Mass Balance Principle and Examples on the Process, Sectoral and Societal Levels

Mass Balance Principle

Mass Balance Principle

Mercury is an element = persistent

It is not destructible
It is not created in processes
It is only "fed" into process, or "society“ and released via process outputs to the environment (including waste deposits)

Total inputs = total outputs

Accumulation in times of changing activity (+/-)

"What goes in - must come out" - only the output pathways differ

UN environment programme

unitar
United Nations Institute for Training and Research

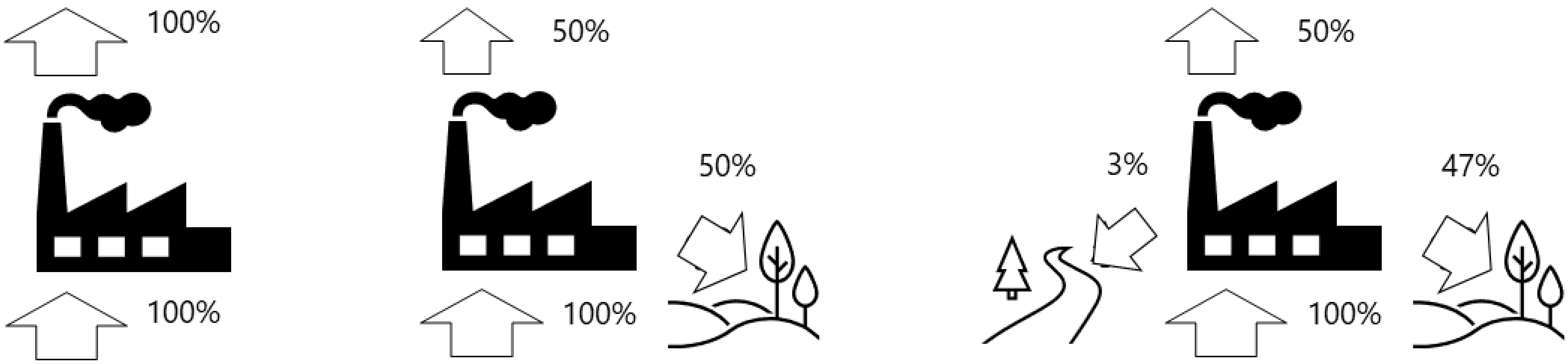
Mass Balance Example

Example: Coal-fired Power

No filter

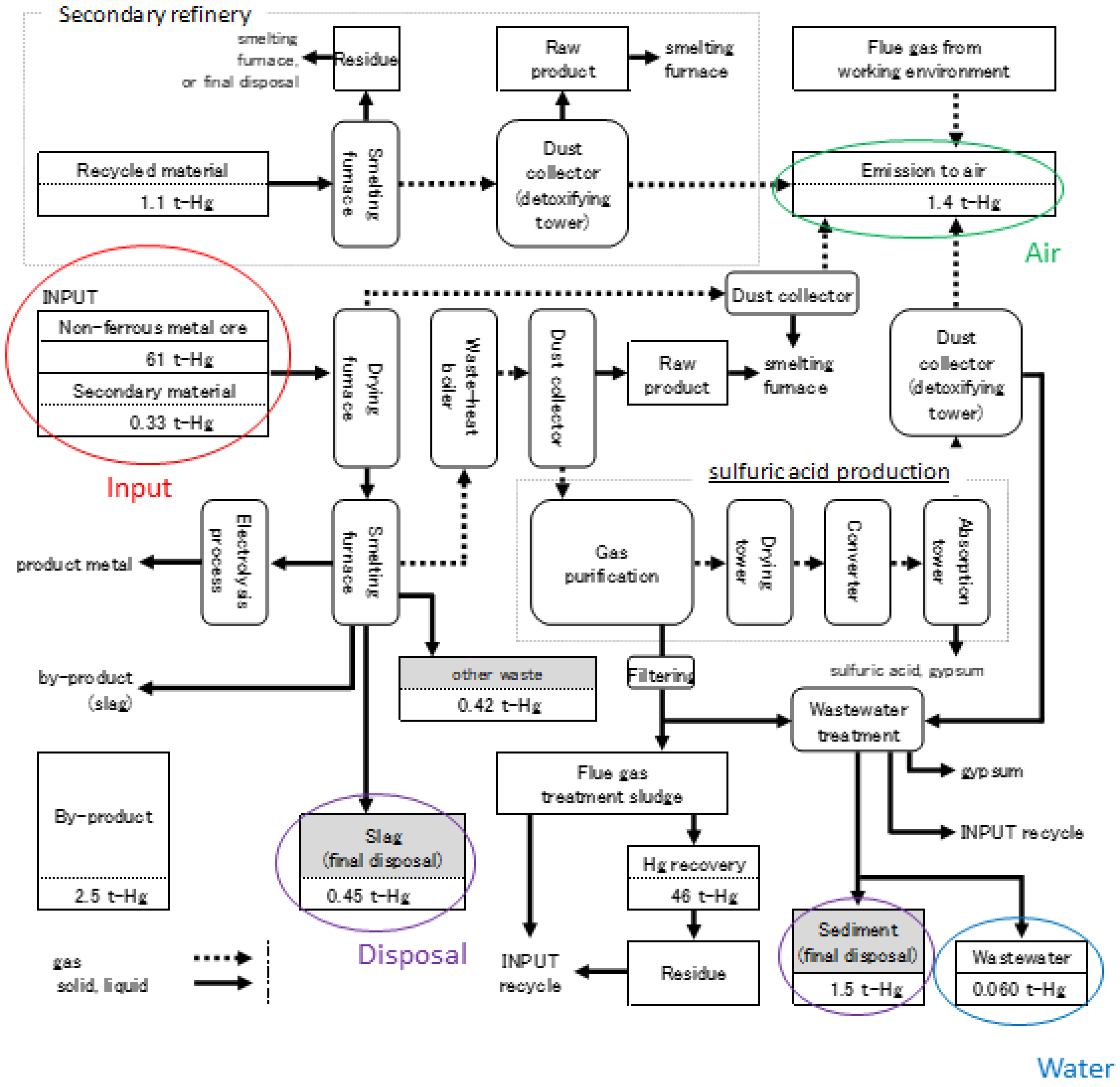
Fabric filter for particulate mater

Wet flue gas desulphurisation system



Process-level Example

Example: Non-ferrous metal smelting facilities



Source: MOEJ (2022). Overview of Mercury Material Flow in Japan (FY2016).

UN environment programme

unitar
United Nations Institute for Training and Research

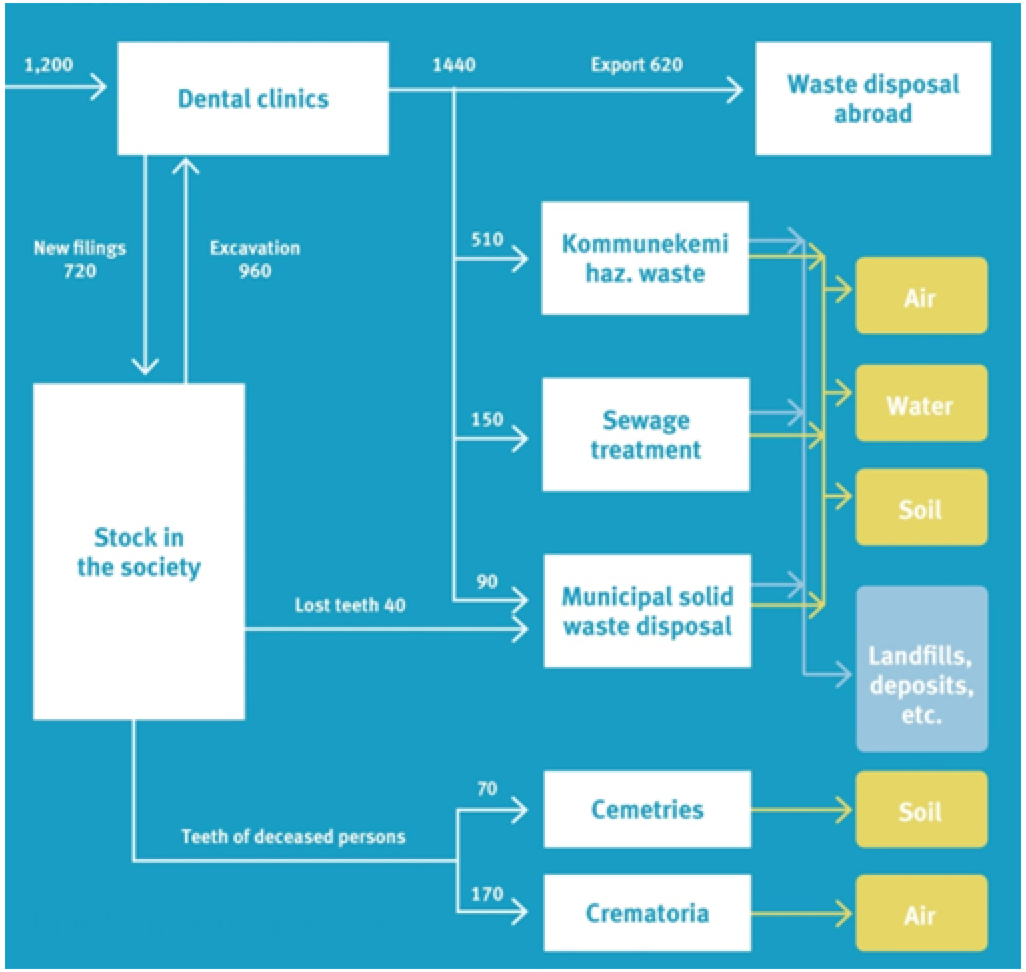
Mass Balance Principle and Examples on the Process, Sectoral and Societal Level

Mass Balance Principle

Sector-level Example

Example:

Life cycle and mass balance of dental amalgam



Unit: kg mercury per year

Source: Christensen *et al.* (2004). Mass flow analysis for mercury 2001.

UN environment programme

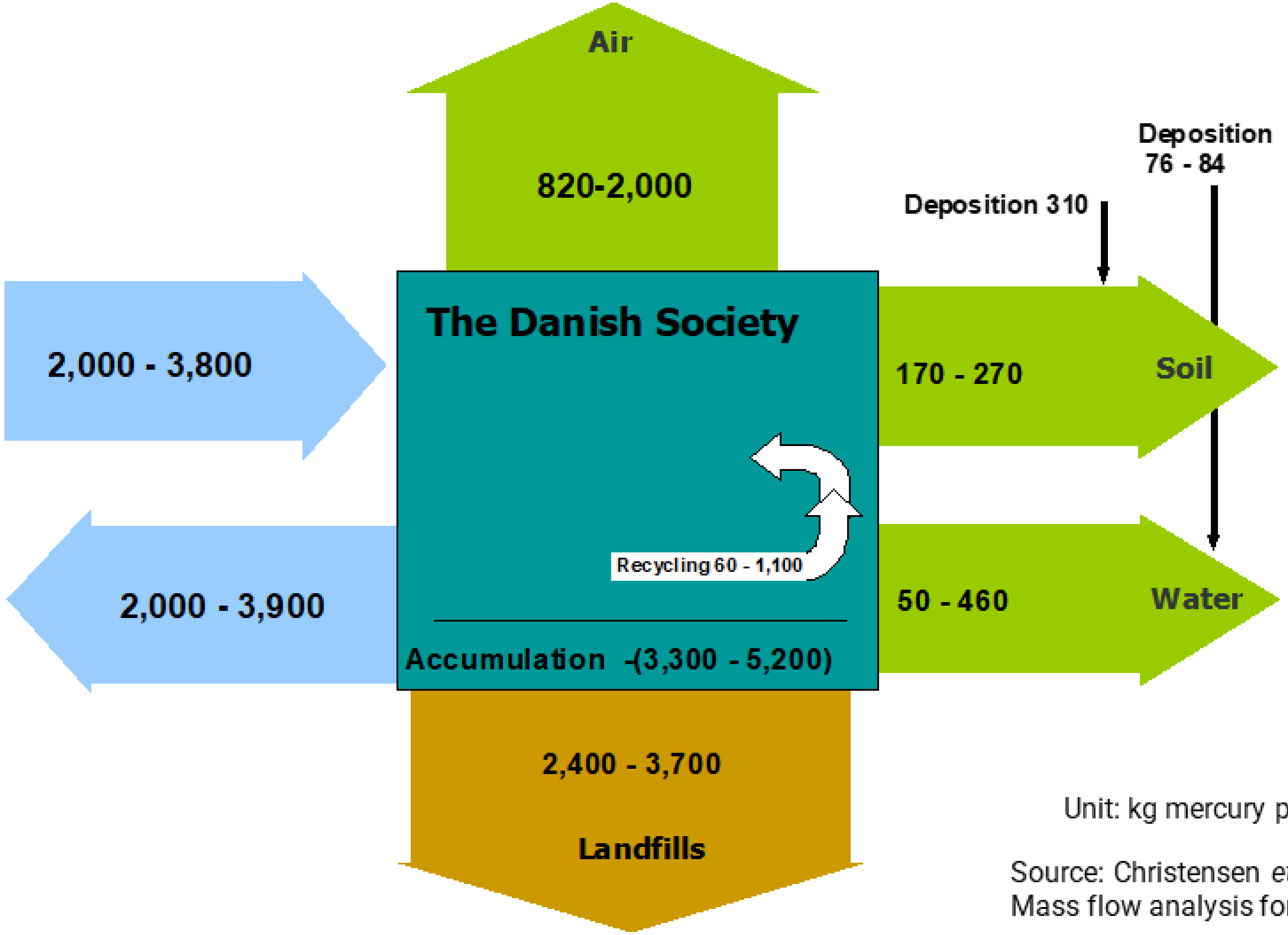
unitar United Nations Institute for Training and Research

Mass Balance Principle and Examples on the Process, Sectoral and Societal Level

Mass Balance Principle

National-level Example (1/2)

Example: Overall mass balance for mercury in Denmark, 2001



Unit: kg mercury per year

Source: Christensen *et al.* (2004). Mass flow analysis for mercury 2001.

UN environment programme

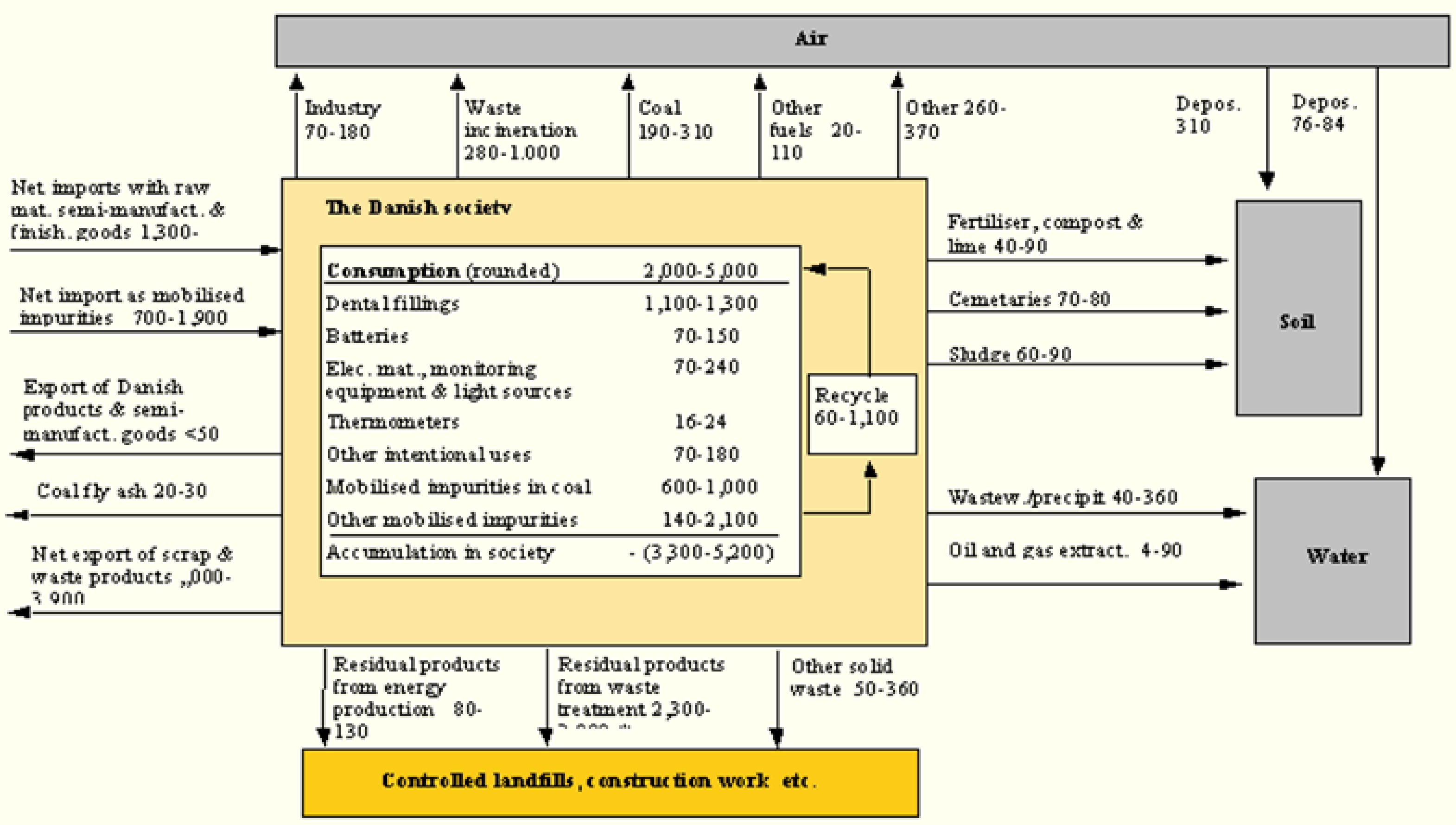
unitar United Nations Institute for Training and Research

Mass Balance Principle and Examples on the Process, Sectoral and Societal Level

Mass Balance Principle

National-level Example (2/2)

Example: Overall mass balance for mercury in Denmark, 2001 (detailed)



*Of this, 1,900-2,900 kg of mercury is exported for deposition abroad.

Unit: kg mercury per year

Source: Christensen *et al.* (2004). Mass flow analysis for mercury 2001.

Key Mass Balance Equations

Mass Balance Equations

INPUTS + FORMATION = OUTPUTS + DEGRADATION + ACCUMULATION

- Or, simplified for an element like mercury, which is neither formed nor degraded

INPUTS = OUTPUTS + ACCUMULATION

- Looking at a country or another “economic” system, it can be detailed to

INPUTS = IMPORT + PRODUCTION = RELEASES + EXPORT + ACCUMULATION

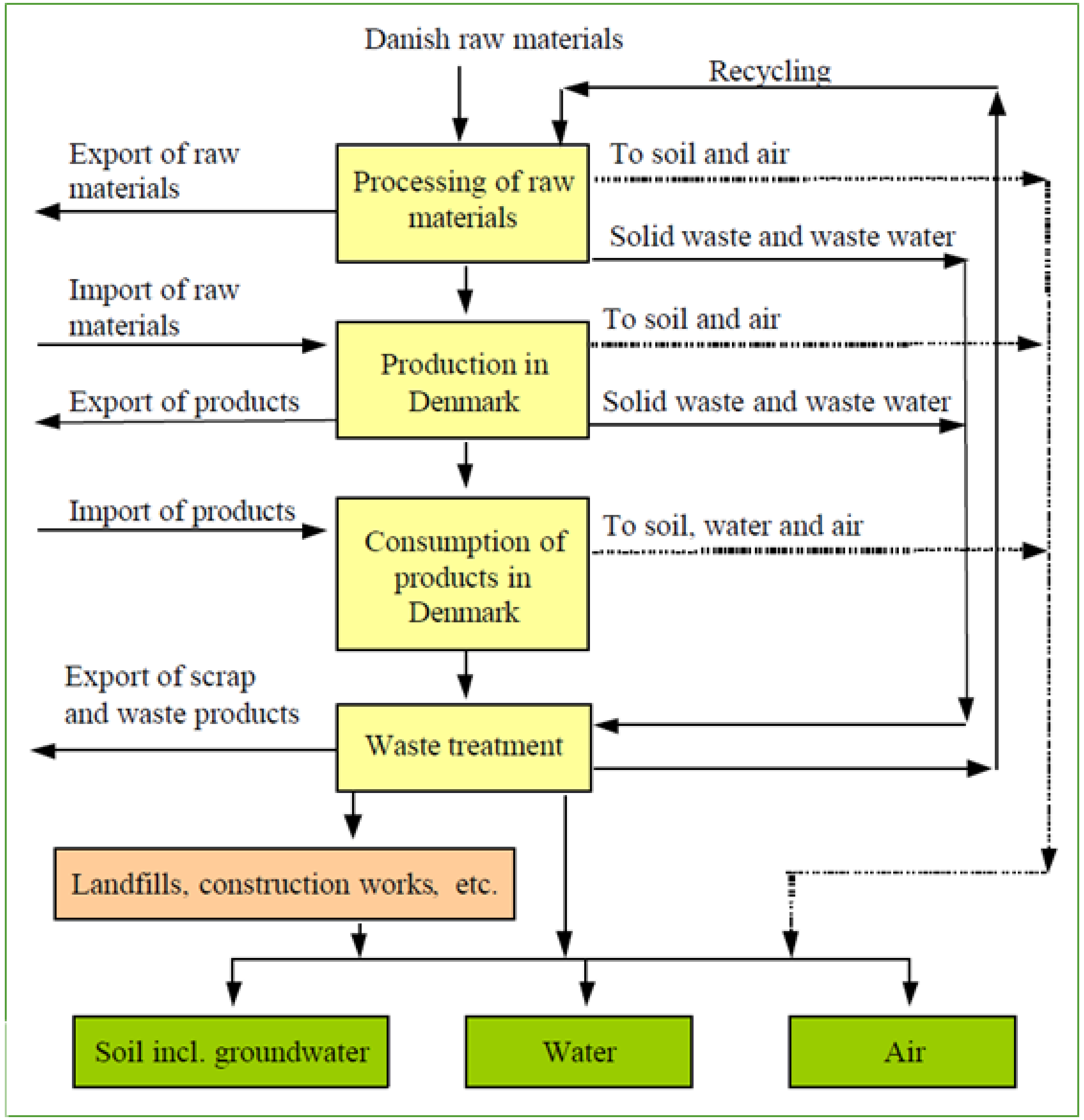
- Note that “releases” is used as a general term for all outputs to the environment, whereas in the Minamata Convention language this would equal emissions to air + releases to land and water

Life Cycle Principle

Example for a country (Denmark; products focus)

When the overall mass balance equation is used in a national perspective, all life cycle steps taking place in the country should be included:

- Raw materials processing
- Product and materials manufacturing
- Use phase
- Waste treatment



Source: Lassen and Hansen (2000). Paradigm for substance flow analyses.

UN environment programme

unitar
United Nations Institute for Training and Research

Mass Balance Principle and Examples on the Process, Sectoral and Societal Level

Key Mass Balance Equations

Domestic Consumption

- Equation for product and material "consumption", also called supply

$$CONSUMPTION = PRODUCTION + IMPORT - EXPORT$$

UN environment programme

United Nations Institute for Training and Research

System Definition and Boundaries

General System Boundaries (1/2)

Physical boundaries: National territory, i.e., the national economy within its territory.	Using the national economy is easiest because the trades and production statistics follow this boundary.	
	Relevant to national reporting required by the Minamata Convention.	
	Consider emissions and releases to the environment as losses or outputs from the economy.	Atmospheric and waterway deposition coming from outside the territory is included as input in some mercury flow analysis.
		Transboundary mercury movement as outputs.

General System Boundaries (2/2)

Time boundary: 1 year, called the base year or reference year (calendar year, or fiscal year whichever easier in the national setting).	It is practical to have this base year a few years back to ensure that the statistical data is available for that year.
	In case more qualified data becomes available later, it can be indicated in the inventory report.
	In case recent data are not available, slightly older data can also be used as an approximation.

UN environment programme

unitar United Nations Institute for Training and Research

Other System Boundaries

In the practical work for developing a mass flow, other boundaries can be delineated.	Sector boundaries: for example, a mass flow for the whole coal-fired power plant sector in the country.
	Process boundaries: for example, a mass flow for one individual coal-fired power plant.

Accumulation: Quantification, Prediction and Implications

What is Accumulation

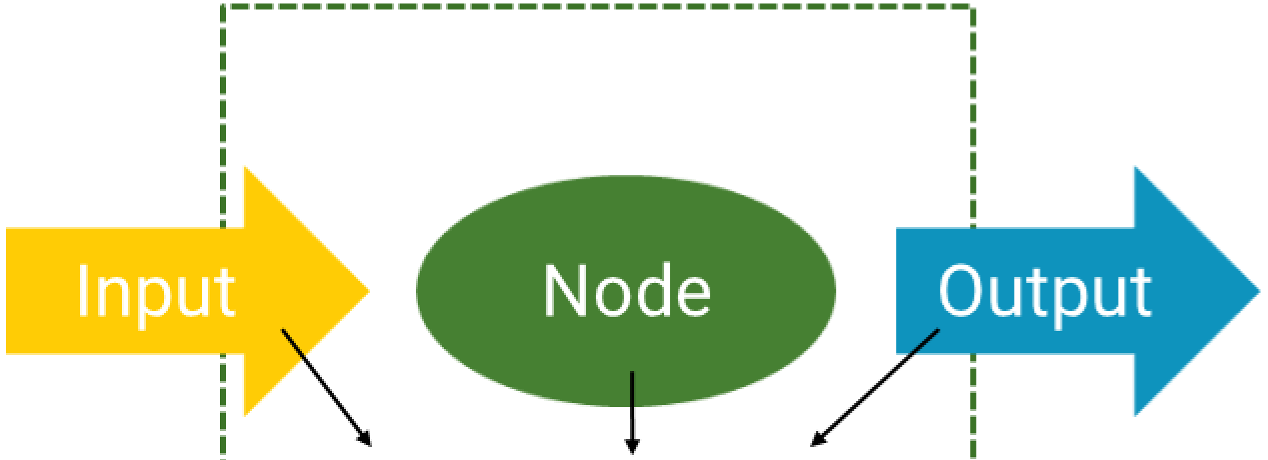
- The total accumulation used here equals to the total 'stock', which is the amount of material, mercury, currently present within the system boundaries.
  - In year 0, when the first mercury was introduced into the economy, there was no accumulation (or stock)
- If *input = output*, a steady state situation, and there will be no accumulation
- If *input > output*, there will be accumulation
- If *input < output*, the accumulation will decrease
- But the accumulated mercury can still result in releases to the environment

UN environment programme

unitar
United Nations
Institute for Training and Research

Mathematical Expression of Accumulation

Mass balance equation around the node, during the time Δt



$$I\Delta t = \Delta S + O\Delta t$$

$$\Delta S = I\Delta t - O\Delta t$$

$$S = S0 + I\Delta t - O\Delta t$$

Boundary of the mass balance

Scales of focusing node

- Process-scale
  - Focused on specific process in the plant
- Plant-scale
  - Focused on the specific plant in the sector
- Sector-scale
  - Focused on industrial sector
- National-scale
  - National statistics of the relevant material/products

I: inflow of mass in tonnes/year, etc.
O: outflow of mass in tonnes/year, etc.
S: stock in node in tonnes, etc.

Different Types of Stocks

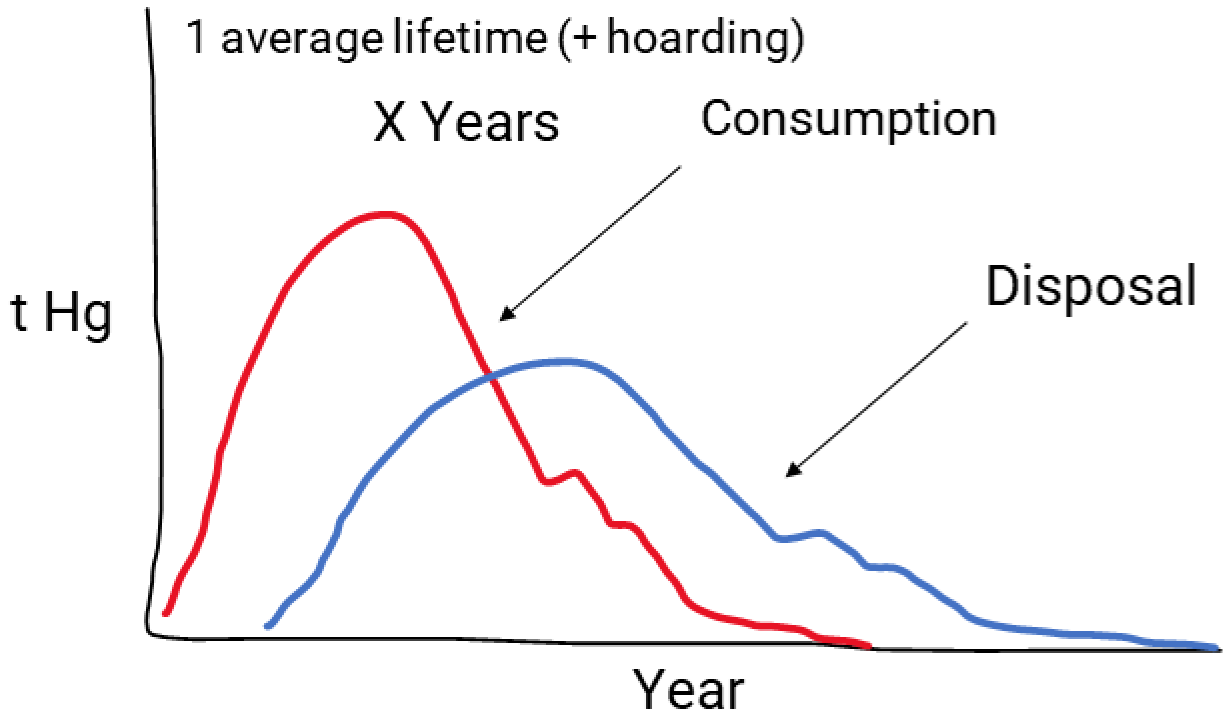
- Various types of stocks, or accumulation in different nature depending on the system
- The total stock in society is the sum of all stocks, including:
  - Stocks with consumers of products in use, or out of use but not yet disposed off (hoarded)
  - Stocks in industry; still in production line, purchased for later internal use, or phased out but not yet disposed of
  - Stocks with recycling/recovering facilities, either in the form of waste material not yet processed or recovered mercury
  - Stocks in mercury trade, accumulated for sale
  - Government stocks for national security

UN environment programme

unitar
United Nations Institute for Training and Research

Delayed Releases and Waste Treatment

The accumulation of mercury in products in use in society means that mercury consumed previously still needs to be managed.

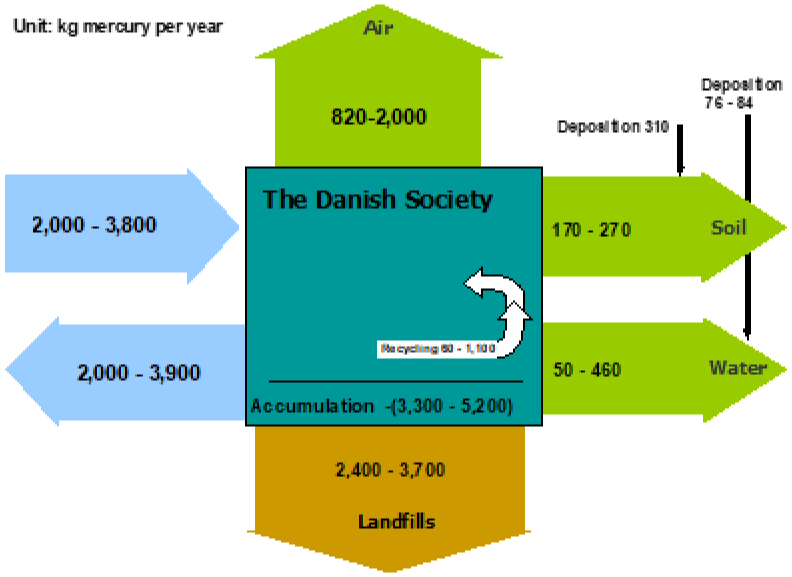


In reality, the disposal curve will have longer tail due to variation in the lifetime of the product

Relations between Mercury Mass Flows and the UNEP Mercury Inventory Toolkit

Mass Balance Principle in UNEP Toolkit

- The Toolkit is based on the mass balance principle, but with some simplifications.
- In the design phase, simplifications were made to:
  - makes it more accomplishable for key target users as data for full mass balances for mercury are still lacking in most countries.
  - makes calculations more standardized.



Source: Christensen *et al.* (2004). Mass flow analysis for mercury 2001.

Key Simplifications / Deviations (1/4)

1. It was chosen that inputs to waste treatment are calculated separately.

Reason: Outputs to waste from mercury-added products uses are generally under-estimated in developing countries due to lack of data

Advantages: The importance of waste management will not be ignored

Disadvantages: Inputs to waste treatment are detached from the inputs to mercury-added products

Key Simplifications / Deviations (2/4)

2. Outputs from (engineered) landfills are signal values, not mass-balance derived.

- Reasons: No data were identified yet from which a mass balance could be derived!
- Advantage: It is signalled, that there are in fact outputs from engineered landfills
- Disadvantage: The values calculated are not reflecting ”true values” (though levels may be reasonable)
- (Un-protected landfills – waste dumps – are considered release to land in the Toolkit)

UN environment programme

unitar
United Nations
Institute for Training and Research

Key Simplifications / Deviations (3/4)

3. To avoid complex mass balance decisions for users, the mass flow from life cycle step 1 to step 2 are separately calculated in a number of cases.

For example, the output of mercury in products from domestic manufacturing is calculated separately from the input to the use phase for products

Reasons/ advantage:

- To avoid tackling case-specific flows
- To avoid potential double-counting
- Calculations can be made with more accessible data

Disadvantage:

- The data available do sometimes not match completely, resulting in (moderate) mis-matching in total inputs vs. total outputs

Key Simplifications / Deviations (4/4)

4. The calculations for dental amalgam are only semi-balanced in Inventory Toolkit Level 1.

- Reasons/advantage: To avoid the need for older input data to reflect current releases from drilling in old fillings
- Disadvantage: Big changes in dental amalgam inputs over time will not be fully reflected in the results
- Inventory Level 2 can be fully balanced if sufficient information is available

Other Simplifications (1/2)

In some cases input factors are aggregated because detailed data are often hard/impossible to get

Example 1: Cement clinker production

- Inputs of mercury from raw materials are aggregated (unit: g Hg input/t cement clinker produced)
- Inputs of mercury from fuels are aggregated by fuel type
- Reasons/advantage: Obtain results without knowing the exact raw material mix and fuel mix
- Disadvantage: Gives moderate deviations from ‘true’ values and requires more work to use local input factors

Other Simplifications (2/2)

Example 2: Use of polyurethane (PU) products with mercury catalysts

- The inputs of mercury are aggregated (unit: g Hg/population – based on EU data) with an adjustment for technological development level (unit-less electrification rate)
- Reasons/advantage: Getting actual data for share of PU with mercury and the supply in one country is almost impossible - simplification allows for indicative results
- Disadvantage: Gives deviations from ‘true’ values

OTHER MERCURY QUANTIFICATION TOOLS

Other Mercury Quantification Tools

Multi-pollutant air emission estimation guidance is available for use in PRTR systems developed under the Kyiv Protocol of Aarhus Convention.

- The EMEP/EEA air pollutant emission inventory guidebook: https://www.eea.europa.eu/publications /emep-eea-guidebook-2019/at_download/file
- Focuses on air emissions, applies different principles and sector definitions and less detailed than UNEP Toolkit for many source categories.
- Used by many countries mostly developed countries.