# IEooc_Methods2_Exercise1: Cement production – systems analysis

# Sample solution

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

***Goal**: Consolidate understanding of basic quantitative system analysis. Transfer of detailed knowledge about energy use and greenhouse gas emissions of the cement industry.*

**1) Estimate the annual demand for cement in a region of your choice, based on a simplified model of the stock-flow-service nexus for residential buildings, non-residential buildings, or infrastructure. Take into account both maintenance of the existing and expansion of the stock.**

Residential buildings in Japan were chosen as case study. The current (2025) in-use stock of residential buildings is about 4850 km² or 4.85 billion m². (See Excel workbook "MEFA_Exercise_3_Cement_ Production_SampleSolution.xlsx", table "task 1" for exact values and the reference IEDC dataset). To keep it simple, we focus on the service/function category 'shelter' and thus take the stock in m² as proxy for the service.

The lifetime of residential buildings in Japan is rather short, a value of 35 yr was chosen from an IEDC dataset (see Excel for details).

For the maintenance part, a simple stationary stock model is applied, where *inflow = stock/lifetime*:

$$F_m = S/T = 4836\ km^2/35yr = 138\ km^2/yr.$$

For the expansion (built-up) part, an annual growth rate was assumed depending on Japan's current stock level and economic activity. A low growth rate of 1%/yr was chosen, since Japan has high per capita stock levels already:

$$F_b = S*r = 4836\ km^2*1\%/yr = 48\ km^2/yr.$$

Which leads to a total new construction of

$$F_{new} = F_m + F_b = 187\ km^2/yr.$$

This inflow of newly constructed buildings into the use phase is converted to the final demand of materials (cement) in those buildings by multiplying it with the average cement content of residential buildings in Japan. Because several distinct construction technologies are popular, there is no single value for this parameter. Rather, we consider a range of cement content of residential buildings in Japan ranging from high values (for residential buildings as concrete structures) to low values (for timber structures). Moreover, there is a difference between single-family and multi-family houses. We consider this by taking the average values for single and multi-family houses and reporting concrete-based and timber-based structures separately:

$MC_{concrete_low} = 309\ kg/m^2$ // $MC_{concrete_high} = 819\ kg/m^2$

By applying a cement content of concrete (mass share) of *ccc = 13%*, we can convert the new construction flow in m²/yr to the flow of cement contained in these new buildings in form of concrete:

$$F_{cement_low} = F_{new} * MC_{concrete_low} * ccc = 7{,}5\ Mt/yr$$

$$F_{cement_high} = F_{new} * MC_{concrete_high} * ccc = 20\ Mt/yr$$

Based on this simple estimation, we see that

- Maintaining the existing stock dominates new construction, the contribution of materials and floorspace related to stock expansion is relatively small, which is typical of countries with high levels of in-use stocks.
- Due to the different building types and construction techniques, the amount of cement required varies considerably, in this case by a factor of about 3 between timber-based and concrete-based construction.

The values calculated above are documented on sheet 'Task 1' of the accompanying Excel workbook (see ILIAS). They can be used below in tasks 5 and 6 to calculate the energy demand and GHG for the production of cement and develop different GHG mitigation scenarios.

**2) 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.**

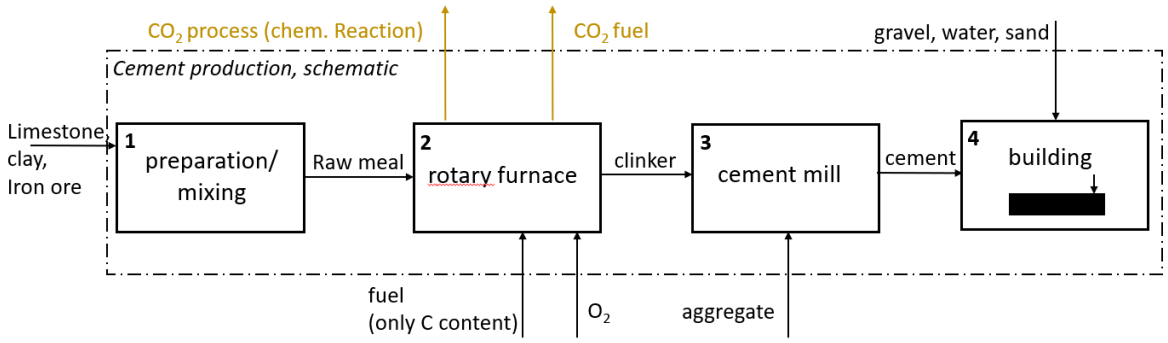


**Fig. 1:** system diagram for cement production and concrete mixing + use.

**3) 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, $CO_2$ process, clinker) and one for fuel (fuel, $O_2$, $CO_2$ 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<br>OR<br>Concrete demand X | Z<br><br>X = Z/α | 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:

$$\gamma = \frac{M(CaCO_3)}{M(CaO)} \cdot x + (1 - x) \quad (1)$$

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

$M(CaCO_3)$ = 100 g/mol, M(CaO)= 56 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:

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

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:

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

**4) Determine the analytical solution of the system for an unkown 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) |
| $\Delta S_4$ | $= X$ | (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) |

**5) Quantify your solution using given data and required additional information for the cement demand obtain in task 1! How do the overall total emissions distribute across process and fuel emissions? (If you skipped task 1, work with the current global demand of ca. 4 Gt/yr)**

→ See excel file "MEFA_Exercise_3_Cement_Production_SampleSolution.xlsx", table "task 5". The provided formulas differ slightly from the formulas given under task 3 above, since here $F_{34}$ and not $\Delta S_4$ 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 $CO_2$ 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.*

**6) Calculate the future process and fuel-related $CO_2$ emissions of the cement demand obtain in task 1 (use the current global cement production of 4 Gt/yr if you skipped task 1). Assume that the following improvements will be implemented and calculated the new material, energy, and GHG flows for the improved system:**

**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 tasks 6 a through e were calculated using excel (file "MEFA_Exercise_3_Cement_Production_SampleSolution.xlsx") for the case of the current global cement production of 4 Gt/yr. For other demand values, all flows scale proportionally. The results are summarized in the following table:

**Table 2:** $CO_2$ emission for various scenarios for the current global cement production of 4 Gt/yr.

| | Process emissions (Gt/yr) | %-Reduction | Fuel emissions (Gt/yr) | %-Reduction | Total emissions (Gt/yr) | %-Reduction |
|---|---|---|---|---|---|---|
| **5 Baseline** | **1.76** | **0** | **0.95** | **0** | **2.70** | **0** |
| **6a Fuel efficiency** | 1.76 | 0 | 0.85 | 10 | 2.61 | 4 |
| **6b Less clinker** | 1.35 | 23 | 0.73 | 23 | 2.07 | 23 |
| **6c Natural gas** | 1.76 | 0 | 0.52 | 45 | 2.27 | 16 |
| **6d Demand reduction** | 1.32 | 25 | 0.71 | 25 | 2.03 | 25 |
| **6e All together** | **1.01** | **42** | **0.27** | **72** | **1.28** | **53** |

Option 6a and 6c 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

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

Option 6b 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 6d depends on macro-economic developments and the future significance of concrete as building material.

Further options like carbon capture and storage (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 where 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 goals 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.