kgCO_2e/kg$	Textile Exchange 2014	2014	PIN
PET (polyester proxy), virgin / recycled	3.864 / 2.214	$kgCO_2e/kg$	UK DESNZ 2025	2025	PIN
Polyamide 6	9.1	$kgCO_2e/kg$	PlasticsEurope 2005	2005	VERIFIED
Natural rubber STR20 (79 % dLUC)	7.50	$kgCO_2e/kg$	Cucci et al. 2025, STOTEN	2025	PIN
Bovine leather, incl. farming / tannery only	110 / 17	$kgCO_2e/m^2$	UNIDO (Knoedler)	2017	CONTESTED
Paper, virgin / recycled	1.345 / 1.050	$kgCO_2e/kg$	UK DESNZ 2025	2025	PIN
Board, virgin / recycled	1.200 / 1.098	$kgCO_2e/kg$	UK DESNZ 2025	2025	CONTESTED
LDPE / HDPE / PP, virgin	2.965 / 3.095 / 2.578	$kgCO_2e/kg$	UK DESNZ 2025	2025	PIN
Glass / aluminium / steel, virgin	1.403 / 9.116 / 2.864	$kgCO_2e/kg$	UK DESNZ 2025	2025	PIN
India grid, FY2024-25 (CO_2, generation)	0.710	$kgCO_2/kWh$	CEA CO_2 Baseline Database v21.0	2025	VERIFIED
China / USA / EU grid	0.560 / 0.384 / 0.213	$kgCO_2/kWh$	Ember Global Electricity Review 2025	2024	VERIFIED
Bangladesh / Vietnam / Türkiye grid (life-cycle)	0.696 / 0.461 / 0.475	$kgCO_2e/kWh$	Ember via Our World in Data	2025	PIN
Container ship / HGV avg / air long-haul (WTW)	0.0198 / 0.1252 / 0.6665	$kgCO_2e/t{\cdot}km$	UK DESNZ 2025	2025	PIN

Material / activity	Value	Unit	Source	Year	Status
Landfill: paper / clothing / plastics	1.164 / 0.497 / 0.009	kgCO_2e/kg	UK DESNZ 2025	2025	PIN

Why the board factor is marked contested. DESNZ's generic board factor (1.20 kg CO_2e/kg) is about 2.4× the FEFCO/Cepi European corrugated headline of 491 kg CO_2e/t (2021 data). Until a mill-specific value or the full FEFCO dataset is used, packaging results built on it overstate corrugated board.

Why most DESNZ values are marked PIN. The government servers were unreachable from the build environment, so the values were read from a machine copy that records the SHA-256 checksum of the official 2025 flat file; PET and HDPE were matched to the last digit against Climatiq's public copy. One pass over the official spreadsheet converts them to VERIFIED.

5.3 Known inconsistencies, disclosed

- **GWP basis.** DESNZ is AR5; CEA and Ember are CO_2-only; several eco-profiles pre-date AR5. Only gas-split fuels and direct gas emissions are recharacterised to AR6. The residual error is a few percent for CO_2-dominated factors and is listed in every report.
- **Grid scope.** CEA and Ember factors are generation CO_2 only, without T&D losses or upstream fuel supply, so electricity is understated relative to a full life-cycle factor. Bangladesh, Vietnam and Türkiye use life-cycle values — a different basis. Both are flagged in the output.
- **Geography.** DESNZ factors describe UK consumption. Used for Indian production they score 4 on geographical representativeness, which widens the uncertainty interval.

6. Data quality and primary data share

Indicator (1 best – 5 worst)	Rule used by the engine	Status
Temporal	|reporting year − data year| ≤ 1 → 1; ≤ 2 → 2; ≤ 3 → 3; ≤ 4 → 4; else 5 (PACT v3 implementation by Climatiq).	PIN
Geographical	1 same country; 2 region containing the country (e.g. EU factor, German use); 3 global average; 4 another specific country; 5 unknown.	Provisional — PACT Table 12 wording not yet verified
Technological	1 exact material/process; 2 same material, different variant or boundary; 3 proxy material; declared per library entry or by the user.	Provisional
Aggregate	Mean of each indicator weighted by absolute emissions of each line.	Engine convention, disclosed

```
PDS_strict   = Σ|GHG_i| where activity data AND factor are primary  /  Σ|GHG_i|
PDS_activity = Σ|GHG_i| where activity data are primary             /  Σ|GHG_i|
(both on the PCF excluding biogenic uptake; PACT v3 §4.2)
```

PACT v3 fixes the principle of primary data share but the exact formula was not in the text reviewed, so the engine reports both readings and names them. An unknown upstream supplier score defaults to the worst case (DQR 5, PDS 0 %), as PACT v3 §4.2 requires.

7. Uncertainty and sensitivity

Each inventory line is treated as lognormal with its deterministic value as the median (the ecoinvent convention). Its spread combines the factor's basic uncertainty, the activity-data uncertainty and five pedigree indicators:

```
ln(GSD_total)² = ln(U_basic)² + ln(U_activity)² + Σ_{i=1..5} ln(U_i)²        (Ciroth et al. 2012, Eq.1)
X_line = value · exp(N(0, ln GSD_total)),   10,000 Monte Carlo runs, seed 42
```

Pedigree score	1	2	3	4	5
Reliability	1.00	1.54	1.61	1.69	1.69*
Completeness	1.00	1.03	1.04	1.08	1.08*
Temporal	1.00	1.03	1.10	1.19	1.29
Geographical	1.00	1.04	1.08	1.11	1.11*
Technological	1.00	1.18	1.65	2.08	2.80

Empirical factors from Ciroth, Muller, Weidema and Lesage (2012), Table 24 VERIFIED. * Not available at level 5 in the source; held at the level-4 value. Basic uncertainty defaults to 1 because ecoinvent's Table 10.3 values could not be verified, so the interval is a **lower bound** on the true uncertainty.

Sensitivity. For every material with a published alternative factor, the engine recalculates the total with the alternative and reports the change. This satisfies ISO 14067's requirement to test significant choices and shows the user where supplier data would pay off first.

8. Output

- **PACT v3 block:** `pcfExcludingBiogenicUptake`, `pcfIncludingBiogenicUptake`, `fossilGhgEmissions`, `fossilCarbonContent`, `biogenicCarbonContent`, `landUseChangeGhgEmissions`, `biogenicCO2Uptake`, `biogenicNonCO2Emissions`, `aircraftGhgEmissions`, `packagingEmissionsIncluded`, `packagingGhgEmissions`, `exemptedEmissionsPercent`, `primaryDataShare`, `dqi`, `ipccCharacterizationFactors`, reference period and declared unit.
- **Result block:** both totals, cradle-to-gate and downstream split, by stage, by category (fossil, dLUC, biogenic non-CO_2), biogenic carbon balance, both primary data shares, Monte Carlo median and 95 % interval, exclusion share.
- **Interpretation:** top-8 hotspots, factor-choice sensitivity, assumptions register, warnings, and the full inventory with every line's activity, factor, source and status.

9. Worked examples

Inputs below are **illustrative** (bill of materials, energy, distances and scenarios invented for demonstration); the factors and method are the library's. They show the engine working end to end, not the footprint of a real product.

Product	Boundary	PCF excl. uptake	PCF incl. uptake	95 % interval	Top hotspot	DQR (T / G / Ti)
Cotton T-shirt, 180 g	Cradle-to-grave, cut-off	5.487 kg CO_2e (gate 2.130)	5.148	3.28 – 12.82	Use-phase electricity, 58 %	1.28 / 2.42 / 1.89
Leather shoe, pair, 730 g	Cradle-to-gate (PACT)	52.01 kg CO_2e	50.51	20.1 – 153.3	Leather incl. farming, 93 %	1.98 / 3.02 / 4.71
Corrugated box, 450 g	Cradle-to-grave, CFF	0.843 kg CO_2e (gate 0.700)	0.109	0.51 – 1.72	Board, CFF material term, 60 %	1.95 / 3.85 / 1.00

What the examples teach

- **T-shirt.** Spinning uses facility data: yarn at 3.0 per kg against comber noil at 0.5 gives a value ratio of 6.0, so PACT v3 forces economic allocation (98.4 % to yarn). The cotton factor choice moves the total by up to 6 %; the illustrative washing scenario dominates the cradle-to-grave figure, which is why it must come from the PEFCR.
- **Shoe.** One methodological choice — whether hides carry cattle-farming emissions — changes the result by 78 %. The engine refuses to pick it for the user and shows the alternative. Natural rubber's 79 % land-use share is reported in the dLUC field. The temporal score of 4.7 says the leather data are too old for a confident claim.
- **Box.** With 80 % recycled content and 70 % recycling at end of life, the CFF gives a net recycling credit of −0.026 kg CO_2e. Landfilled board (30 %) adds 0.157 kg CO_2e of methane — more than all converting energy. The biogenic uptake nearly cancels the fossil total in the incl.-uptake figure, which is exactly why PACT reports both.

10. Gaps to close before external claims

#	Gap	Action	Effort
1	DESNZ values are PIN	Open the official 2025 xlsx and re-verify every DESNZ row; switch status to VERIFIED	1 hour
2	No free factors for EVA, SBR, PU foam, elastane, viscose, wool, dyes	Collect supplier EPDs / PACT PCFs; or license ecoinvent / EF 3.1 for background data	ongoing
3	PEF Annex C (A, R2, Qs/Qp) not read	Download Annex C v2.1 and load default parameters per material	half a day
4	Use-phase and EoL defaults for apparel	Load PEFCR A&F v3.1 §6.4 Tables 39–43 and EoL defaults	half a day
5	PACT v3 Table 12 DQR criteria	Replace the provisional geographical and technological rules with the published matrix	2 hours
6	GLEC v3 transport defaults and distance factors	Load GLEC and SFC India default values (India road WTW) to replace UK freight factors for Indian legs	half a day

#	Gap	Action	Effort
7	Board factor 2.4× FEFCO	Use FEFCO/Cepi 2024 dataset or mill-specific data	1 hour
8	Grid factors CO_2-only	Add T&D losses and upstream fuel for India when a published source is found	1 hour
9	Third-party review	ISO 14067 critical review before any public or comparative claim	external

11. Sources

- ISO 14067:2018 Greenhouse gases — Carbon footprint of products (status: confirmed 2024, revision in preparation). https://www.iso.org/standard/71206.html
- WBCSD PACT Methodology v3.0 (30 Apr 2025). https://docs.carbon-transparency.org/ref/methodology/pact-methodology-v3.0.pdf
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- PEFCR Apparel & Footwear v3.1 (29 Apr 2025). https://www.carbonfact.com/hubfs/A&FW_PEFCR_v3.1.pdf
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- FEFCO/Cepi European Database for Corrugated Board LCA. https://www.fefco.org/lca/data
- Ciroth, Muller, Weidema, Lesage (2012) Refining the pedigree matrix approach in ecoinvent. https://lca-net.com/files/Pedigree_report_final_May2012.pdf
- Climatiq, PACT data quality implementation. https://www.climatiq.io/docs/guides/climatiq-product-suite/api/pcf/data-quality
- Background reading supplied: CarbonBright, Ecochain, Sylvera, PRé Sustainability, ecoinvent and Cyient LCA primers (data categories, four ISO phases, boundaries, primary vs secondary data).