Economic Value Analysis

In this section, we use $B_S$ to denote the accumulated (net) economic value in sector $S$, which can be either positive or negative. We use $C_{f_{I,J}}$ to represent the value associated with P flow $f_{I,J}$ in the previous section. In general, the direction of the value flow opposes that of the physical P flow (because the seller usually gets paid and the buyer pays for the product). However, for certain waste streams, the direction of value flow and P flow are the same (because the waste producer needs to pay a tipping fee to take the product).

Mining Sector

The value balance in this sector is given in equation (0.1). The phosphate rock extracted in the mining sector is sent to the chemical sector at a price $C_{\text{rock}}$ (USD per tonne of phosphate rock) and $C_{f_{\text{MIS,CS}}}$ can be calculated using equation (0.2), where $x_{\text{rock}}$ is the P content in the phosphate rock. The P loss will incur a penalty cost due to the degradation of the environment. This penalty cost $C_{f_{\text{MIS,ES}}}$ is usually charged by a local government and can be
calculated using equation (0.3), where \( C_{waste} \) is the unit cost of waste P (USD per tonne of waste P).

\[
B_{MIS} = C_{fMIS,CS} - C_{fMIS,ES} \tag{0.1}
\]

\[
C_{fMIS,CS} = \frac{1}{x_{rock}} C_{rock} f_{MIS,CS} \tag{0.2}
\]

\[
C_{fMIS,ES} = C_{waste} f_{MIS,ES} \tag{0.3}
\]

**Chemical Sector**

The value balance in this sector is given by equation (0.4), where \( C_{fCS,DC} \) is the revenue for selling the chemical additives and \( C_{fCS,S} \) is the revenue for selling the fertilizers. These values can be calculated using equation (0.5) and (0.6), where \( C_{add} \) is the price of the additives (USD per tonne of additives), \( C_{fert} \) is the price of fertilizers (USD per tonne of fertilizers), and \( x_{add}, x_{fert} \) are the P content in the additives and fertilizers, respectively.

\[
B_{CS} = C_{fCS,DC} + C_{fCS,S} - C_{fMIS,CS} - C_{fCS,ES} \tag{0.4}
\]

\[
C_{fCS,DC} = \frac{1}{x_{add}} C_{add} f_{CS,DC} \tag{0.5}
\]

\[
C_{fCS,S} = \frac{1}{x_{fert}} C_{fert} f_{CS,S} \tag{0.6}
\]

This sector produces significant environmental impact and the discharges should be treated according to the environmental policy. The penalty cost associated with the P loss stream in this sector is given in equation (0.7).

\[
C_{fCS,ES} = C_{waste} f_{CS,ES} \tag{0.7}
\]

**Agricultural Sector**

In the agricultural sector (AS) (where the crops are cultivated, harvested, and processed) the soil condition defines the yields and the qualities (P content) of the crops that will be
used for the subsequent sectors in the network (e.g., dairy and urban sector). The economic gain generated from selling crops is the main retribution in this sector while, during the production of crops, the use of fertilizer produces soil degradation and water pollution. The value balance in the agricultural sector is given in equation (0.8), where the positive terms ($C_{fHC,F}$ and $C_{fHC,DC}$) are the revenue by selling crop products, the negative terms include the costs for fertilizers ($C_{fM,S}, C_{fWS,S}$, and $C_{fCS,S}$) and the environmental costs for P loss in each sub-sectors ($C_{fS,ES}, C_{fRC,ES}$, and $C_{fHC,ES}$).

$$B_{AS} = C_{fHC,F} + C_{fHC,DC} + C_{fHC,B} - C_{fM,S} - C_{fWS,S} - C_{fCS,S} - C_{fS,ES} - C_{fRC,ES} - C_{fHC,ES}$$ (0.8)

The value of crop products sent to subsequent sectors is estimated using equation (0.9) and (0.10) by assuming that the price of a certain crop is the same in different sectors, where $C_{corn}$ price of corn (USD per tonne of corn), $X_{corn}$ is the fraction of corn in the feed of the dairy sector, $x_{corn}$ is P content in corn, $C_{silage}$ is price of silage (USD per tonne of silage), $X_{silage}$ is the fraction of silage in the feed of the dairy sector, and $x_{silage}$ is P content in the silage. The value of crops sent to external regions outside the system boundary is calculated by equation (0.11) (this assumes that the prices are the same).

$$C_{fHC,F} = \frac{1}{x_{corn}}C_{corn}f_{HC,F}$$ (0.9)

$$C_{fHC,DC} = \left( \frac{X_{corn}C_{corn}}{x_{corn}} + \frac{X_{silage}C_{silage}}{x_{silage}} \right) f_{HC,DC}$$ (0.10)

$$C_{fHC,B} = \frac{1}{x_{corn}}C_{corn}f_{HC,B}$$ (0.11)

The soil receives different types of fertilizers including chemical fertilizers, treated manure, and wastewater sludge. The values for treated manure and wastewater sludge are given in equation (0.12) and (0.13), where $C_{manure,t}$ is the price of treated manure (USD per tonne of treated manure), $x_{manure,t}$ is the P content in the treated manure, $C_{sludge}$ is the value
of the wastewater sludge (USD per tonne of sludge), and \( x_{sludge} \) is the P content in the sludge.

\[
C_{f_{M,S}} = \frac{1}{x_{manure,t}} C_{manure,t f_{M,S}} \tag{0.12}
\]

\[
C_{f_{WS,S}} = \frac{1}{x_{sludge}} C_{sludge f_{WS,S}} \tag{0.13}
\]

In the three sub-sectors, the P loss are of particular interest because the use of nutrients by the crops depend mainly on the absorption efficiency. The cost for having a P loss in each sub-sector is given in equation (0.14)-(0.16)

\[
C_{f_{S,ES}} = C_{waste f_{S,ES}} \tag{0.14}
\]

\[
C_{f_{RC,ES}} = C_{waste f_{RC,ES}} \tag{0.15}
\]

\[
C_{f_{HC,ES}} = C_{waste f_{HC,ES}} \tag{0.16}
\]

**Urban Sector**

The value balance of different streams in the urban sector is obtained from equation (0.17). We note that the urban sector always loses money because they need to purchase food, pay for the tipping fee for wastewater, and pay for the environmental penalty cost (this sector does not generate revenue).

\[
B_{US} = -C_{f_{ cUS}} - C_{f_{US,WS}} - C_{f_{US,ES}} \tag{0.17}
\]

The value of the products supplied to the urban sector is calculated using equation (0.18) under the assumption that there is no value accumulation in the food distribution stage. In this equation, \( C_{f_{HC,F}} \) corresponds to the cost of buying crop sector (which is given in equation (0.9)), and \( C_{f_{DS,F}} \) corresponds to the cost of purchased dairy products, which will
be introduced in section.

\[ Cf_{US} = Cf_{HC,F} + Cf_{DS,F} \]  

(0.18)

The tipping fee required for urban P discharges to the wastewater treatment infrastructure is given in equation (0.19) where \( C_{desh} \) is the tipping cost of the wastewater (USD per tonne) from the urban sector, and \( x_{desh} \) is the P content in the urban wastewater. The environmental cost is given in equation (0.20).

\[ Cf_{US,WS} = \frac{1}{x_{desh}} C_{desh} f_{US,WS} \]  

(0.19)

\[ Cf_{US,ES} = C_{waste} f_{US,ES} \]  

(0.20)

**Waste Management (Wastewater Treatment)**

The value balance in the wastewater treatment infrastructure is given in equation (0.21). The positive terms represent the revenue generated by selling wastewater sludge as fertilizer \( (Cf_{WS,S}) \) and the tipping fee from the urban sector \( (Cf_{US,WS}) \). The only negative term is the environmental cost for P loss, which can be calculated using equation (0.22).

\[ B_{WS} = Cf_{WS,S} + Cf_{US,WS} - Cf_{WS,ES} \]  

(0.21)

\[ Cf_{WS,ES} = C_{waste} f_{WS,ES}. \]  

(0.22)

**Dairy Sector**

The actual prices in the market of the dairy products depend on the price fluctuations of the raw materials, chemicals, waste and the costs of operation along the sectors in the system. The value balance of the dairy sector (DST) is given in equation (0.23), where the positive terms are the revenue achieved by selling manure \( (Cf_{DC,M}) \), selling dairy products to in-state and out-of-state customers \( (Cf_{DS,E} \text{ and } Cf_{DS,F}) \), and selling excess products \( (Cf_{DS,B}) \).
The negative terms correspond to the costs of purchasing chemical additives ($C_{fCS,DC}$) and feed crops ($C_{fHC,DC}$), as well as the environmental cost for P losses ($C_{fDC,ES}$).

$$B_{DST} = C_{fDC,M} + C_{fDS,E} + C_{fDS,F} - C_{fHC,DC} - C_{fDC,ES} - C_{fCS,DC} \quad (0.23)$$

The value of the manure generated is calculated using equation (0.24), where $C_{manure,r}$ is the price of raw manure (USD per tonne of raw manure) and $x_{manure,r}$ is the P content in raw manure. We note that the price of raw manure can either be positive or negative depending on the study region, which means the dairy sector can either sell the manure to the processing site, or pay a fee to it (in the form of a tipping cost). Here we treat this term as a revenue based on the fact in the State of Wisconsin. 7

$$C_{fDC,M} = \frac{1}{x_{manure,r} f_{DC,M}} C_{manure,r} \quad (0.24)$$

The value of the export stream is calculated using equation (0.25), where $X_{milk}$ is the fraction of P present in milk, $X_{cheese}$ is the fraction P present in cheese, and $C_{milk}, C_{cheese}$ are current prices for milk (USD per liter) and cheese (USD per tonne), respectively. And similarly, the value of in-state product stream can be calculated using equation and (0.26).

$$C_{fDS,E} = \left( \frac{X_{milk} C_{milk}}{x_{milk}} + \frac{X_{cheese} C_{cheese}}{x_{cheese}} \right) f_{DS,E} \quad (0.25)$$

$$C_{fDS,F} = (\beta_{mp} C_{milk} + \beta_{chp} C_{cheese}) P_{human} = \left( \frac{X_{milk} C_{milk}}{x_{milk}} + \frac{X_{cheese} C_{cheese}}{x_{cheese}} \right) f_{DS,F} \quad (0.26)$$

The value of the agricultural products and chemical additives are computed in equation (0.10) and (0.5). The environmental cost associated to this sector is given in equation (0.27).

$$C_{fDC,ES} = C_{waste f_{DC,ES}} \quad (0.27)$$
Waste Management (Manure Processing)

The value balance in the manure processing sector is given in equation (0.28). The positive terms represent the revenue made by selling the treated manure as fertilizer ($C_{f_{M,S}}$). The negative terms are the cost associated to the purchase of raw manure $C_{f_{M,DC}}$ and the environmental cost for P loss, which are calculated using equation (0.29).

$$B_M = C_{f_{M,S}} - C_{f_{DC,M}} - C_{f_{M,ES}} \quad (0.28)$$

$$C_{f_{M,ES}} = C_{waste}f_{M,ES}. \quad (0.29)$$

Total Value Balance

The global value for the system is presented as the sum of the accumulated value in each sectors, as indicated by equation (0.30). Here, the value balance for every sector is interpreted as profit (if positive) or cost (if negative). Consequently, the total balance is the total systems-level profit or cost.

$$B_{TOTAL} = B_{MIS} + B_{CS} + B_{AS} + B_{US} + B_{WS} + B_{DST} + B_M \quad (0.30)$$

The value balance also defines a 28 dimensional linear system of equations that is solved along the P flow balance.

Parameters

The parameters used in this study are listed in Table 1.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<th>Units</th>
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</thead>
<tbody>
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<tr>
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<td>$C_{desh}$</td>
<td>10</td>
<td>12</td>
<td>USD/tonne wastewater</td>
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References


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