Supplementary Material

Manuscript: Production-Phase Carbon Footprint of Photopolymer Resin Workflows for Direct-Print Orthodontic Aligners: A Screening Carbon-Footprint Assessment

Table S1. Monte Carlo input distributions

U = uniform; T = triangular (minimum, mode, maximum). Manufacturer-supplied ranges were mapped to uniform or triangular distributions; single-point values were assigned a triangular distribution with a stated ±10% measurement uncertainty unless noted. N = 10,000 iterations, fixed seed.

Parameter	Workflow	Distribution	Bounds	Source
Print power	A	U	180–250 W	Manufacturer range
Build time	A	U	30–60 min (50–100 µm)	Manufacturer range
Aligners per build	A	U	6–10	Manufacturer
Resin volume	A	T	4 / 5.5 / 7 mL	Manufacturer range, incl. supports
Print power	B	T ±10%	32.4 / 36 / 39.6 W (heating off)	Manufacturer point
Build time	B	T	45 / 60 / 90 min	Representative; manufacturer range 45 min–3 h
Aligners per build	B	U	6–8	Manufacturer
Resin volume	B	T	4 / 5.5 / 7 mL	Manufacturer range, incl. supports
Print power	C	U	76–128 W (light-off to light-on)	Manufacturer range
Build time	C	T ±8%	69 / 75 / 81 min	Manufacturer point
Aligners per build	C	T ±5%	11.4 / 12 / 12.6	Manufacturer point
Resin yield	C	U	120–150 aligners/kg (6.67–8.33 g/aligner)	Manufacturer range

Parameter	Workflow	Distribution	Bounds	Source
Wash power	C	T ±10%	67.5 / 75 / 82.5 W	Manufacturer (iLuxWash)
Wash time	C	T ±10%	7.2 / 8 / 8.8 min	Manufacturer
Drying power	C	T ±10%	850.5 / 945 / 1039.5 W	Manufacturer (LuxOven Pro)
Drying time	C	T ±10%	9 / 10 / 11 min	Manufacturer
Cure power	C	T ±10%	297 / 330 / 363 W	Manufacturer (iLuxCure Pro)
Cure time	C	T ±10%	18 / 20 / 22 min	Manufacturer
Solvent volume	C	T ±10%	22.5 / 25 / 27.5 mL per aligner	Manufacturer (3 L per 120 aligners)
Print power	D	T ±10%	25.9 / 28.75 / 31.6 W	Manufacturer point
Build time	D	U	39–57 min (100–50 μm)	Manufacturer range
Aligners per build	D	T ±5%	4.75 / 5 / 5.25	Manufacturer point
Resin volume	D	T	2.0 / 2.5 / 3.0 mL	Manufacturer point, incl. supports
Cure power (THC2)	A, B, D	T	200 / 230 / 300 W	LED 200 W (manual); 300 W power-supply ceiling; mode interpolated
Cure time	A, B, D	T ±10%	18 / 20 / 22 min	Manufacturer
Cure batch	A, B, D	U	8–9 aligners	Manufacturer
Spin power	A, B, D	T ±10%	45 / 50 / 55 W	Manufacturer (Graphy Spinner)
Spin time	A, B, D	T	3 / 5 / 8 min	Estimate; power confirmed, duration not
Spin batch	A, B, D	U	12–16 aligners	Manufacturer
Failed-print rate	all	T	0 / 0.02 / 0.08	Literature-calibrated (see below)

Parameter	Workflow	Distribution	Bounds	Source
Resin emission factor	all	T	3.0 / 4.523 / 6.5 kg CO_2e/kg	Published range; mode from [32]
Thermoformed burden	comparator	T	3.5 / 4.0 / 4.5 kg CO_2e per series	Literature [12, 14]
Aligners per series	comparator	T	14 / 20 / 30	Clinical literature

Fixed factors and constants

Parameter	Value	Source
Grid emission factor	0.480 kg CO_2e/kWh (2023 global average)	Ember, Global Electricity Review 2024
IPA emission factor	1.85 kg CO_2e/kg	Panagiotopoulou et al. 2023
IPA density	0.785 g/mL at 25 °C	Sigma-Aldrich; NIST WebBook (CAS 67-63-0)
Graphy resin density	1.061 g/mL	Manufacturer
LuxCreo resin density	1.04 g/mL	Manufacturer

Failed-print rate

The rate is sampled as T(0, 0.02, 0.08) and applied as a factor of 1/(1 − r) to the printing electricity and resin terms only. No published failure rate specific to photopolymer printing of dental appliances was found, and none is claimed here. The manufacturers consulted report near-zero failure with experienced operators; the 8% upper bound is a conservative ceiling adopted by the authors, not a measured value. A single value is drawn per iteration and used for every term in that iteration. The parameter ranks below 0.13 in the sensitivity analysis of all four workflows, and fixing it at either bound changes the workflow means by no more than 8% without altering any comparison (manuscript Section 3.6).

Parameters that are estimates rather than manufacturer-confirmed measurements

- Mode and upper bound of the THC2 cure power (230 W mode; 300 W power-supply ceiling)
- Graphy Spinner cycle time, T(3, 5, 8) min — power confirmed, duration not
- Representative print time for the Asiga workflow, T(45, 60, 90) min
- Failed-print rate, T(0, 0.02, 0.08)

All four rank below 0.20 in the sensitivity analysis of every workflow.

File S2

The complete model is provided as `carbon_model_v3.py`. Running it with the fixed seed reproduces every value reported in the manuscript, including the contribution analysis, the per-workflow sensitivity rankings, the resin scenarios and the break-even series lengths.