

IEooc_Methods2_Exercise1: Cement production – systems analysis

This exercise is a modified version of an original developed by Daniel B Müller (NTNU Trondheim), and used with permission.

- 1) Draft a simplified system diagram ‘cement production and use’ including the process steps ‘preparation/mixing’, ‘rotary furnace’, ‘cement mill’ and ‘buildings’. Identify the central material and fuel streams that are important for the process balance sheet. Identify the system variables.

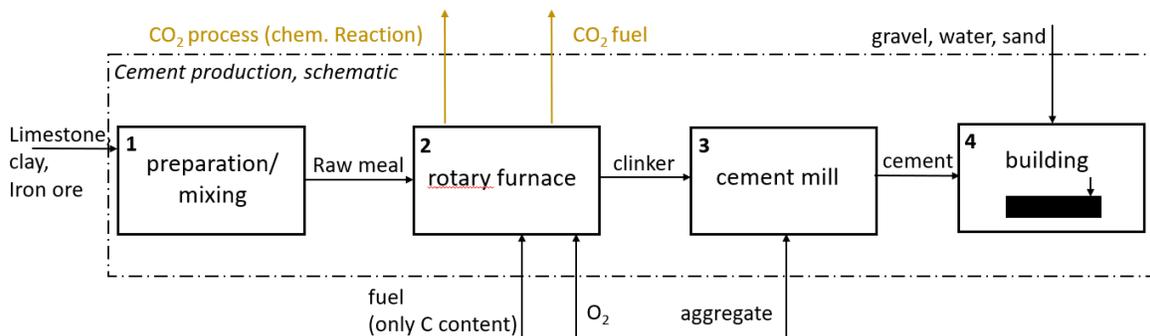


Fig. 1: system diagram.

- 2) How many system variables are present? How many system/information units do you need to quantify the entire system? Compile a list of model parameters that are required to solve the system! Trace back your listed model parameters to the information in the text (using equations)! What additional information is required?

Figure 1 shows 10 flows, one inventory/stock change and one inventory/stock. Consequently, 12 system variables are present. With four processes there are at least four balance equations. After closer inspection you can discover that the rotary furnace fulfills two balance equation: one for the material throughput (raw meal, CO₂ process, clinker) and one for fuel (fuel, O₂, CO₂ fuel). Consequently, there are five balance equations which requires 7 additional parameters to fully quantify the system. The information given in the text is more extensive than needed to solve the system. For example, while the gravel, water and sand content for the concrete is given, we are only interested in the cement content while the rest is provided by the mass balance. We neglect the stock of concrete the assessment of which would require a time series analysis. Only the inventory change is considered.

First, we look at processes 1, 3 and 4, which are the easiest to model:

Process 1 is fully described through the mass balance and no additional parameters are required. Processes 3 and 4 link three flows and since one can be obtained from the mass balance, we only need one parameter for each processes.

Table 1: List of system parameters chosen to solve the system

Name/Description	Symbol	Value	Source/Formula
Concrete/cement stock (simplification)	S	0 Gt (not considered)	Assumption
Cement content of concrete (describes process 4)	α	0.13	Straight from text
Clinker content of cement (describes process 3)	β	0.86	Straight from text
Raw mineral powder per clinker (describes throughput in process 2)	γ	1.51	Formula 1
Fuel per clinker (describes fuel requirements in process 2)	δ	0.075	Formula 2
Oxygen requirement per fuel, rotary furnace	σ	2.67	Formula 3
Cement demand OR Concrete demand X	Z $X = Z/\alpha$	4 Gt/yr	Straight from text

Now we are taking on process 2: here we choose one parameter, “raw mineral powder per clinker” γ calculated by using in text information and stoichiometric data:

$$\gamma = \frac{M(\text{CaCO}_3)}{M(\text{CaO})} \cdot x + (1 - x) \quad (1)$$

Here, x describes the share of CaO in clinker (65 %) and M(C) the molar mass of the chemical compound C.

$M(\text{CaCO}_3) = 100 \text{ g/mol}$, $M(\text{CaO}) = 56 \text{ g/mol}$.

Hint: to derivate this formula you can draft a detailed mini-MFA for the rotary furnace itself, which resolves the flows for CaO, Fe_2O_3 , etc.

Further we need a parameter “fuel per clinker” δ , which links carbon within the fuel to the clinker flow:

$$\delta = \text{carbon_content_fuel} \cdot \frac{\text{energy_requirement_clinker}}{\text{heating_value_fuel}} \quad (2)$$

Hereby the right term provides the fuel requirement per kg of clinker (MJ/kg / MJ/kg) which is further multiplied with the carbon content of the fuel.

Now we can calculate the oxygen demand for the combustion (per kg C in the fuel) using simple stoichiometry:

$$\sigma = \frac{M(O_2)}{M(C)} = \frac{32}{12} = 2.67 \quad (3)$$

3) Determine the analytical solution of the system for a random quantity of concrete X!

The equation system is fairly simple, and the matrix method is not applied. Instead the solution is determined straightforward:

S_4	$= 0$	(assumption)
ΔS_4	$= X$	(Concrete is added to the overall inventory)
$F_{34} = \alpha \cdot \Delta S_4$	$= \alpha \cdot X$	(Cement = cement_content_concrete x cement_flow)
$F_{04} = (1-\alpha) \cdot \Delta S_4$	$= (1-\alpha) \cdot X$	(mass balance)
$F_{23} = \beta \cdot F_{34}$	$= \beta \cdot \alpha \cdot X$	(clinker = clinker_content_cement x cement_flow)
$F_{03} = (1-\beta) \cdot F_{34}$	$= (1-\beta) \cdot \alpha \cdot X$	(mass balance)
$F_{12} = \gamma \cdot F_{23}$	$= \gamma \cdot \beta \cdot \alpha \cdot X$	(raw mineral powder per clinker)
$F_{20a} = (\gamma-1) \cdot F_{23}$	$= (\gamma-1) \cdot \beta \cdot \alpha \cdot X$	(mass balance throughput rotary furnace)
$F_{01} = F_{12}$	$= \gamma \cdot \beta \cdot \alpha \cdot X$	(mass balance mixer)
$F_{02a} = \delta \cdot F_{23}$	$= \delta \cdot \beta \cdot \alpha \cdot X$	(fuel per clinker)
$F_{02b} = \sigma \cdot \delta \cdot F_{23}$	$= \sigma \cdot \delta \cdot \beta \cdot \alpha \cdot X$	(oxygen per fuel)
$F_{20b} = F_{02a} + F_{02b}$	$= (\sigma+1) \cdot \delta \cdot \beta \cdot \alpha \cdot X$	(mass balance fuel rotary furnace)

4) Quantify your solution using given data and potential additional information produced for the global cement production of 4 Gt/yr! How do the overall total emissions distribute across process and fuel emissions?

→ See excel file “IEooc_Methods2_Exercise1_Cement_Solution.xlsx”, table “exercise 4”. The provided formulas differ slightly from the formulas given in exercise 3 above, since here F_{34} and not ΔS_4 was given exogenously, and hence calculations were performed using $Z = \alpha \cdot X$ parameter instead of X . The total CO_2 emissions are about 2.7 Gt/yr, of which 65 % are process emissions and 35 % fuel-related emissions.

Since the cement industry is one of the biggest industrial CO₂ emitters, emissions will have to be substantially reduced in the future. Several strategies exist, and the emissions savings potential of the different strategies shall be quantified here.

5) Calculate the process and fuel related CO₂ emissions of a hypothetical global cement production of 4 Gt/yr at some point in the future assuming the following improvements:

- a) potential reduction of energy requirements of the rotary furnace from currently 3 MJ/kg to 2.7 MJ/kg (,best' possible energy intensity for large new dry kilns. 5. IPCC-Sachstandsbericht III, page 758).
- b) potential reduction of clinker share in cement to 66 % (through increasing use of CaO rich slag from other processes like power plants and furnaces)
- c) large scale application of natural gas as fuel for rotary furnaces (energy content 55 MJ/kg, C content 75 %)
- d) potential reduction of demand for cement through increased material efficiency and longer durability of buildings and infrastructure of 25 %.
- e) Options a) to d) combined.

How do overall emissions determined in section a) through e) split among process and fuel emissions? How do the improvements compare to global and EU wide climate goals?

The results for task 5 a through e were calculated using excel (file "IEooc_Methods2_Exercise1_Cement_Solution.xlsx") and summarized in the following table:

Table 2: CO₂ emission for various scenarios:

	Process emissions (Gt/yr)	%-Reduction	Fuel emissions (Gt/yr)	%-Reduction	Total emissions (Gt/yr)	%-Reduction
4 Baseline	1.76	0	0.95	0	2.70	0
5a Fuel efficiency	1.76	0	0.85	10	2.61	4
5b Less clinker	1.35	23	0.73	23	2.07	23
5c Natural gas	1.76	0	0.52	45	2.27	16
5d Demand reduction	1.32	25	0.71	25	2.03	25
5e All together	1.01	42	0.27	72	1.28	53

Option 5a and 5c affect fuel consumption only, hence process emissions remain unchanged. Even though fuel-related emission savings are significant (10 % and 45 %) their influence on overall emissions remains

Part II: Methods

Methods Part 2 (Basics of material flow analysis)

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modest (4 % and 16 %). To achieve significant overall emission reductions, process emission reductions are essential.

Option 5b depends heavily on the availability of sufficient quantities of substitute materials (furnace slag and fly ash) and on whether the produced cement meets structural engineers' standards.

Option 5d depends on macro-economic developments and the future significance of concrete as building material.

Further options like CCS and alternative materials for cement were not considered in this analysis. However, these alternatives are currently under development.

Combining together the investigated strategies can lead to a system-wide emission reduction of about 50 %.

In 2000, the reference year for many climate targets, the global cement production volume was only 1.6 Gt/yr, which means that overall emissions from the cement sector were much lower than today simply because the annually produced quantity was more than 50% lower than today. The global emissions reduction target for the 2°C mark for the time period 2000-2050 is about 50 % and the EU goal is 80 %. Consequently, the emissions reduction measures investigated in this exercise are nowhere near to being sufficient for reducing the contribution of the cement industry on global climate change.