The P-graph Methodology as a Tool for Supply Chain Design in the Food-Energy-Water Nexus

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Outline

- The P-Graph Framework
- Sustainability
- Illustration: Supply Chain Design
- Summary

The P-Graph Framework

P-Graph Axioms:

combinatorially feasible process networks

For given process synthesis problem, a P-graph satisfying the following five axioms is a combinatorially feasible structure:

(S1) Every final product is represented in the structure

(S2) A material represented in the structure is a raw material if and only if it is not an output of any operating unit represented in the structure

(S3) Every operating unit represented in the structure is defined in the synthesis problem

(S4) Any operating unit represented in the structure has at least one path leading to a product

(S5) If a material belongs to the structure, it must be an input to or output from at least one operating unit represented in the structure

Process Synthesis by P-graph framework

PNS problem: (P, R, O)

↓

Automatic model generation: MSG

↓

Maximal structure

↓

Optimization with ABB

↓

Optimal structure

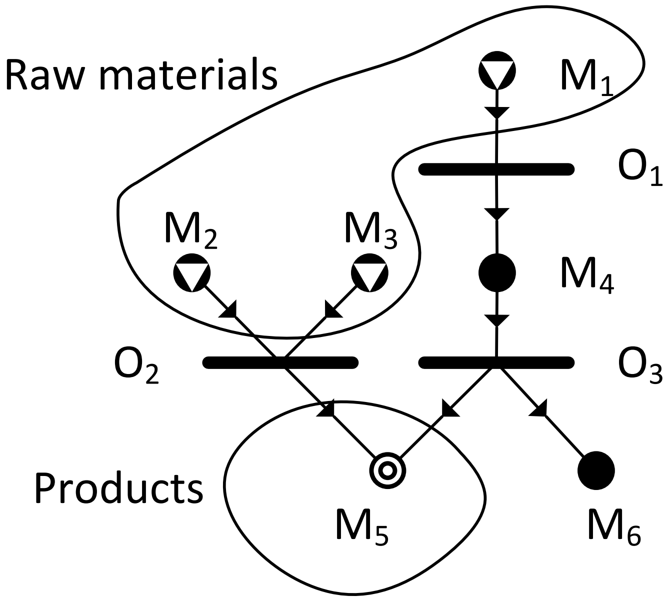
P-Graph Process Synthesis (Friedler and Fan, 1992-)

Synthesis

Building blocks:

- **materials:**
  - **raw materials:**
  - **products:**
  - **intermediates:**
- **operating units:**

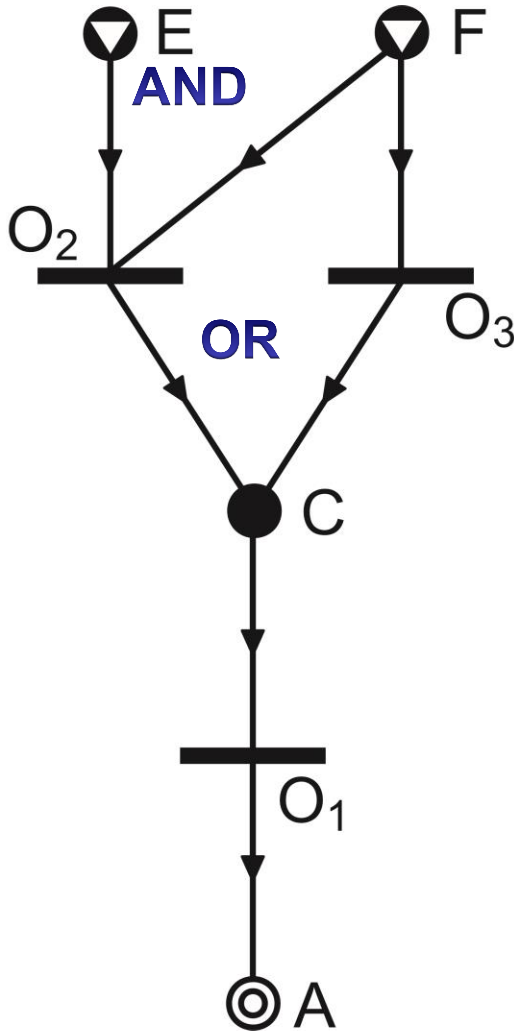
Process structure:



P-graph methodology: Structural Representation

Clear logical interpretation

- **Each precondition (E AND F) has to be satisfied to operate an activity (O_2)**
- **Any of the activities (O_2 OR O_3) having the same effect can potentially be sufficient to initiate the consecutive step (O_1)**



Sustainability

Ecological Footprint Basics

Land is categorized into:

- –**arable land**
- –**forest land**
- –**pasture land**
- –**sea**
- –**energy land**
- –**built land**

blog.lib.umn.edu/tupp0008/environment/2008/02/

Ecological Footprint Basics

- ***Ecological Footprint*** **(demand) = land area required to meet level of consumption and waste generation by the human population**
- ***Biocapacity*** **(supply) = land area available to support the human population**

Assumptions:

- **Can track of resources and waste generated**
- **Resource and waste flows can be converted to land area**

Sustainability Criteria: Ecological Footprint does not increase and Biocapacity does not decrease

$\Delta EF \leq 0$ ***and*** $\Delta B \geq 0$

Ecological Footprint (EF) and Biocapacity (BC) Calculation

For each land type i:

$$EF_i = \frac{T}{Y_i} \times YF_i \times EQF$$

$$BC_i = S_i \times YF \times EQF$$

- **T = Annual quantity of produced**
- **Y_i = local yield**
- **YF_i = yield factor (Y_i / Y_w)**
- **Y_w = world yield**
- **EQF_i = (Maximum Productivity i)/(Avg Productivity All *i*)**

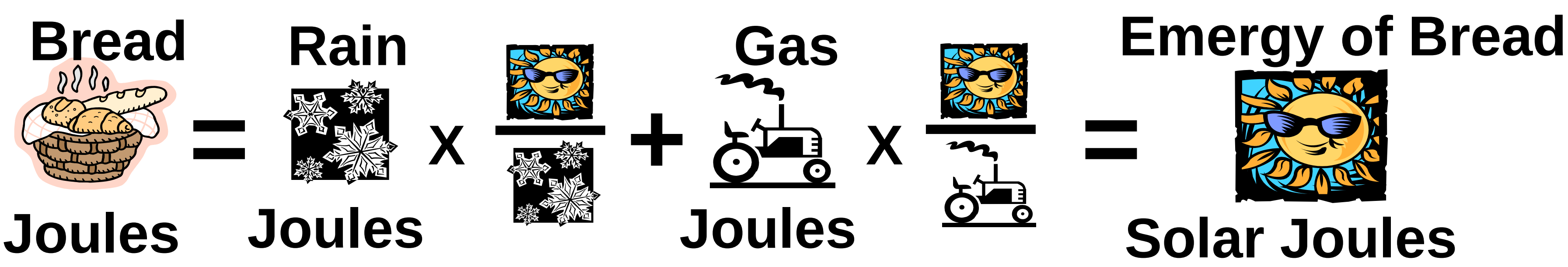
Total Footprint (EF) and Biocapacity (BC):

$$EF = \sum_i EF_i \qquad BC = \sum_i BC_i$$

Courtesy of Dr. M. Hopton, US EPA

Emergy: Basics

Emergy: the sum of all different kinds of energy previously used (directly and indirectly) to make a product



Emergy: Energy Resources

Emergy: the energy resources (in solar joules) invested by the environment in an operation or in a product

Emergy: the sum of all of the different kinds of energy previously used up, directly and indirectly, to make an item

Sustainability Criteria for Supply Chains:

(Total Emergy of Inputs) → Minimum

(Renewable Emergy Use) / (Total Emergy Use) → 1

Emergy Calculation

For a material *x* produced by a process *y*:

$$Em(seJ) = b_{x,y}\left[\frac{seJ}{kg\ of\ x\ produced\ by\ process\ y}\right] \cdot [A\ kg\ of\ x\ produced\ by\ process\ y]$$

For electricity produced by process *y*:

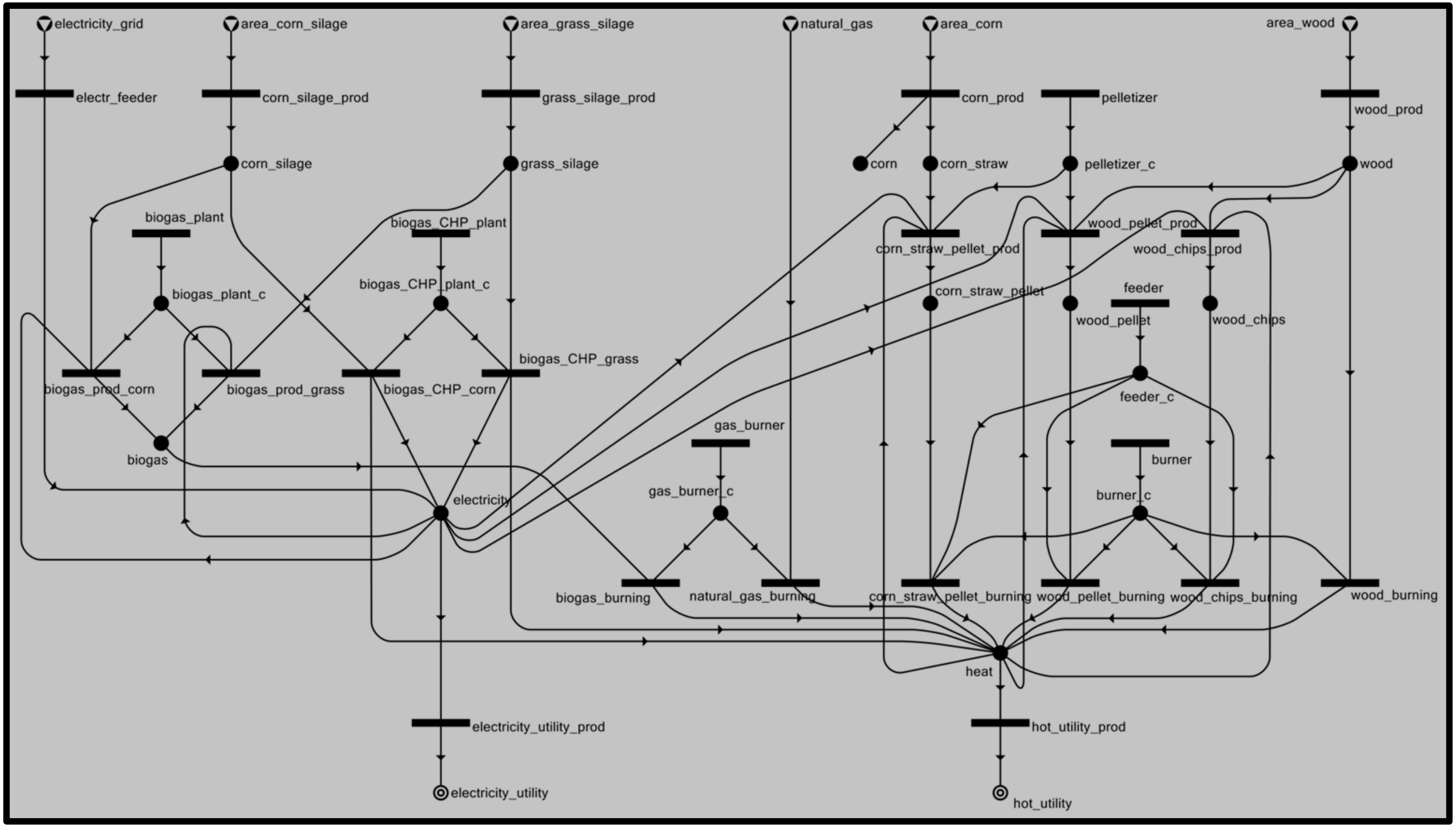
$$Em(seJ) = b_{e,y}\left[\frac{seJ}{joule\ of\ electricity\ produced\ by\ y}\right] \cdot [A\ joules\ of\ electricity\ produced\ by\ y]$$

Sustainable Supply Chain Design

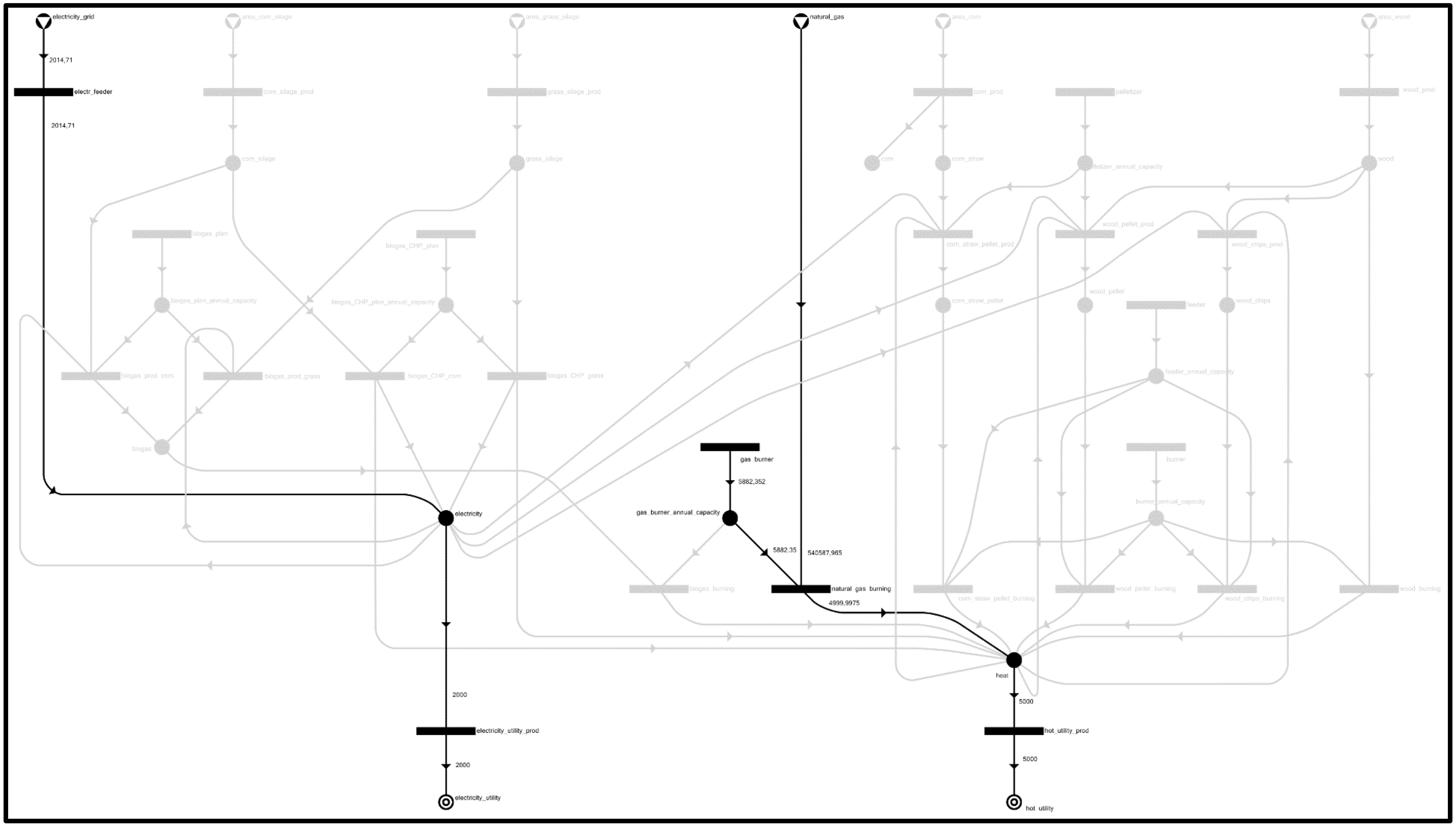
Raw Material & Energy Inputs

Solution structures	Raw materials					
	electricity_grid [TJ/yr]	natural_gas [m³/yr]	area_corn [ha/yr]	area_corn_silage [ha/yr]	area_grass_silage [ha/yr]	area_wood [ha/yr]
Structure1	7.37					500.00
Structure2				117.69		367.73
Structure3					128.54	367.73
Structure4				120.03		393.66
Structure5	7.57					539.13
Structure6					131.10	393.66
Structure7		399,272.00		116.30		
Structure8			72.96	126.77		
Structure9				124.78		380.69
Structure10		399,272.00			127.02	
Structure11			72.96		138.46	
Structure12					136.29	380.69
Structure13	7.25	540,588.00				
Structure14	7.99					529.10
Structure15	8.17		102.04			
Structure16				214.45		
Structure17				125.12	98.01	
Structure18				90.05	135.88	
Structure19					234.67	
Structure20	7.95			125.00		
Structure21	8.02				136.36	

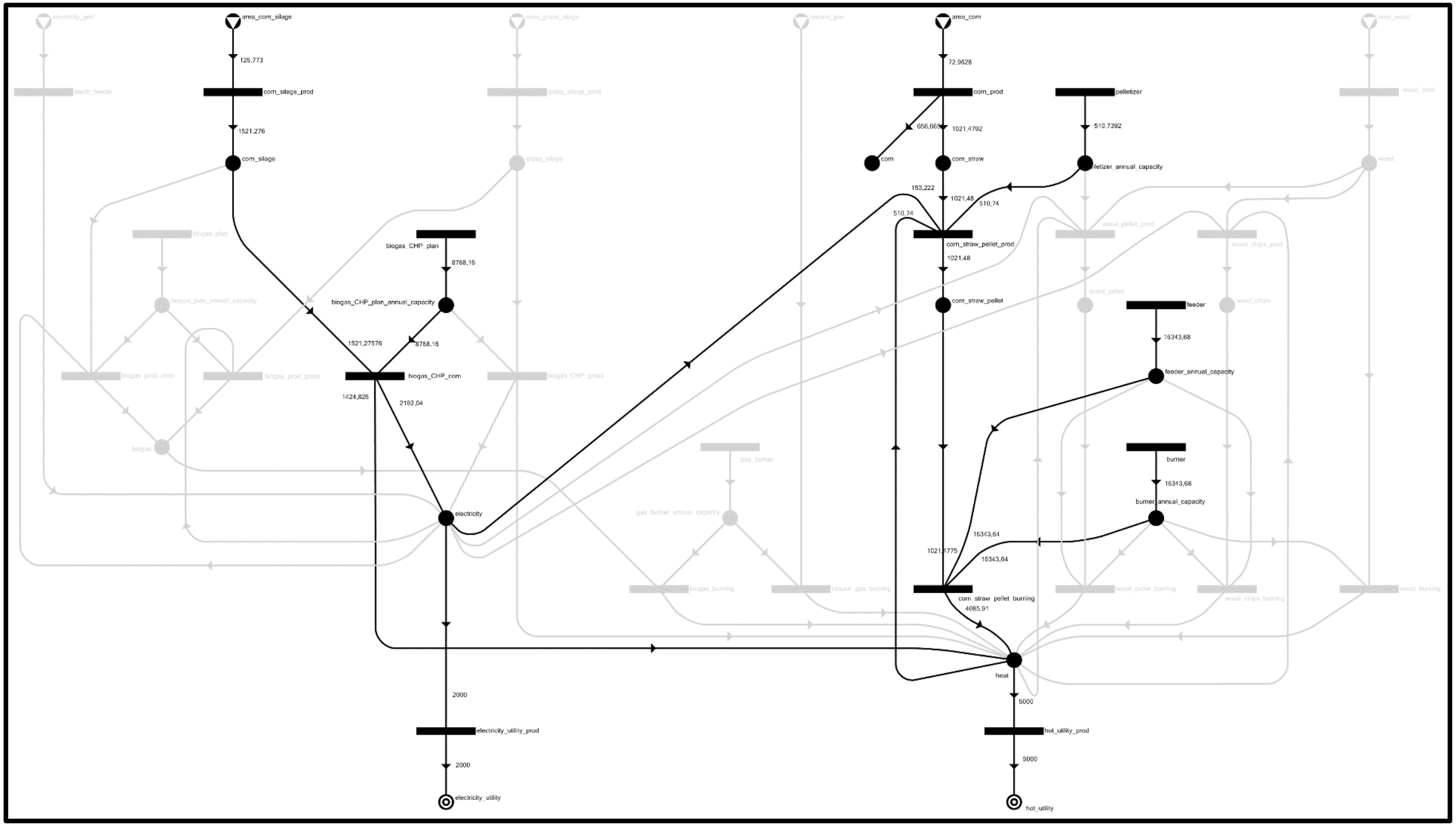
Maximal Supply Chain Structure



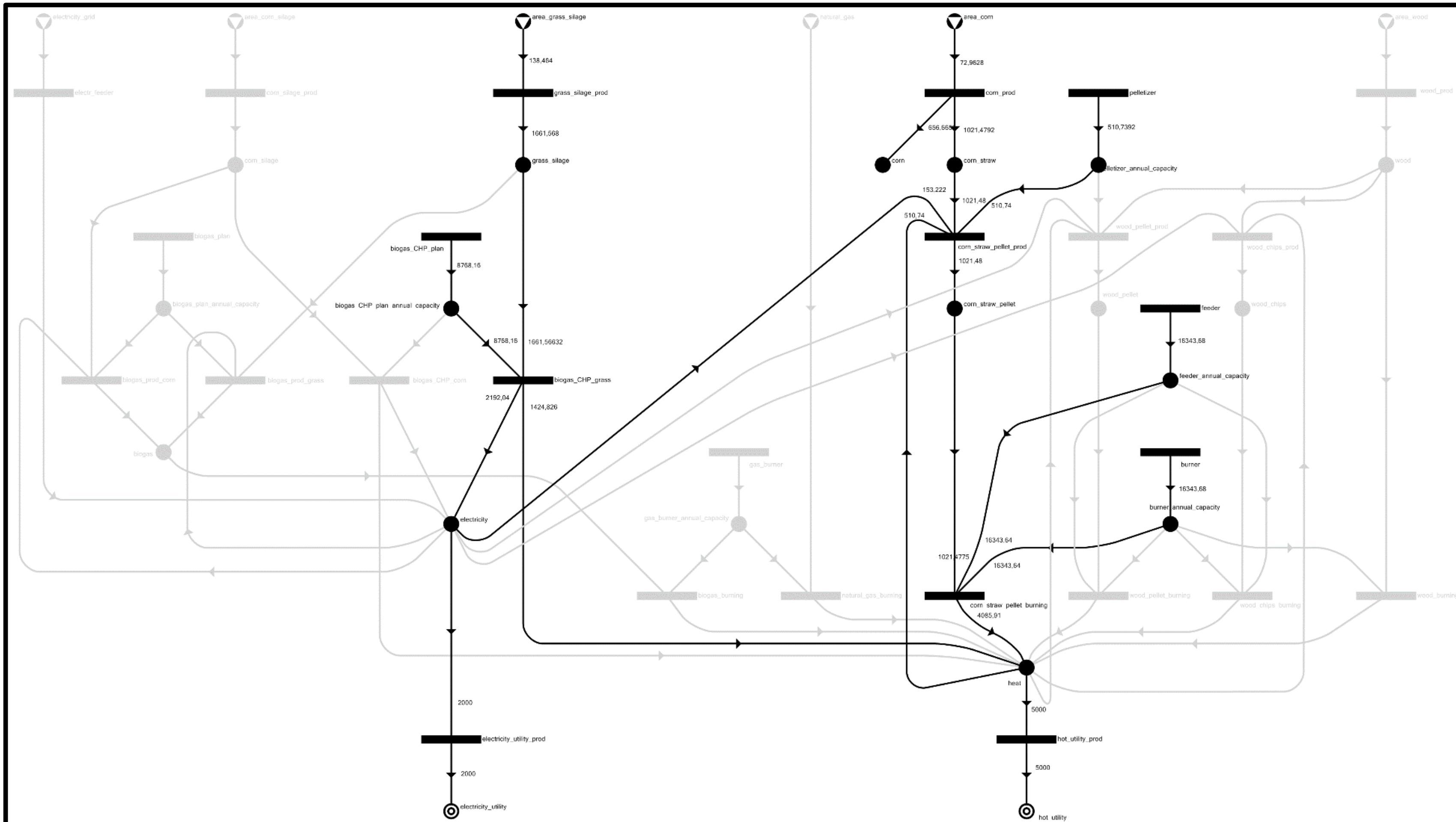
Supply Chain Structure #13: Grid Electricity & Natural Gas



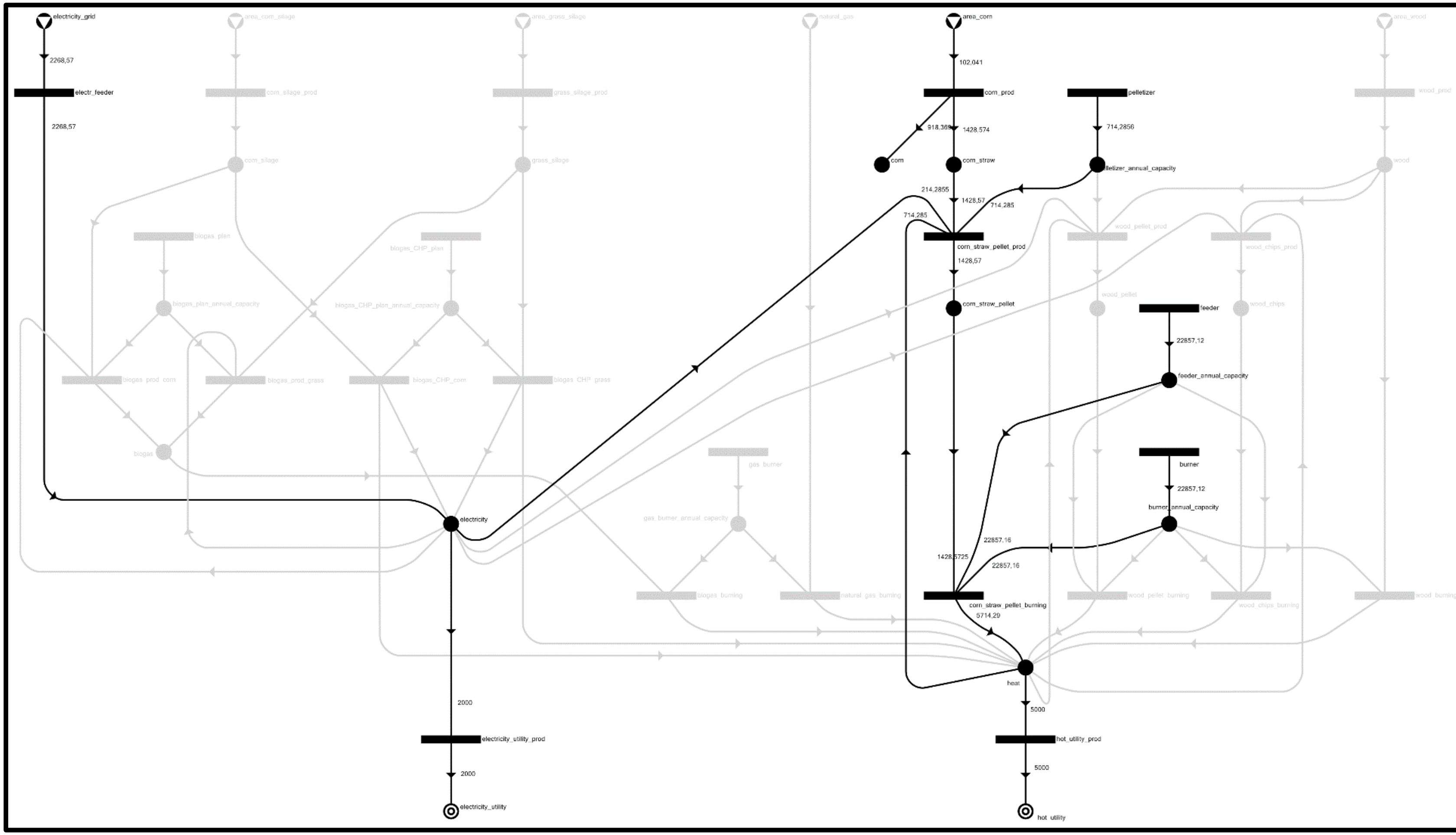
Supply Chain Structure #8: Corn Straw & Corn Silage



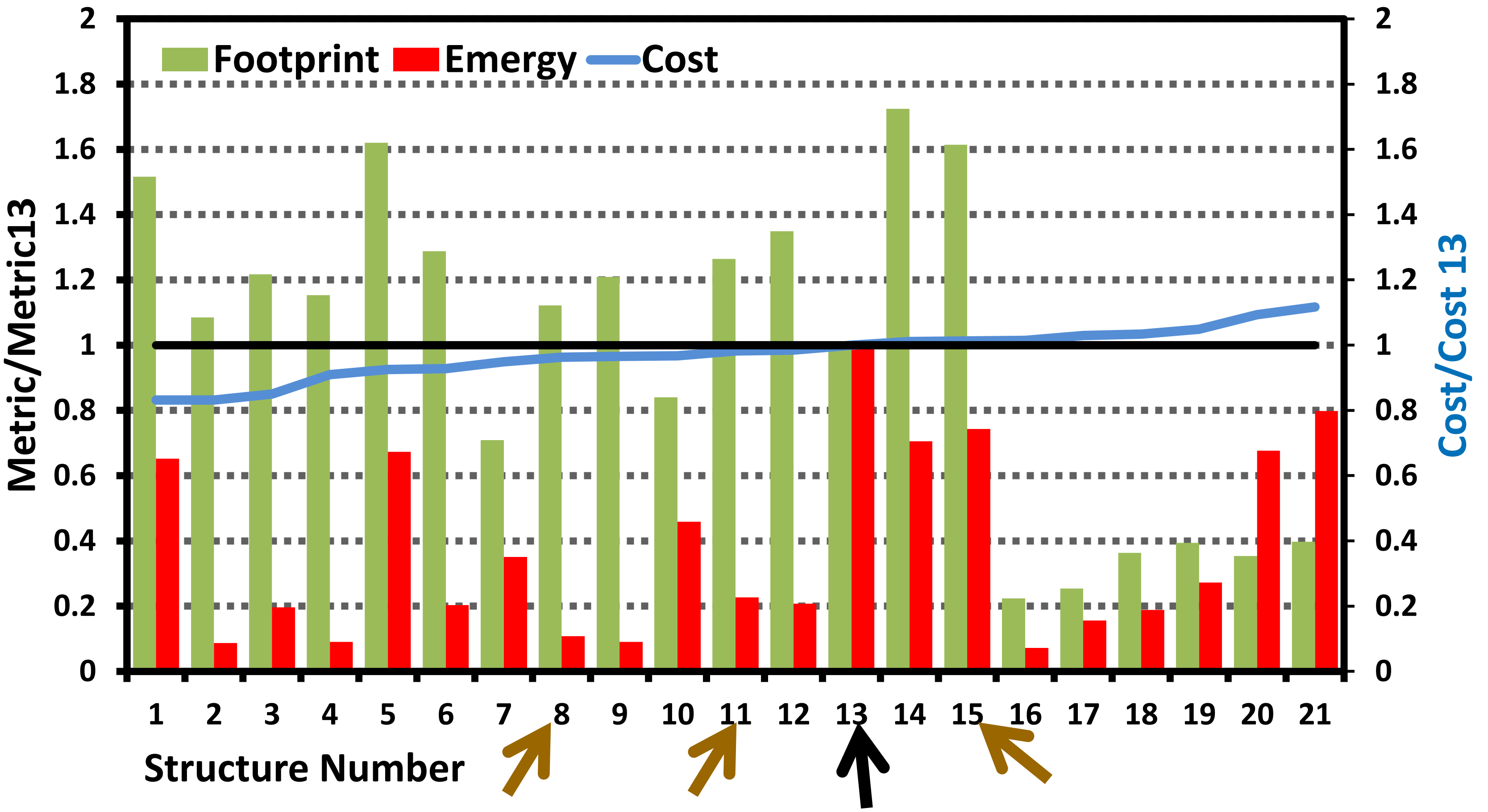
Supply Chain Structure #11: Corn Straw & Grass Silage



Supply Chain Structure #15: Corn Straw & Grid Electricity



Supply Chain Structures



Summary

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- Sustainability is about meeting human needs within the limits of the Earth so it can continue to support human existence for the indefinite future.
- Sustainability metrics based on science can provide necessary and actionable guidance.
- Application to real systems such as supply chains is both possible and essential.
- The P-Graph framework through the PNS Studio and PNS Draw provides accessible and free tools for supply chain and process design.