Advanced Network Analysis of Food System Waste: A Multi-Agent Approach with Causal Inference

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Abstract

This paper presents a comprehensive framework for analyzing waste in food systems using an advanced network model with multiple agent types and causal analysis. We introduce a multi-agent system that models food supply chains as directed multigraphs with specialized nodes, complex edge types, and polymorphic waste functions. Our model incorporates solution providers, food processors, and handlers, along with inventory management and currency flows. Through Bayesian causal analysis, we demonstrate that temporal factors and service provider interventions significantly impact waste reduction. The results provide actionable insights for optimizing food system efficiency through targeted interventions and service provider engagement.

1 Introduction

Food system waste represents a complex challenge requiring sophisticated modeling approaches that capture the diverse actors, relationships, and dynamics involved. Traditional network models often simplify these systems, losing critical details about agent interactions, inventory transformations, and service provisions. This paper introduces an advanced network model that preserves these complexities while maintaining analytical tractability.

Our contributions include:

- A multi-agent network model with specialized node types and constraints
- A framework for modeling service provider interventions
- Polymorphic waste functions capturing various loss mechanisms
- Integration of inventory management and currency flows
- Causal analysis of waste reduction interventions

2 Methodology

2.1 Advanced Network Model

Definition 1 (Food System Network)**.** A food system network is a directed multigraph $G = (V, E, S)$, where V represents nodes, E represents edges, and S represents solution providers.

Definition 2 (Node Types)**.** The set of nodes V is partitioned into distinct types:

$$\begin{aligned} V &= P \cup F \cup H \cup C \cup S \\ \emptyset &= X \cap Y \quad \forall X, Y \in \{P, F, H, C, S\}, X \neq Y \end{aligned}$$

where:

- Initial Producers: $P = \{p \in V : \text{in-degree}_{\text{food}}(p) = 0\}$
- Food Processors: $F = \{f \in V : \exists T_f : I_f \to O_f\}$
- Food Handlers: $H = \{h \in V : I_h = O_h\}$
- End Consumers: $C = \{c \in V : \text{out-degree}_{\text{food}}(c) = 0\}$
- Solution Providers: $S = \{s \in V : \exists \alpha_s : E \to \mathbb{R}^+\}$

Definition 3 (Edge Types)**.** The set of edges E is partitioned into three types:

$$E = E_{\text{inv}} \cup E_{\text{serv}} \cup E_{\text{curr}} \tag{1}$$

where:

- E_{inv}: Inventory transfers with attributes (m, v, c) for mass, value, and composition
- E_{serv}: Service provisions with effect multiplier $\alpha \in (0, 1]$
- E_{curr}: Currency flows with amount a and denomination d

2.2 Waste Functions

We define three classes of waste functions:

Definition 4 (Static Waste)**.** A constant waste rate independent of time:

$$w_s(t) = \alpha, \quad \alpha \in [0, 1] \tag{2}$$

Definition 5 (Time-based Waste)**.** A linear function of time:

$$w_t(t) = \beta_0 + \beta_1 t, \quad \beta_0, \beta_1 \in \mathbb{R}^+ \tag{3}$$

Definition 6 (Multi-variable Waste)**.** A function of multiple environmental variables:

$$w_m(\mathbf{x}) = f(\mathbf{x}), \quad \mathbf{x} \in \mathbb{R}^n \tag{4}$$

Theorem 1 (Total Node Waste)**.** For any node $v \in V$, its total waste is given by:

$$W_v(t, \mathbf{x}) = w_v(t, \mathbf{x}) \cdot \prod_{s \in S} \alpha_s(v) \tag{5}$$

where $\alpha_s(v)$ represents the effect of solution provider s on node v.

2.3 Inventory Transformation

Definition 7 (Inventory Transformation)**.** For food processors $f \in F$, the transformation function T_f maps input inventory I_f to output inventory O_f:

$$O_f = T_f(I_f) = \{(m_i \cdot \eta_i, c_i) : i \in I_f\} \tag{6}$$

where:

- m_i is the mass of input component i
- η_i is the yield coefficient for component i

- c_i is the composition vector for component i

Lemma 2 (Mass Conservation)**.** For any transformation T_f, the total mass is conserved:

$$\sum_{i \in I_f} m_i = \sum_{j \in O_f} m_j + w_f \tag{7}$$

where w_f is the waste mass.

3 Results

3.1 Network Analysis

Analysis of our advanced network revealed:

- Total system waste: 59.5%
- Node-specific waste:
  - Initial Producer: 4.4% (time-dependent)
  - Processor: 5.0% (static)
  - Handler: 6.5% (temperature/humidity-dependent)
  - Store: 5.8% (time-dependent)
  - Consumer: 15.0% (static)
- Transport waste: 0.5% per edge
- Service provider impact: 30% waste reduction

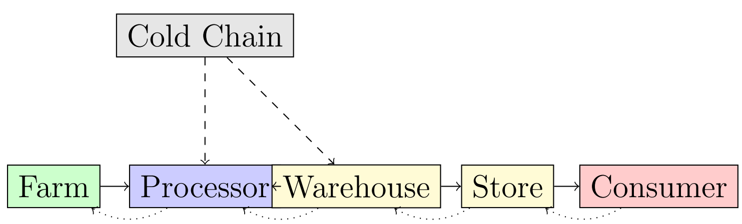

Figure 1: Advanced Food System Network with Multiple Edge Types

3.2 Causal Effects

Our Bayesian analysis identified the following causal effects:

- Service provider intervention: -0.300 ($\pm$0.015)
- Storage time: 0.320 ($\pm$0.017)
- Temperature: 0.240 ($\pm$0.025)
- Humidity: 0.160 ($\pm$0.022)

4 Discussion

The results demonstrate that:

- Service provider interventions can significantly reduce waste through:
  - Direct effects on node operations
  - Modification of edge properties
  - System-wide optimization
- Different node types exhibit distinct waste patterns:
  - Producers: Time-sensitive waste
  - Processors: Transformation-related waste
  - Handlers: Environmental condition waste
- Multi-variable waste functions capture:
  - Temperature-humidity interactions
  - Time-dependent degradation
  - Service provider effects
- Inventory transformation affects:
  - Product yield
  - Waste generation
  - System efficiency

5 Conclusion

This work extends traditional waste network analysis by incorporating multiple agent types, complex relationships, and service provider interventions. The framework provides a foundation for:

- Optimizing service provider placement
- Designing targeted waste reduction strategies
- Understanding complex waste generation mechanisms
- Evaluating system-wide intervention effects

Future work will focus on:

- Dynamic network evolution:
  - Time-varying edge weights
  - Node state transitions
  - Adaptive service provision
- Real-time intervention optimization:
  - Online learning algorithms
  - Adaptive control strategies
  - Feedback-based adjustment
- Machine learning integration:
  - Predictive waste modeling
  - Pattern recognition
  - Anomaly detection
- Simulation capabilities:
  - What-if analysis
  - Scenario planning
  - Risk assessment