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Computer Science & Digital Society

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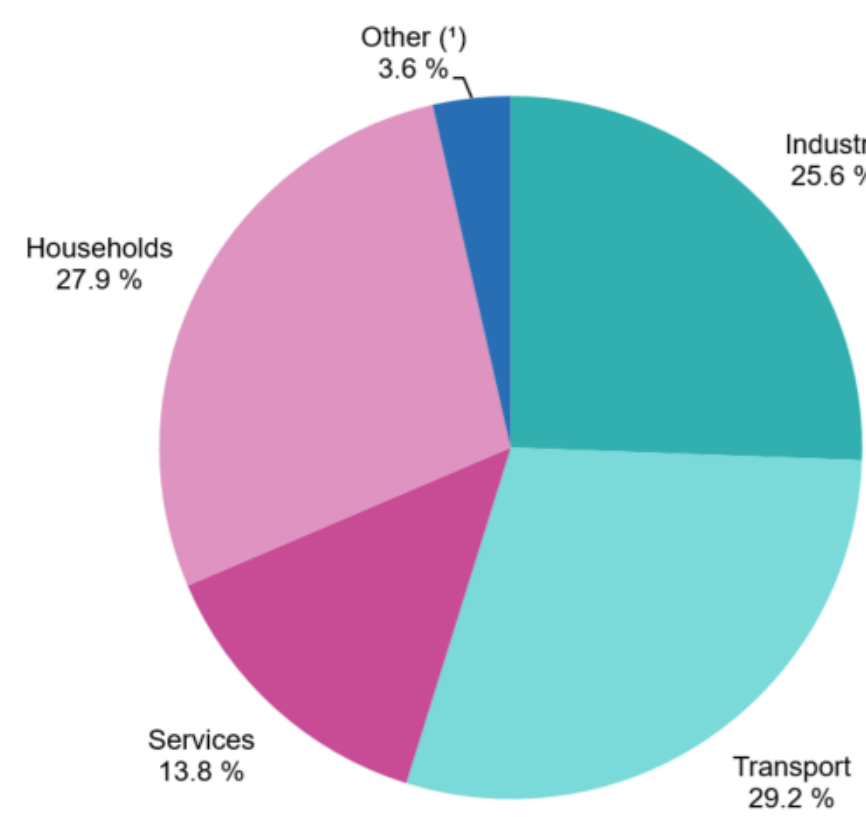
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ENERGY EFFICIENCY Optimization in a Two-level SUPPLY CHAIN Model: Incorporating SHORTAGE Considerations

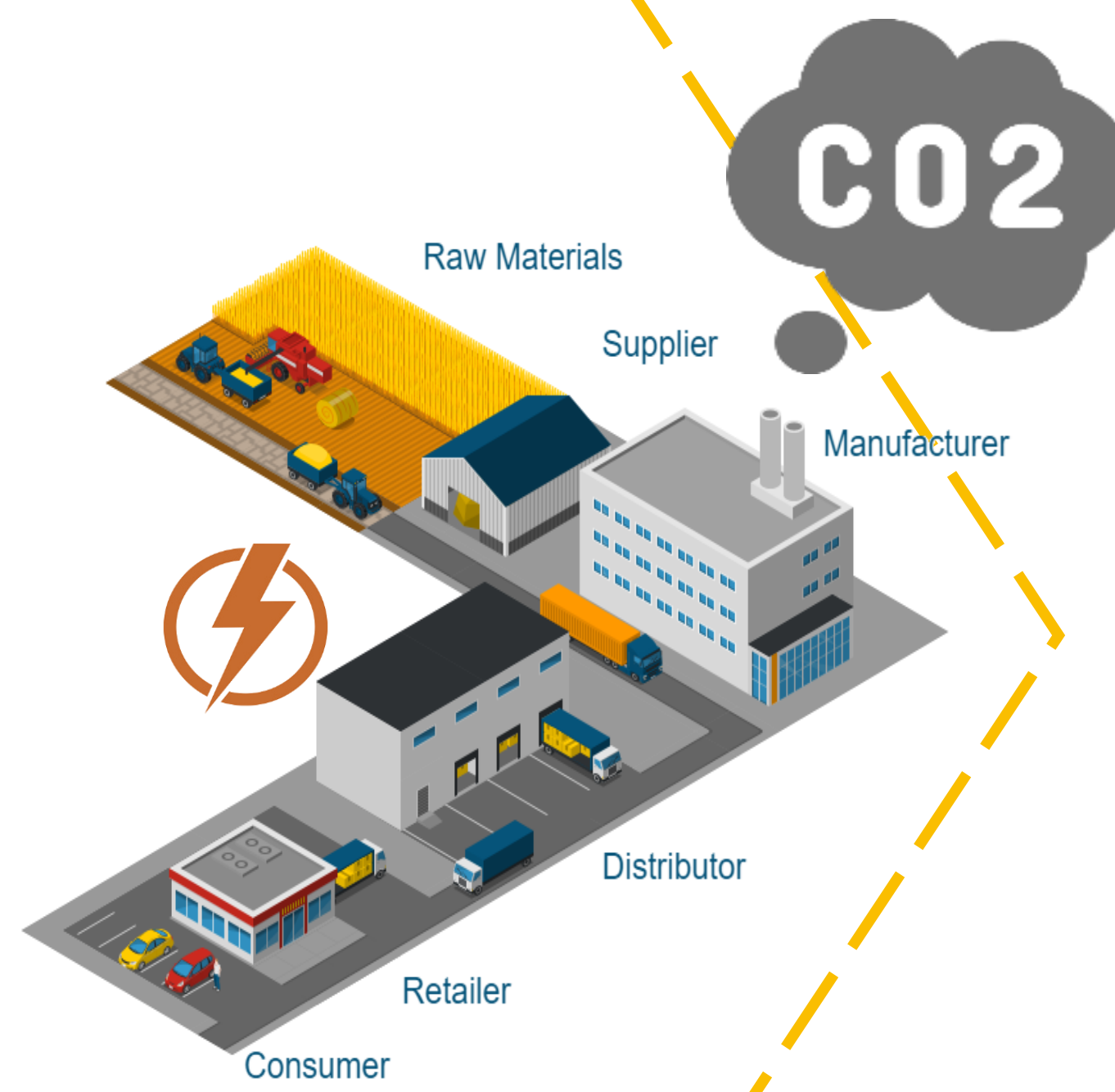
Introduction

Final energy consumption by sector, EU, 2021 (% of total, based on terajoules)



(*) International aviation and maritime bunkers are excluded from category Transport. Source: Eurostat (online data code: nrg_bal_c)

eurostat



Contributions

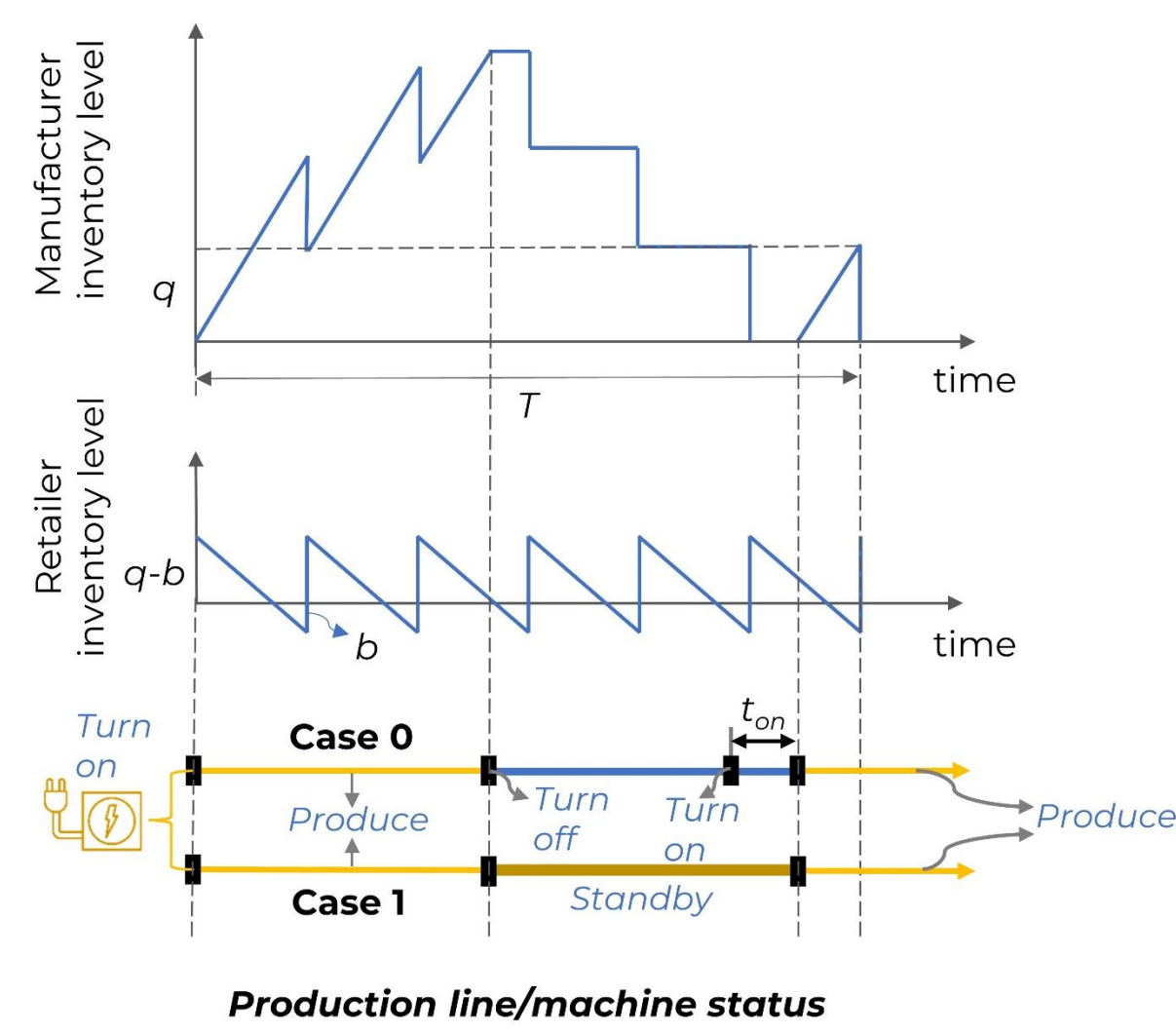
Ref.	Inventory model	No. of stages	OMS	Shortages	Energy aspects	CO ₂ aspects
Wu and Ouyang (2003)	EPQ/JELS	2	✓	✓	✓	✓
Zanoni et al. (2014)	EPQ	2	✓	✓	✓	✓
Biel and Glock (2016)	EPQ	2	✓	✓	✓	✓
Sarkar et al. (2018)	EPQ	1	✓	✓	✓	✓
Daryanto and Wee (2018)	EPQ	1	✓	✓	✓	✓
Taleizadeh et al. (2018)	EPQ	1	✓	✓	✓	✓
Taleizadeh et al. (2018)	EPQ/JELS	2	✓	✓	✓	✓
Marchi et al. (2019)	EPQ	1	✓	✓	✓	✓
Mishra et al. (2020)	EPQ	1	✓	✓	✓	✓
Nguyen et al. (2022)	EPQ	1	✓	✓	✓	✓
Nguyen et al. (2023b)	EPQ	1	✓	✓	✓	✓
Nguyen et al. (2023a)	EPQ	1	✓	✓	✓	✓
This study	EPQ/JELS	2	✓	✓	✓	✓

JELS: Joint economic lot sizing; OMS: optimizing of machine status.

- The integration of energy consumption and backorder concerns into a two-level inventory model;
- The resolution method to minimize the average total cost function including energy consumption cost;
- Optimization of production rate, maximum backordering quantity, number of shipments per batch, quantity transported per delivery and the production line status.

Modeling

Parameter
D demand rate (unit/h)
S_1 setup cost of the manufacturer (€/setup)
S_2 order cost of the retailer (€/order)
H_1 inventory holding cost of the manufacturer (€/unit.h)
H_2 inventory holding cost of the retailer (€/unit.h)
B shortage cost (€/unit.h)
W idle power of the production line (kW)
K energy consumption of the production line to produce one unit (kWh/unit)
E energy cost (€/kWh)
F multiplication factor for the power required during the setup of the production line
t_{on} re-setup time of the production line (h)
T cycle time (h)
Decision variables
P production rate (unit/h)
b The maximum backordering quantity at the buyer (unit)
n The number of shipments per batch production run, a positive integer
q quantity transported per delivery (unit/delivery)



Specific energy consumption from production [Gutowski et al., 2006]

$$SEC \left(\frac{kWh}{unit} \right) = \frac{W}{P} + K \quad (1)$$

Case 0: The production line is turned off/on

$$TC_0(P, q, n, b) = \underbrace{H_1 q \left[\frac{D}{P} + \frac{n}{2} \left(1 - \frac{D}{P} \right) - \frac{1}{2} \right]}_{\text{Manufacturer}} + \underbrace{\frac{D}{nq} S_1 + \frac{DS_2}{q} + \frac{H_2(q-b)^2}{2q} + \frac{Bb^2}{2q}}_{\text{Retailer}} + \underbrace{\left(\frac{W}{P} + K \right) DE + \frac{DFW t_{on} E}{nq}}_{\text{Energy cost}} \quad (2)$$

Case 1: The production line is kept on standby

$$TC_0(P, q, n, b) = \underbrace{H_1 q \left[\frac{D}{P} + \frac{n}{2} \left(1 - \frac{D}{P} \right) - \frac{1}{2} \right]}_{\text{Manufacturer}} + \underbrace{\frac{D}{nq} S_1 + \frac{DS_2}{q} + \frac{H_2(q-b)^2}{2q} + \frac{Bb^2}{2q}}_{\text{Retailer}} + \underbrace{(W + KD)E}_{\text{Energy cost}} \quad (3)$$

The overall Mixed-integer nonlinear programming (MINLP) problem for both cases can be summarized as follows

$$\text{Minimize } TC_i(P, q, n, b) \quad (4)$$

$$P_{min} \leq P \leq P_{max} \quad (5)$$

$$t_{on} < \frac{nq}{D} \left(1 - \frac{D}{P} \right) \quad (5)$$

where the indicator i stands for the two options of the production line during the non-production phase which takes the values of 0 and 1. The constraint (5) is for re-setup time in when the production line in turned off/on (case 0).

Conclusion and perspectives

- Conclusion:** This study integrates energy consumption optimization into a two-level supply chain production system, consisting of a single manufacturer and a single retailer. We analyze the energy consumption of the system through two phases of the manufacturer's production line: the production phase and the non-production phase. A resolution procedure for the mixed-integer non-linear programming problem is proposed to determine the optimal values of four decision variables by minimizing the total cost function, which includes production costs. To illustrate the model, a numerical example is performed. Through this example, we can observe the importance of considering energy factors in the cost model of inventory systems.
- Future research:** incorporating additional energy-consuming components of a supply chain, such as warehousing and transportation; investigating more complex systems involving multi-level or multi-product aspects.

Resolution

Referring to Wu and Ouyang (2003), the objective functions can be rewritten as

$$TC_i(P, q, n, b) = \frac{1}{2q} \left\{ \left(\frac{H_2 B}{B + H_2} + H_1 X_a \right) (q - \sqrt{Z_{a,i}})^2 + (B + H_2) \left[b - \frac{H_2}{B + H_2} q \right]^2 \right\} + \left(\frac{H_2 B}{B + H_2} + H_1 X_a \right) \sqrt{Z_{a,i}} + M_i \quad (6)$$

where

$$M_i = \begin{cases} \left(\frac{W}{P} + K \right) DE, & \text{when } i = 0 \\ (W + KD)E, & \text{when } i = 1 \end{cases}$$

$$Z_{a,i} = \frac{2D(B + H_2)Y_{a,i}}{H_2 B + H_1 B X_a + H_1 H_2 X_a} > 0$$

$$X_a = n \left(1 - \frac{D}{P} \right) + \frac{2D}{P} - 1 > 0$$

$$Y_{a,i} = S_2 + \frac{S_1 i}{n} > 0$$

The optimal value of q and b can be yielded as

$$q_i^*(P, n) = \sqrt{Z_{a,i}} = \sqrt{\frac{2D(B + H_2)Y_{a,i}}{H_2 B + H_1 B X_a + H_1 H_2 X_a}} \quad (7)$$

$$b_i^*(P, n) = \frac{H_2}{B + H_2} q_0^* \quad (8)$$

(6) becomes

$$TC_i^*(P, n) = \sqrt{2D \left(S_2 + \frac{S_1 i}{n} \right)} \cdot \sqrt{\frac{H_2 B}{B + H_2} + H_1 \left[n \left(1 - \frac{D}{P} \right) + \frac{2D}{P} - 1 \right]} + M_i$$

Let

$$X_b = H_2 B + H_1 (B + H_2) \left(\frac{2D}{P} - 1 \right) \text{ and } Y_b = H_1 (B + H_2) \left(1 - \frac{D}{P} \right)$$

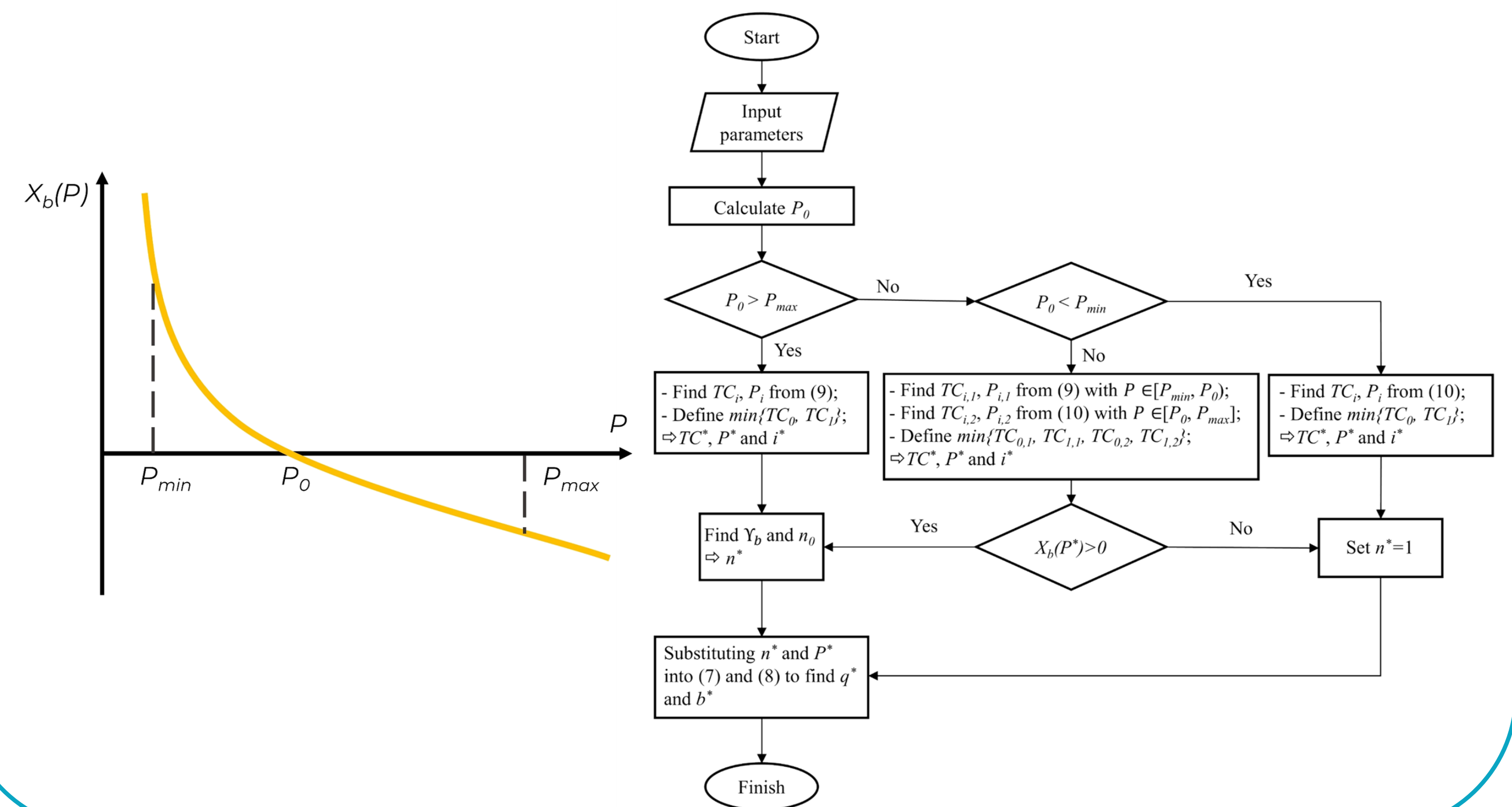
When $X_b > 0$: $n_i^* = \lceil n_{0,i} \rceil$ if $TC^*(\lceil n_{0,i} \rceil) \leq TC^*(\lfloor n_{0,i} \rfloor + 1)$; otherwise $n_i^* = \lfloor n_{0,i} \rfloor + 1$ where $n_{0,i} = \sqrt{S_{1,i} X_b / (S_2 Y_b)}$.

$$TC_i^*(P) = \sqrt{\frac{2D}{B + H_2} \left(S_2 X_b + S_{1,i} Y_b + 2 \sqrt{S_{1,i} S_2 X_b Y_b} \right)} + M_i \quad (9)$$

When $X_b \leq 0$: $n_i^* = 1$.

$$TC_i^*(P) = \sqrt{2D(S_{1,i} + S_2) \left(\frac{H_2 B}{H_2 + B} + H_1 \frac{D}{P} \right)} + M_i \quad (10)$$

Resolution procedure



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Numerical instance

D	0.521	unit/h	t_{on}	0.01	h
S_1	400	€/setup	W	2	kW
S_2	25	€/order	F	2	
H_1	4.57e-04	€/unit.h	K	0.05	kWh
H_2	5.71e-04	€/unit.h	E	0.2	€/kWh
B	1.14e-03	€/unit.h	P	[1.042;2.604]	unit/h

Models	P^*	n^*	q^*	b^*	TC^*
Wu and Ouyang (2003)	1.667	3	177	59	0.931
This model					
Case $i = 0$	2.604	2	529.243	176.373	1.249
Case $i = 1$	1.042	6	222	0	4.436

Models	Inventory cost	Shortage cost	Energy cost	TC
Wu and Ouyang	0.557	0.011	1.255	1.82
This model	0.41	0.034	0.806	1.249
Δ	-26.4%	209.1%	-35.8%	-31.5%