

Supplementary Materials

Detailed Development of the OPEX Calculation

1. Development of the OPEX calculation

For the present preliminary OPEX development, only the annual cost items that were explicitly quantified in the base case were included, namely energy consumption, water service, packaging, direct operating labour, maintenance, insurance, and local taxes. The calculation was built from the annual process requirements obtained in the process design and mass and energy balances, together with explicit tariffs, sectoral benchmarks, and standard preliminary cost-estimation factors taken from published sources. In this framework, energy consumption included both the annual electricity demand of the line and the thermal energy required for blanching, since the blanching stage was assumed to operate with electric resistances. Water service was estimated from the annual mass entering blanching and the specific water-generation factor reported for peas, and was then valued with industrial tariffs for water supply, sewerage, and depuration. Packaging was calculated from the annual amount of packaged flour and the cost of one bag. Direct operating labour was estimated from a sectoral benchmark for pulse-flour production, while maintenance, insurance, and local taxes were estimated as annual fractions of the installed plant capital. Items not directly quantified in the base case, such as rejected-pea feedstock purchase, transport and distribution, external cleaning services, sanitation consumables, quality-control analyses, depreciation, financing charges, plant overhead, and additional on-site wastewater treatment beyond standard service tariffs, were excluded from the present development.

1.1. Installed plant capital used for annual factor-based costs

Since maintenance, insurance, and local taxes were estimated as annual fractions of the installed plant capital, the first step was to define the fixed-capital basis used in the OPEX calculation. The installed plant capital was obtained by applying the Lang factor previously adopted for a solid process plant to the purchased-equipment CAPEX reported in the main manuscript [1].

$$\begin{aligned} \text{FCI} &= \text{CAPEX}_{\text{equipment}} \cdot f_{\text{Lang}} \quad (1) \\ \text{FCI} &= 924,096 \cdot 3.10 = 2,864,697.60 \text{ €} \end{aligned}$$

2. Included OPEX items

2.1. Energy consumption

The annual energy cost was calculated by combining the electricity demand of the line and the thermal energy required for blanching, both valued with the average non-household electricity price in the European Union for the second half of 2024, equal to 0.1629 €/kWh [2]. This approach was adopted because the blanching stage was assumed to operate with electric resistances rather than with an external fuel-based heat supply. The annual electricity demand and the annual thermal demand were taken directly from the process balances reported in the main manuscript.

$$C_{\text{energy}} = (E_{\text{el}} + E_{\text{th}}) \cdot p_{\text{el}} \quad (2)$$

where:

E_{el} = annual electricity demand

E_{th} = annual thermal demand of blanching, since the blanching stage was assumed to operate with electric resistances

p_{el} = electricity tariff

$$\begin{aligned} C_{energy} &= (295,498 + 129,600) \cdot 0.1629 \\ C_{energy} &= 425,098 \cdot 0.1629 = 69,248.46 \text{ €/year} \end{aligned}$$

2.2. Water service

The annual water-service cost was estimated from the annual mass entering blanching and the specific value reported for peas blancher effluent, equal to 0.85 m³/t [3]. The annual mass entering blanching was derived from the blanching throughput and the annual upstream operating time reported in the process design. The resulting annual water volume was then valued with the industrial tariffs published by CCAM for water supply, sewerage, and depuration, including the corresponding fixed annual service charges [4].

The annual mass entering blanching was calculated as:

$$\begin{aligned} M_{blanch} &= \dot{m}_{blanch} \cdot t_{upstream} \quad (3) \\ M_{blanch} &= 1336 \cdot 960 = 1,282,560 \text{ kg/year} = 1,282.56 \text{ t/year} \end{aligned}$$

The corresponding annual water volume was estimated as:

$$\begin{aligned} V_{water} &= M_{blanch} \cdot f_{water} \quad (4) \\ V_{water} &= 1,282.56 \cdot 0.85 = 1,090.176 \text{ m}^3/\text{year} \end{aligned}$$

The variable water cost was calculated using the industrial volumetric brackets:

$$C_{acqua} = 50t_1 + 50t_2 + 50t_3 + (V_{water} - 150) t_4 \quad (5)$$

where:

$$\begin{aligned} t_1 &= 1.751079 \text{ €/m}^3 \\ t_2 &= 2.424175 \text{ €/m}^3 \\ t_3 &= 2.551762 \text{ €/m}^3 \\ t_4 &= 2.934527 \text{ €/m}^3 \end{aligned}$$

$$\begin{aligned} C_{acqua} &= 50(1.751079) + 50(2.424175) + 50(2.551762) + (1090.176 - 150)(2.934527) \\ C_{acqua} &= 3,095.32 \text{ €/year} \end{aligned}$$

The sewerage and depuration costs were calculated as:

$$C_{fog} = V_{water} \cdot t_{fog} \quad (6)$$

$$C_{dep} = V_{water} \cdot t_{dep} \quad (7)$$

where:

$$t_{\text{fog}} = 0.344488 \text{ €/m}^3$$

$$t_{\text{dep}} = 0.535870 \text{ €/m}^3$$

$$C_{\text{fog}} = 1090.176 \cdot 0.344488 = 375.55 \text{ €/year}$$

$$C_{\text{dep}} = 1090.176 \cdot 0.535870 = 584.19 \text{ €/year}$$

The annual fixed charges were summed as:

$$C_{\text{fixed,water}} = q_{\text{acqua}} + q_{\text{fog}} + q_{\text{dep}} \quad (8)$$

$$C_{\text{fixed,water}} = 89.311685 + 21.689981 + 40.828199 = 151.83 \text{ €/year}$$

The total annual water-service cost was therefore:

$$C_{\text{water,total}} = C_{\text{acqua}} + C_{\text{fog}} + C_{\text{dep}} + C_{\text{fixed,water}} \quad (9)$$

$$C_{\text{water,total}} = 3,095.32 + 375.55 + 584.19 + 151.83 = 4,206.90 \text{ €/year}$$

2.3. Packaging

Packaging cost was estimated from the annual amount of packaged flour and the cost of one bag. Since the base case considered 1 kg final packs, the annual number of bags was taken equal to the annual mass of packaged flour expressed in kilograms. As an explicit commercial basis, a market quotation for 1 kg / 2 kg kraft flour paper bags was used, reporting a range of US\$0.02–0.05 per piece [5]. To remain consistent with the base case previously fixed, the explicit commercial value US\$0.029 per piece was used as the unit reference. This value was converted into euros using the ECB euro foreign exchange reference rate of 1 EUR = 1.1373 USD [6]. The annual packaged-flour output was taken from the main manuscript.

The annual number of bags was calculated as:

$$N_{\text{bags}} = \frac{m_{\text{flour,annual}}}{m_{\text{bag}}} \quad (10)$$

$$N_{\text{bags}} = \frac{627,770}{1} = 627,770 \text{ bags/year}$$

The reference bag cost in euros was obtained as:

$$c_{\text{bag}} = \frac{0.029 \text{ USD/bag}}{1.1373 \text{ USD/EUR}} = 0.02550 \text{ €/bag} \quad (11)$$

The annual packaging cost was then:

$$C_{\text{pack}} = N_{\text{bags}} \cdot c_{\text{bag}} \quad (12)$$

$$C_{\text{pack}} = 627,770 \cdot 0.02550 = 16,007.50 \text{ €/year}$$

2.4. Direct operating labour

Direct operating labour was estimated from a sectoral benchmark for pulse-flour production. A reference besan plant was used, for which the manpower requirement explicitly includes Technical Staff 2 and Labour 3 [7]. In order to retain only the plant personnel directly associated with operation in the base case, the direct labour requirement was fixed at 4 direct workers. To estimate the annual employer-side labour cost, the average hourly earnings in Italy (16.4 €/h) reported by ISTAT for 2022 were combined with the euro-area share of non-wage costs in total labour costs (25.5%) published by Eurostat [8, 9]. The annual number of hours worked per worker was kept equal to the annual labour basis adopted in the base-case screening.

The employer-side hourly labour cost was calculated as:

$$c_{lab,h} = \frac{w_{gross,h}}{1 - s_{nonwage}} \quad (13)$$

where:

$$\begin{aligned} w_{gross,h} &= 16.4 \text{ €/h} \\ s_{nonwage} &= 0.255 \\ c_{lab,h} &= \frac{16.4}{1 - 0.255} = 22.0134 \text{ €/h} \end{aligned}$$

The annual labour cost per worker was then:

$$\begin{aligned} C_{lab,worker} &= c_{lab,h} \cdot h_{annual} \quad (14) \\ C_{lab,worker} &= 22.0134 \cdot 1662.56 = 36,598.66 \text{ €/worker} \cdot \text{year} \end{aligned}$$

The total direct operating labour cost became:

$$\begin{aligned} C_{lab,total} &= N_{workers} \cdot C_{lab,worker} \quad (15) \\ C_{lab,total} &= 4 \cdot 36,598.66 = 146,394.63 \text{ €/year} \end{aligned}$$

2.5. Maintenance

Maintenance was estimated as an annual fraction of the installed plant capital. A factor of 3% of FCI was adopted, which lies within the explicit range of 2–10% of fixed-capital investment reported in standard plant-economics material based on reference [10].

$$\begin{aligned} C_{maint} &= f_{maint} \cdot FCI \quad (16) \\ C_{maint} &= 0.03 \cdot 2,864,697.60 = 85,940.93 \text{ €/year} \end{aligned}$$

2.6. Insurance

Insurance was estimated as 0.5% of FCI, within the explicit range of 0.4–1.0% of fixed-capital investment reported in the same source [10].

$$C_{ins} = f_{ins} \cdot FCI \quad (17)$$

$$C_{\text{ins}} = 0.005 \cdot 2,864,697.60 = 14,323.49 \text{ €/year}$$

2.7. Local taxes

Local taxes were estimated as 1% of FCI, within the explicit range of 1–4% of fixed-capital investment reported in the same source [10].

$$C_{\text{tax}} = f_{\text{tax}} \cdot FCI \quad (18)$$

$$C_{\text{tax}} = 0.01 \cdot 2,864,697.60 = 28,646.98 \text{ €/year}$$

3. Annual OPEX summary

The total annual OPEX included in the present supplementary development was obtained by summing the seven quantified items described above.

$$OPEX_{\text{annual}} = C_{\text{energy}} + C_{\text{water,total}} + C_{\text{pack}} + C_{\text{lab,total}} + C_{\text{maint}} + C_{\text{ins}} + C_{\text{tax}} \quad (19)$$

$$OPEX_{\text{annual}} = 69,248.46 + 4,206.90 + 16,007.50 + 146,394.63 + 85,940.93 + 14,323.49$$

$$+ 28,646.98$$

$$OPEX_{\text{annual}} = 364,768.89 \text{ €/year}$$

Table S1. Summary of included annual OPEX items.

OPEX item	Annual cost (€ / year)
Energy consumption	69,248.46
Water service	4,206.90
Packaging	16,007.50
Direct operating labour	146,394.63
Maintenance	85,940.93
Insurance	14,323.49
Local taxes	28,646.98
Total annual OPEX	364,768.89

References

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