Towards a green and sustainable aviation fuel transition: a multi-objective optimization framework for cost-effective advanced biofuels production

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Context

Hydrothermal liquefaction (HTL) converts microalgae into bio-oil, a biofuel precursor that is expected to play a pivotal role in the forthcoming energy transition. **Enhancing the bio-oil productivity and chemical composition is crucial** to ensure compatibility with subsequent upgrading processes and to guarantee the final fuel properties. Nevertheless, operating conditions that enhance bio-oil yield frequently compromise its quality and **the economic implications of energy-intensive, yield-maximizing regimes relative to more balanced strategies remain insufficiently assessed.** Therefore, we present a **multivariable optimization framework** integrating experimental design, process simulation, and techno-economic analysis (TEA) to accelerate a sustainable transition towards biofuels derived from microalgae in small European countries like Belgium.

Methodology

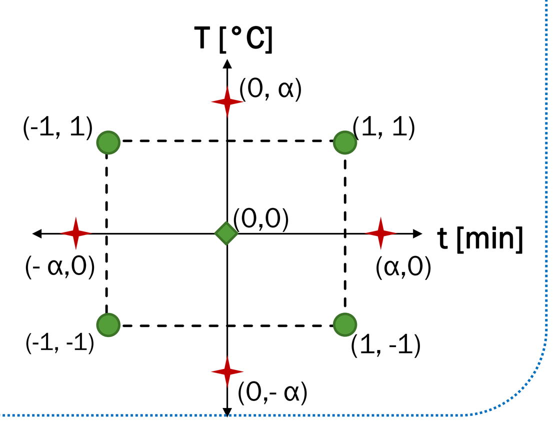
1. Experimentation

Preliminary screening

- Temperature: 260 – 340 °C.
- Time: 0 – 80 min.

+

Central Composite Design



Response variables:
Bio-oil yield and quality (O/C)

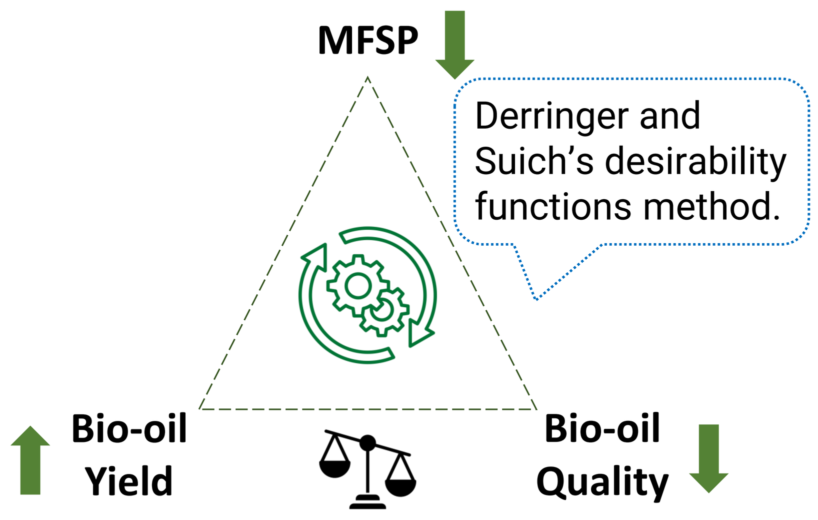
2. Process Simulation & Technoeconomic Assessment

Analysis for 2 production scales:

- Low productivity (LP): 10.9 g/m2/day on 1000-acre. ***(adapted to Belgian conditions)***
- High productivity (HP): 17.5 g/m2/day on 5000-acre.

Response variables:
Minimal fuel selling price (MFSP), for both scenarios (LP & HP)

3. Multi-objective Optimization

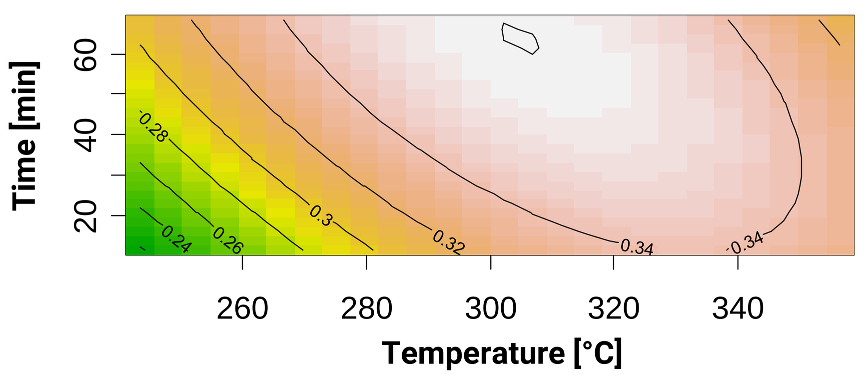


Optimization balancing the 3 response variables, in parallel for the 2 scenarios.

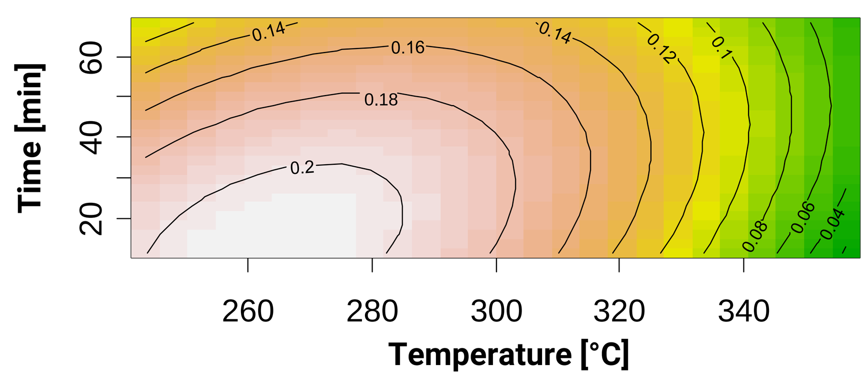
Results

Experimentation reveal competing optima between Yield, Quality and Cost

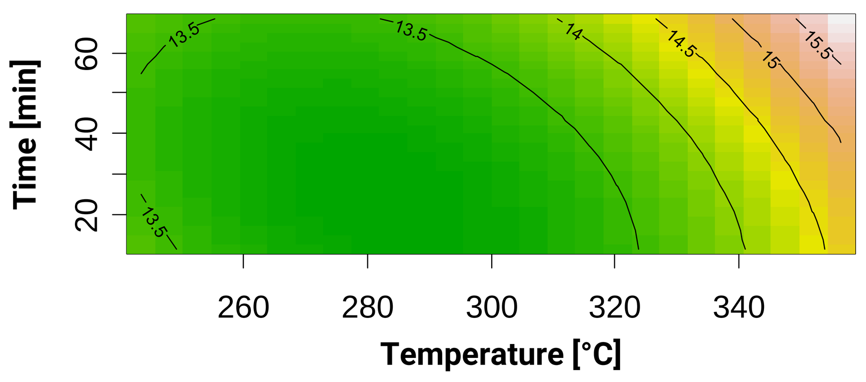
Bio-oil yield — T ≈ 300 °C, t = 40 – 60 min



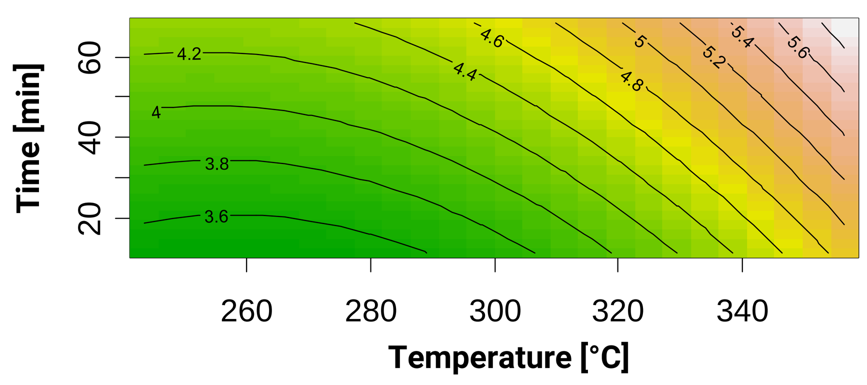
Bio-oil O/C — T ≥ 340°C, t ≥ 40 min



MFSP (LP) — T = 260 – 300 °C, ∀ t



MFSP (HP) — T ≈ 260°C, short times

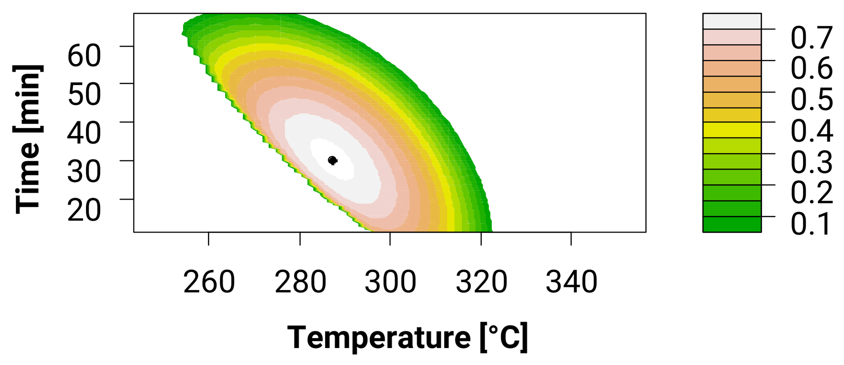


- Different optimization paths required for the 3 variables.
- Larger scales demand low severity to improve prices.
- Total reduction of O/C is not required during HTL.

Therefore: **Economic optimum ≠ Yield optimum ≠ Quality optimum**

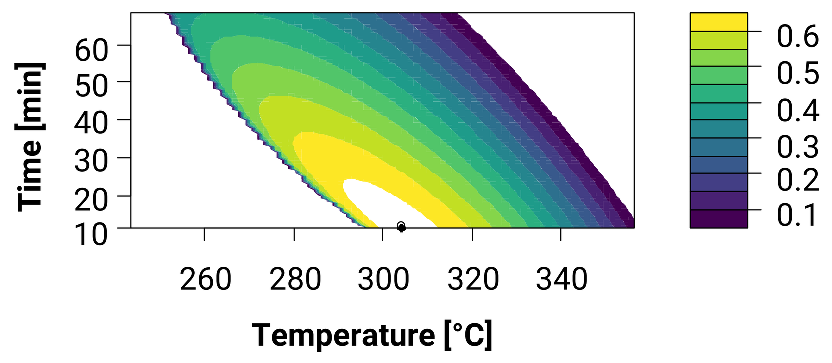
Multi-objective Optimization Reduces Fuel Cost Compared with Yield-Based Optimization

Low Productivity Scenario



- Temperature: 287.3°C
- Time: 30.1 min
- Yield: 33.26%
- O/C: 0.1969
- MFSP: 13.04 €/l

High Productivity Scenario



- Temperature: 304.2°C
- Time: 11.7 min
- Yield: 32.84%
- O/C: 0.1712
- MFSP: 3.77 €/l

VS

Single-factor Optimization
(Applied for bio-oil yield)

- Temperature: 305.6°C
- Time: 64 min
- Yield: 36%
- **MFSP (LP): 13.75 €/l**
- **MFSP (HP): 4.67 €/l**

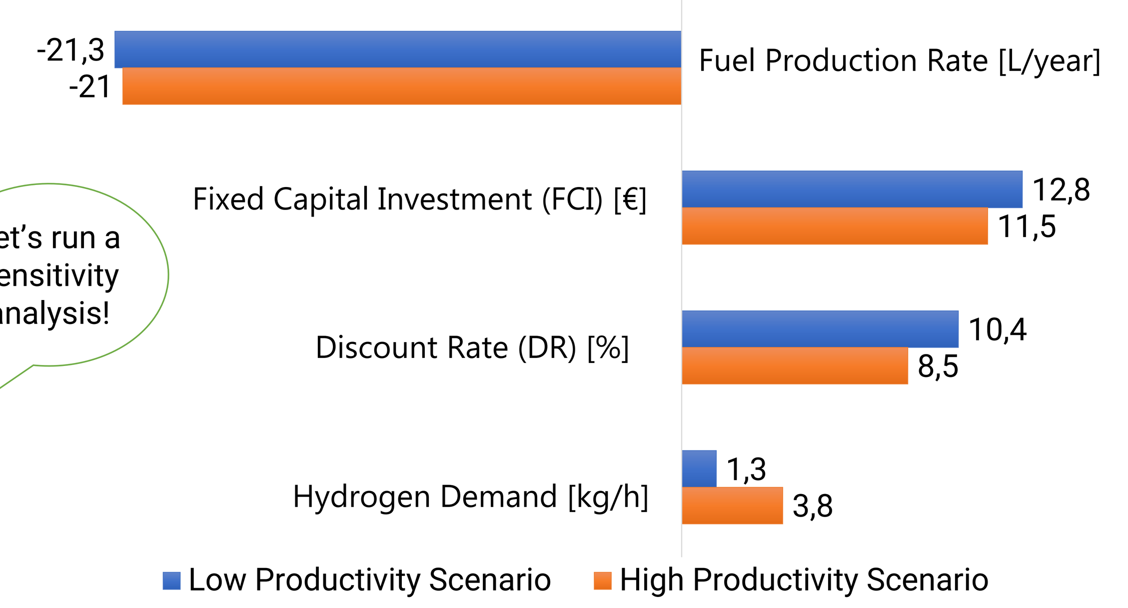
MFSP improvement: **5.16%**

MFSP improvement: **19.27%**

Integrating Technoeconomic Analysis (TEA) into process optimization unlocks **lower-cost operating windows** overlooked by conventional, single-metric approaches.

Economic Feasibility depends on Scale, Biomass Productivity and Production rates

Contribution to variance on the MFSP



- MFSP strongly influenced by production rate, FCI and DR.
- Enhancing biomass loading and reactor's efficiency is critical.

Key Takeaways

- TEA must be integrated to process optimization.
- Production scale influence the optimization strategy, as energy demands might not be compensated by bio-oil productivity at large scale.
- For land-restricted countries, increasing microalgal productivity efficiently is critical. Therefore, the development of cost-effective photo-bioreactors is advised.

Future Prospects

- Coupling microalgae culture with wastewater remediation
- Co-processing bio-oil in existing infrastructure
- Aqueous phase to cultivation or for energy recovery
- Co-product integration & Biorefinery Approach

Acknowledgments

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