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# Design of an Agent-Based Computational Economics Approach to Forecasting Future Freight Flows for the Chicago Region

*Prepared for:*
TRB SHRP 2 C43 Symposium on
Innovations in Freight Modeling & Data

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# Overview

- Background and motivation
- Agent-based computational economics
- Overview of current model system
- Overview of proposed model design
- Procurement market game
- Next steps

# Background

- The Chicago Metropolitan Agency for Planning (CMAP) has recently developed a two-tiered modeling system to analyze regional freight traffic
  - Original work: FHWA BAA Research project (2011), Cambridge Systematics, University of Illinois-Chicago, RSG, Inc.
  - Address complexities of freight modeling: commodities produced and consumed, local pick-up and delivery, warehousing and tour formation
- The first tier is referred to as the "mesoscale model" or "national supply chain model" and represents freight flows between the CMAP region and the rest of the U.S.
- The second tier model operates within the region, modeling local freight-hauling truck movements using a tour-based microsimulation and has been dubbed the "microscale model" or the "tour-based truck model"
- Commodity flows, including future freight flows, are derived from those found in the Freight Analysis Framework, Version 3 ($FAF^3$) data products, developed by the Federal Highway Administration (FHWA).

# Motivation

- **For policy and planning sensitivity analysis, CMAP would like a tool to systematically vary forecasts to reflect:**
  - Potential changes in macroeconomic conditions (e.g., foreign trade levels, price of crude oil);
  - Large-scale infrastructure changes (e.g., port expansions, new intermodal terminals);
  - Technological shifts in logistics and supply chain practices (e.g., near-sourcing, out-sourcing, productivity enhancements); and
  - Other assumptions and scenario inputs related to the economic competitiveness of the Chicago region and its infrastructure investments.

***To support these objectives…***

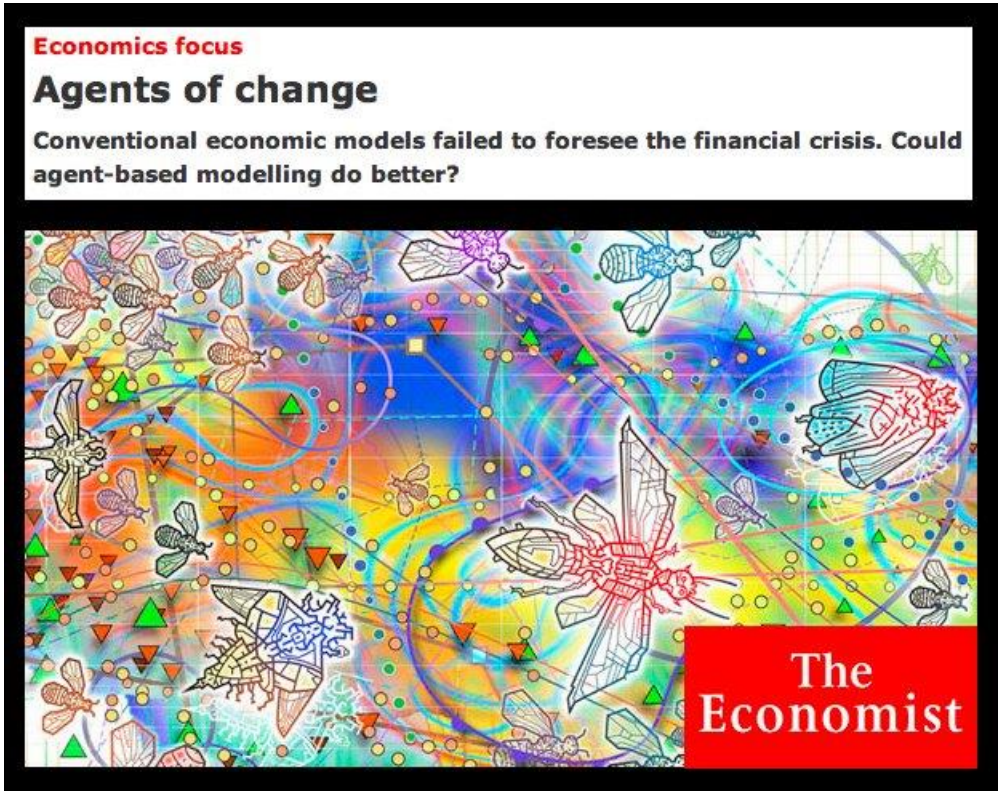
- **Future freight forecasts will need to be produced endogenously—focus on producer sourcing decisions to meet production levels**
- **Foreign trade and macroeconomic conditions will need to included in the producer sourcing decisions**
- **Price signals—transport and logistics costs and other costs will need to be part of sourcing decisions**

# Theoretical Drivers Behind Approach

- **Supply chain decisions are made by individuals on behalf of the companies for whom they work, characterized by:**
  - Imperfect information
  - Cultural baggage
  - Personal affinity for particular business partners
  - Limited search efforts based on custom, imitation, satisficing behavior
- **Purchasing agents want to save costs and selling agents want to maximize revenues, but It may not be realistic to assume that agents will make mathematically optimal decisions**
- **Variation in value systems across markets (examples):**
  - Emphasize cost savings for bulk commodities with low storage costs
  - Emphasize frequency of shipments for perishable commodities
  - Practice vertical integration (in-house sourcing) for complex commodities, such as components of high-precision medical equipment
- **Variation in market mechanisms**
  - Ad hoc bi-lateral agreements
  - Auctions and bidding
  - Collusions, side agreements
  - Varying levels of competition

# What is agent-based computational economics?

- ACE research characterized by rigorous study of economic systems through computational experiments
- "Bottom up" approach in which individual agents are simulated in a virtual world in which they make decisions, ***interact*** with and react to each other, and patterns ***emerge*** from the collective actions of many agents
- Interactions between agents typically take the form of cooperation games
- Methodological kinship with complex systems studies in social and natural sciences
  - Electric power trading
  - Social choice and voting
  - Racial segregation in housing
  - School choice
  - Habitat destruction
  - Honeybee swarms

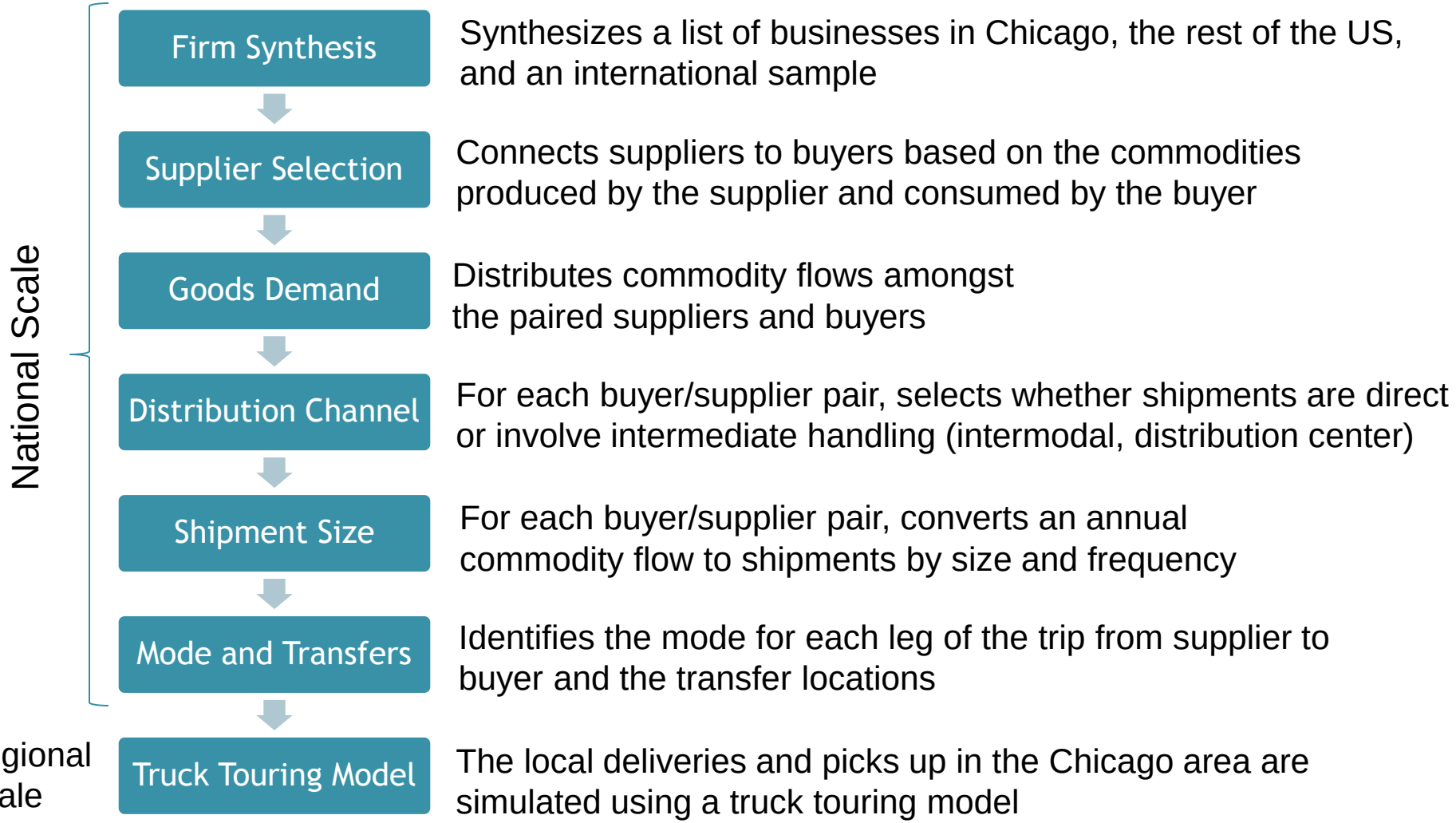



Source of graphic: http://computationallegalstudies.com/2010/07/27/agents-of-change-agent-based-models-and-methods-the-economist/

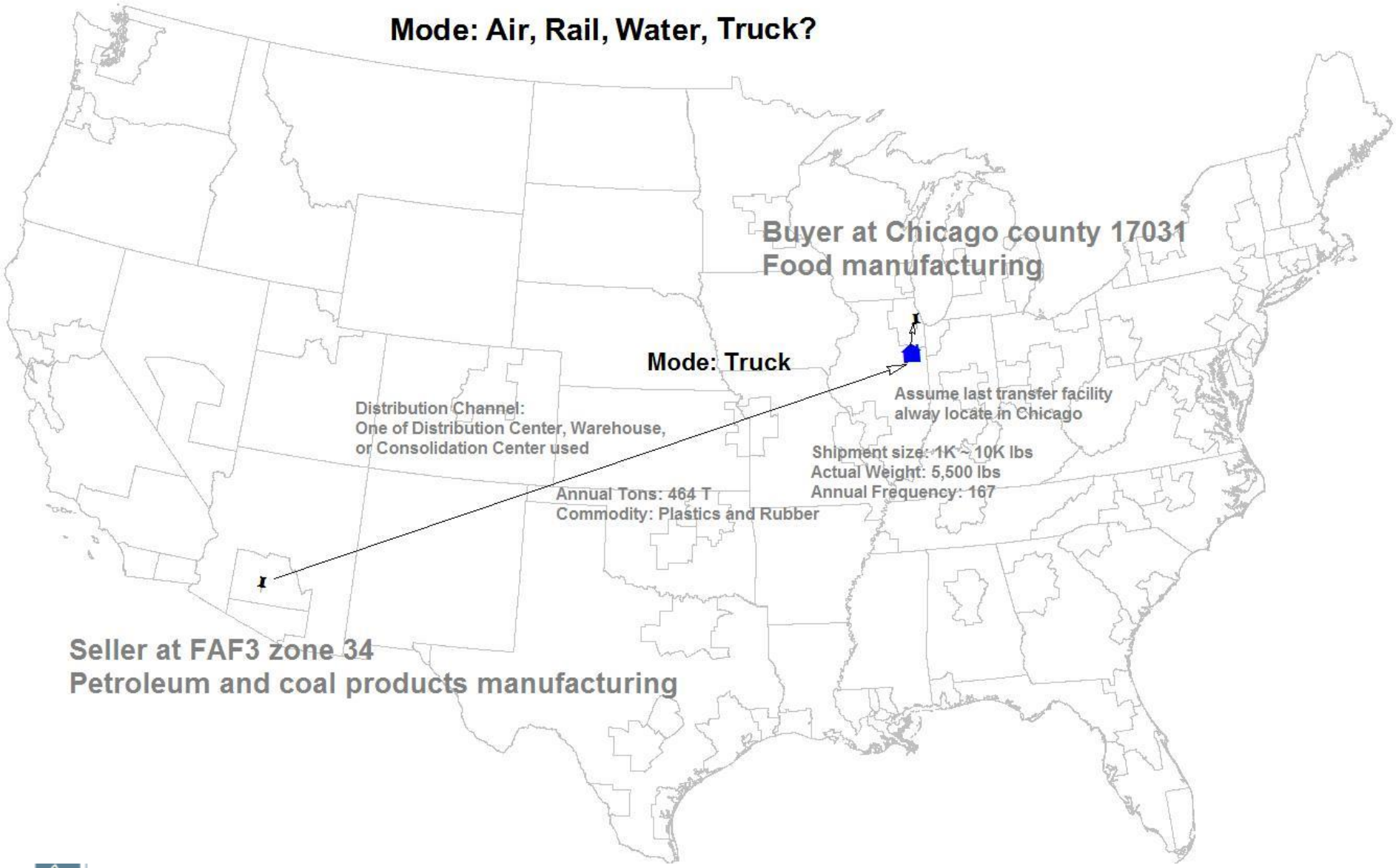
# ACE: Answering questions about complex systems

- **Why have certain global regularities emerged and persisted despite the absence of centralized planning and control, while other global outcomes have not been observed?**
  - How are trends in supply-chain and logistics practices, such as insourcing, outsourcing, and near-sourcing influenced by privately held values and beliefs regarding various forms of uncertainty, asset specificity, and commodity attributes?
  - How much is simply imitation?
- **What types of micro-level dynamics of individual traders lead to the collective patterns market behavior that we observe?**
  - Which agents in the supply chain network have the greatest influence on other agents (commodities, industries)?
  - Are there ties between agent/industries that may be important to assessing regional competitiveness and the likely trends in future freight flows?
- **How can good economic (infrastructure) policies be designed to achieve their intended effect?**
  - Road pricing, traffic flow management, trade tariffs, port capacity expansions

# Current Mesoscale Freight Model



# National Scale Model Sequence

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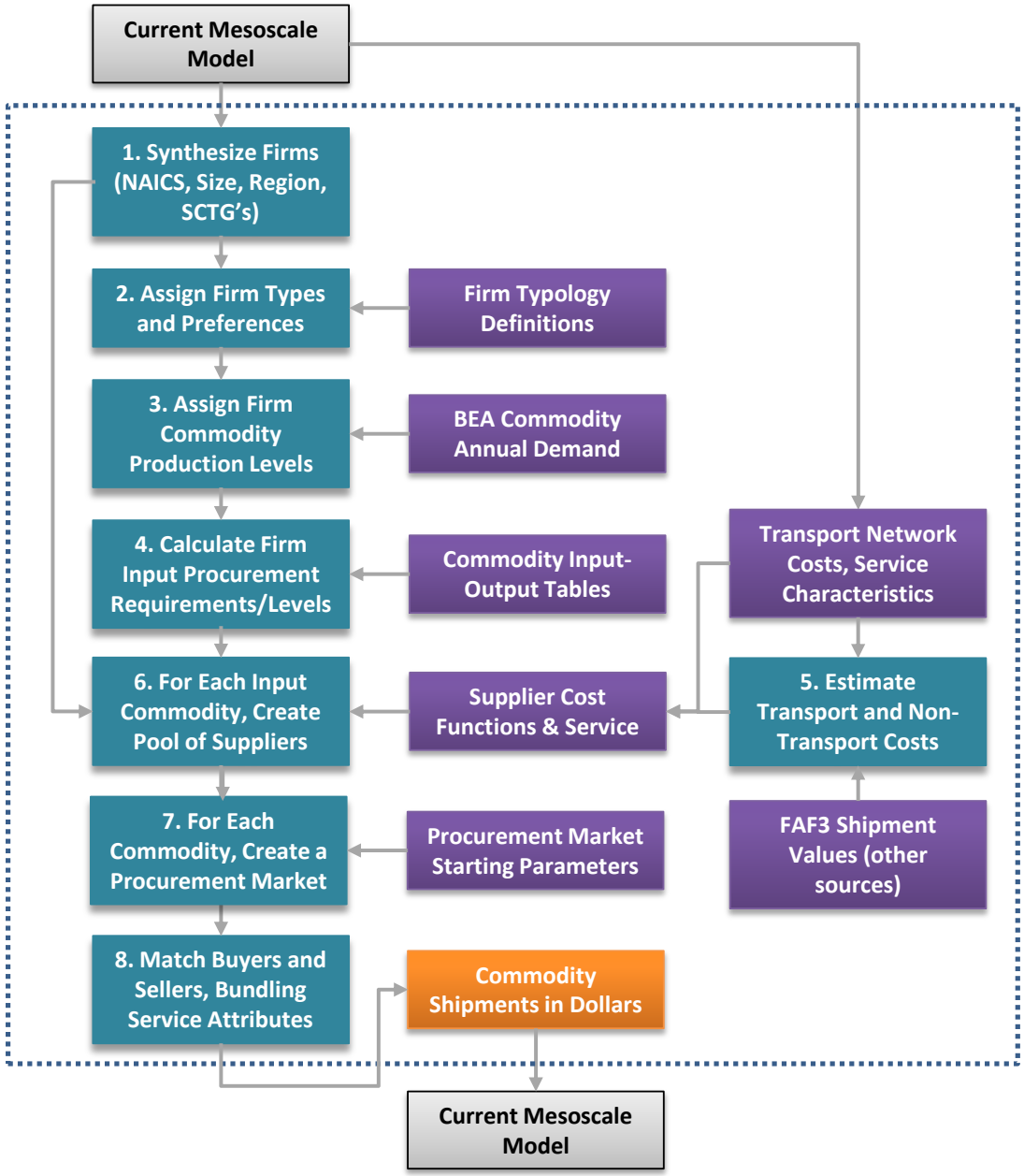
# Major Changes to Mesoscale Model Design

- Adding attributes to describe firms/establishments, based on operating typologies
- Commodity flow data no longer basis for predictions, but used in calibration and testing as benchmarks
- Business linkages, shipment demand, and mode determined through a joint decision framework, based on the outcome of agent-based simulations
- Outcome are shipments that feed directly into the truck touring model (simulation of delivery and pickup)

# Model Design Overview and Integration



# Synthesize Firms

- Start with existing method of firm synthesis
- Within the CMAP region, firms are treated as establishments in that they are situated in a single location and function as establishments
- Outside of the CMAP region, "representative" firms will be created to represent a single industry, and region/country (FAF zone)
  - E.g., Wyoming Coal Producers
- Firm attributes
  - Industry Code (NAICS)
  - CPB Zone (County Business Patterns zone used during supplier selection)
  - FAF Zone (country/region)
  - CMAP modeling zone
  - Commodity Type(s) Produced (SCTG)
  - Size (number of employees)
  - Production capacity (commodity units produced per year)

# Assign Firm Types and Preferences

- **Purpose to define firms' sourcing preferences (tradeoffs) for various combinations of source offerings ("attribute bundles")**
- **Commodity Service Offerings**
  - Unit cost / total cost
  - Average shipment time
  - Frequency of shipments / Average shipment size
  - Proximity of supplier
  - Perceived reliability of the supplier
  - Perceived quality of the supplier's commodity (assert for certain scenarios)
- **Firm Operational Types**
  - Efficiency vs. Responsiveness: Is commodity "innovative" or "functional"?
  - Geographic Proximity: Are there preferences for near-sourcing vs. far-sourcing?
  - Centralization Tendencies: Is commodity likely to utilize warehousing and distribution systems?
  - Vertical Integration Tendencies: Is commodity likely to be produced in-house?

# Assign Firm Commodity Production Levels

- U. S. Bureau of Economic Analysis (BEA) data will be used to estimate the total dollar-value of output commodities based on firm size
- Account for production cost differences for non-U.S. countries
- For imports, BEA reports producer prices at U.S. port of entry in U.S. dollars

| Commodity | Industry | | | Total Intermediate | Total Final Uses | Total Commodity Output |
|---|---|---|---|---|---|---|
| | Industry A | Industry B | Industry C | | | |
| Commodity A | 50 | | 10 | 60 | 25 | 85 |
| Commodity B | 40 | 60 | 20 | 120 | -10 | 110 |
| Commodity C | - | 10 | 110 | 120 | 100 | 220 |
| Total Intermediate | 90 | 70 | 140 | 300 | - | - |
| Total Value Added | 40 | 20 | 40 | - | 115 | - |
| Total Industry Output | 130 | 90 | 180 | - | - | 400 |

# Calculate Input Procurement Requirements

- **BEA Input-Output (I-O) tables**
  - "Use" tables after redefinitions to represent only *direct* inputs
  - Normalized becomes Direct Requirements table

| | Commodities/Industries | 11 | 21 | 22 | 23 | 31G | 42 |
|---|---|---|---|---|---|---|---|
| IOCode | Name | Agriculture, | Mining | Utilities | Constructio | Manufacturi | Wholesale |
| 11 | Agriculture, forestry, fishing, and hunting | 0.1950 | 0.0000 | 0.0000 | 0.0011 | 0.0480 | 0.0001 |
| 21 | Mining | 0.0028 | 0.0816 | 0.1332 | 0.0084 | 0.1046 | 0.0002 |
| 22 | Utilities | 0.0154 | 0.0184 | 0.0003 | 0.0033 | 0.0140 | 0.0048 |
| 23 | Construction | 0.0045 | 0.0263 | 0.0107 | 0.0007 | 0.0031 | 0.0016 |
| 31G | Manufacturing | 0.2005 | 0.1242 | 0.0081 | 0.2442 | 0.3524 | 0.0488 |
| 42 | Wholesale trade | 0.0475 | 0.0140 | 0.0010 | 0.0232 | 0.0448 | 0.0343 |
| 44RT | Retail trade | 0.0018 | 0.0016 | 0.0000 | 0.0360 | 0.0016 | 0.0005 |
| 48TW | Transportation and warehousing | 0.0216 | 0.0240 | 0.0342 | 0.0135 | 0.0232 | 0.0337 |
| 51 | Information | 0.0007 | 0.0020 | 0.0008 | 0.0061 | 0.0040 | 0.0077 |
| FIRE | Finance, insurance, real estate, rental, and leasing | 0.0782 | 0.0529 | 0.0067 | 0.0300 | 0.0189 | 0.0483 |
| PROF | Professional and business services | 0.0103 | 0.1061 | 0.0129 | 0.0812 | 0.0618 | 0.1155 |
| 6 | Educational services, health care, and social assistance | 0.0021 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0004 |
| 7 | Arts, entertainment, recreation, accommodation, and food servic | 0.0010 | 0.0014 | 0.0029 | 0.0027 | 0.0031 | 0.0056 |
| 81 | Other services, except government | 0.0019 | 0.0019 | 0.0005 | 0.0130 | 0.0030 | 0.0082 |
| G | Government | 0.0003 | 0.0000 | 0.0001 | 0.0000 | 0.0005 | 0.0068 |
| Used | Scrap, used and secondhand goods | 0.0022 | 0.0001 | 0.0000 | 0.0007 | 0.0014 | 0.0000 |
| Other | Noncomparable imports and rest-of-the-world adjustment | 0.0002 | 0.0019 | 0.0005 | 0.0002 | 0.0047 | 0.0071 |
| V001 | Compensation of employees | 0.1070 | 0.1506 | 0.1820 | 0.3723 | 0.1617 | 0.3476 |
| V002 | Taxes on production and imports, less subsidies | -0.0007 | 0.0725 | 0.1592 | 0.0076 | 0.0135 | 0.1409 |
| V003 | Gross operating surplus | 0.3076 | 0.3206 | 0.4468 | 0.1558 | 0.1358 | 0.1881 |
| | **Total** | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |

(partial table shown)

# Estimate Transport and Non-Transport Costs

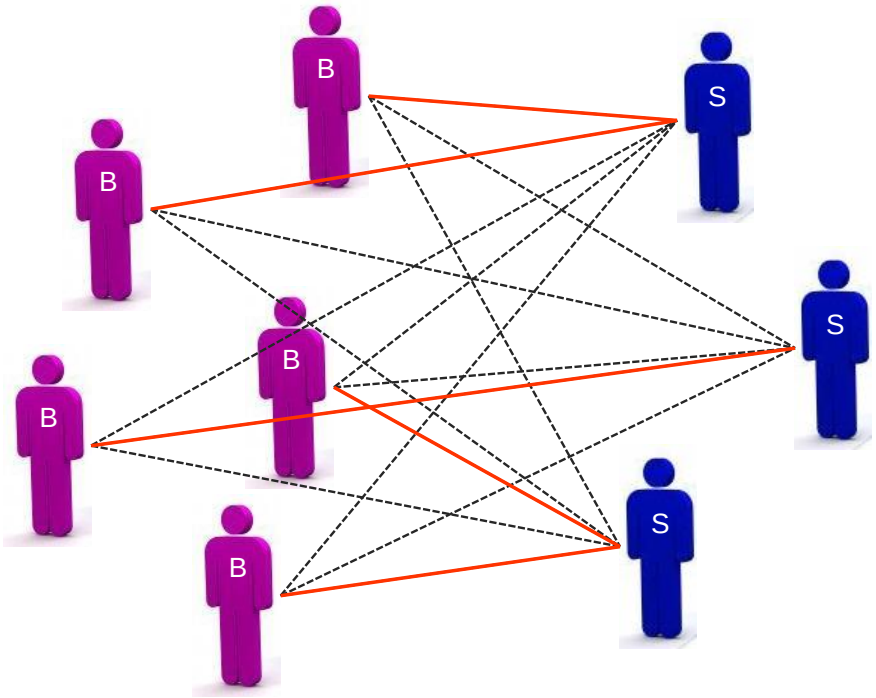
- **Transport and Logistics Costs**
  - Use skims from the multi-modal network model and unit costs created as part of the current mesoscale model to provide *transport and logistics costs*, composed of:
    - Ordering cost
    - Transport and handling cost
    - Damage cost
    - Inventory in-transit cost
    - Carrying cost
    - Safety stock cost

- **Total Costs**
  - Use FAF[3] estimates of total shipment values between FAF zones to provide a *total cost* figure

- **Non-Transport/Logistics Costs = Total Costs - Transport Costs**

# Match Buyers and Sellers, Bundling Service Attributes

- Create buyer agents with preferences for bundled cost-service attributes
- For each of the 43 commodity types under consideration, a procurement market model will be run
- This is done through a "**procurement market game**"
- The objective of this step is to find suppliers for every commodity input required by buyers
- Outcome is joint choice of supplier, shipment size, distribution center use and mode-path



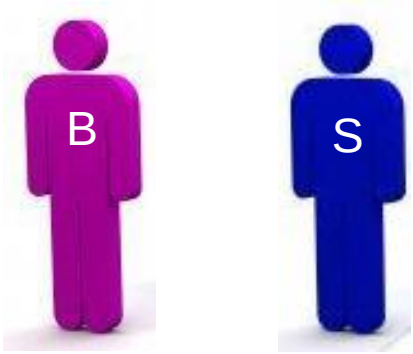
# Procurement Market Game (PMG)

- **Research literature in supply chain sourcing decisions focuses on auction mechanisms that can be used to optimize outcomes**
  - E-procurement systems require efficient, robust algorithms (algorithmic game theory)
  - Common objectives are to induce suppliers to bid at true cost, avoid collusion, and other forms of strategic lying
    - Example: "2nd Price Sealed Bid" (Vickery 1961)
- **Appropriateness of auction mechanisms for Mesoscale Freight Model**
  - Industry and commodity-specific
  - Not necessarily applicable to smaller and less technologically advanced firms
  - Typically designed for optimization
  - Won't necessarily capture idiosyncratic behavior of agent preferences, habits and beliefs
- **ACE approaches offer a more general, flexible framework**
- **PMG inspired by Trade Network Game (TNG)** (Tesfatsion, McFadzean, Iowa State U.)
  - Agents are buyers, sellers and dealers (buy or sell)
  - 2 x 2 Payoff matrix – "cooperate" or "defect" labeling (e.g., Prisoners Dilemma)
  - Evolutionary programming framework (genetic algorithm)
  - Multiple rounds of pairwise trades
  - Agent expectations about other trading partners are updated after each round based on outcomes of all pairwise trading games
  - Market properties emerge through iterative play

# Initializing Agents

*Buyer Attributes*

- NAICS
- Size (# employees)
- FAF Zone
- Output commodity
- Input commodity
- Input commodity requirements ($ annual purchase) demand




*Seller Attributes*

- NAICS
- Size (# employees)
- FAF Zone
- Output commodity
- Production level ($ annual output) capacity

| Payoff Matrix (example) | | |
|---|---|---|
| Decision | ***Yes*** | ***No*** |
| ***Yes*** | 3 / 2 | 0 / 2 |
| ***No*** | -1 / 0 | 1 / 1 |

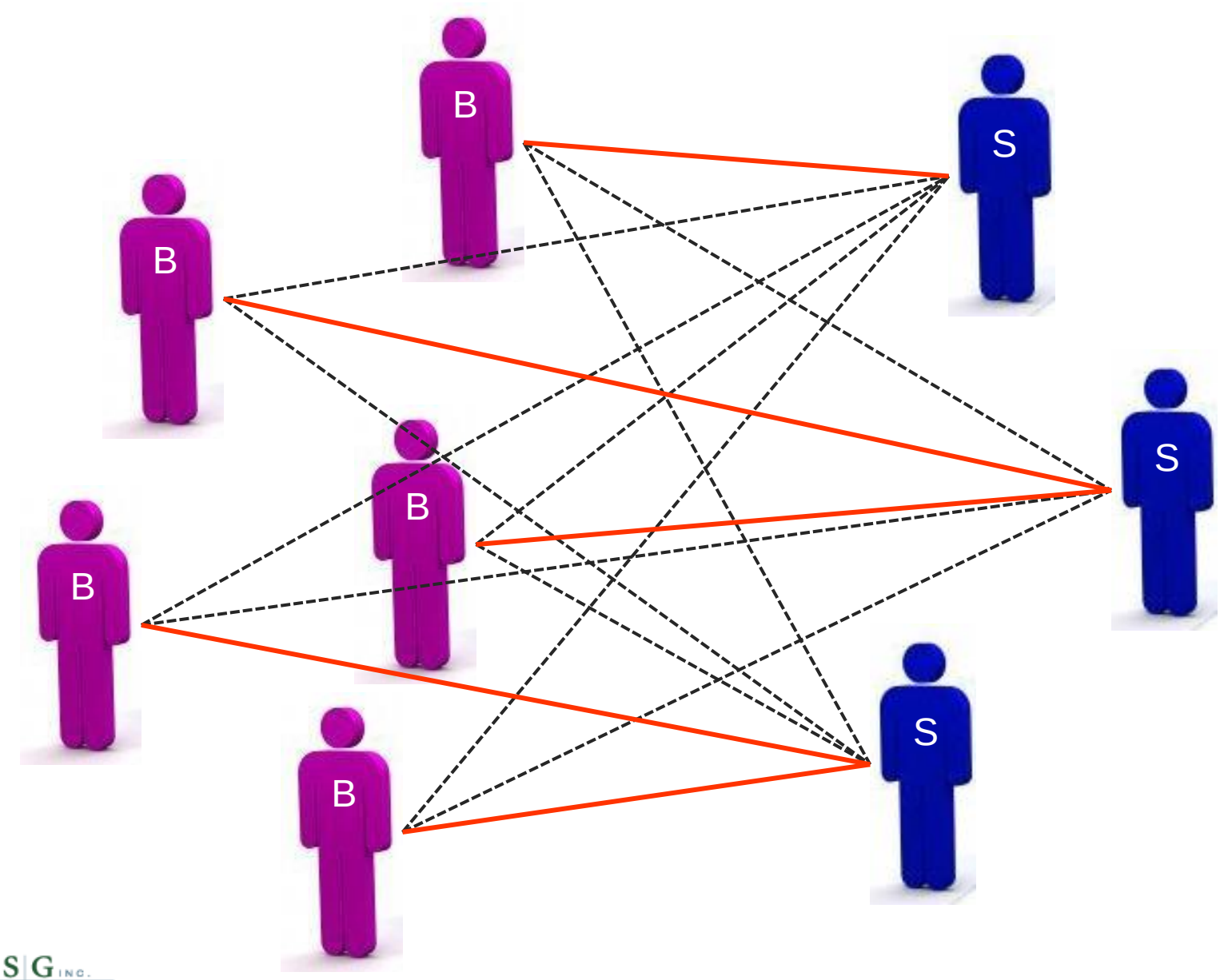
*Buyer Preferences*

- Efficient vs. Responsive
- Near-source vs. Far-source
- Centralized Distribution
- Vertical Integration

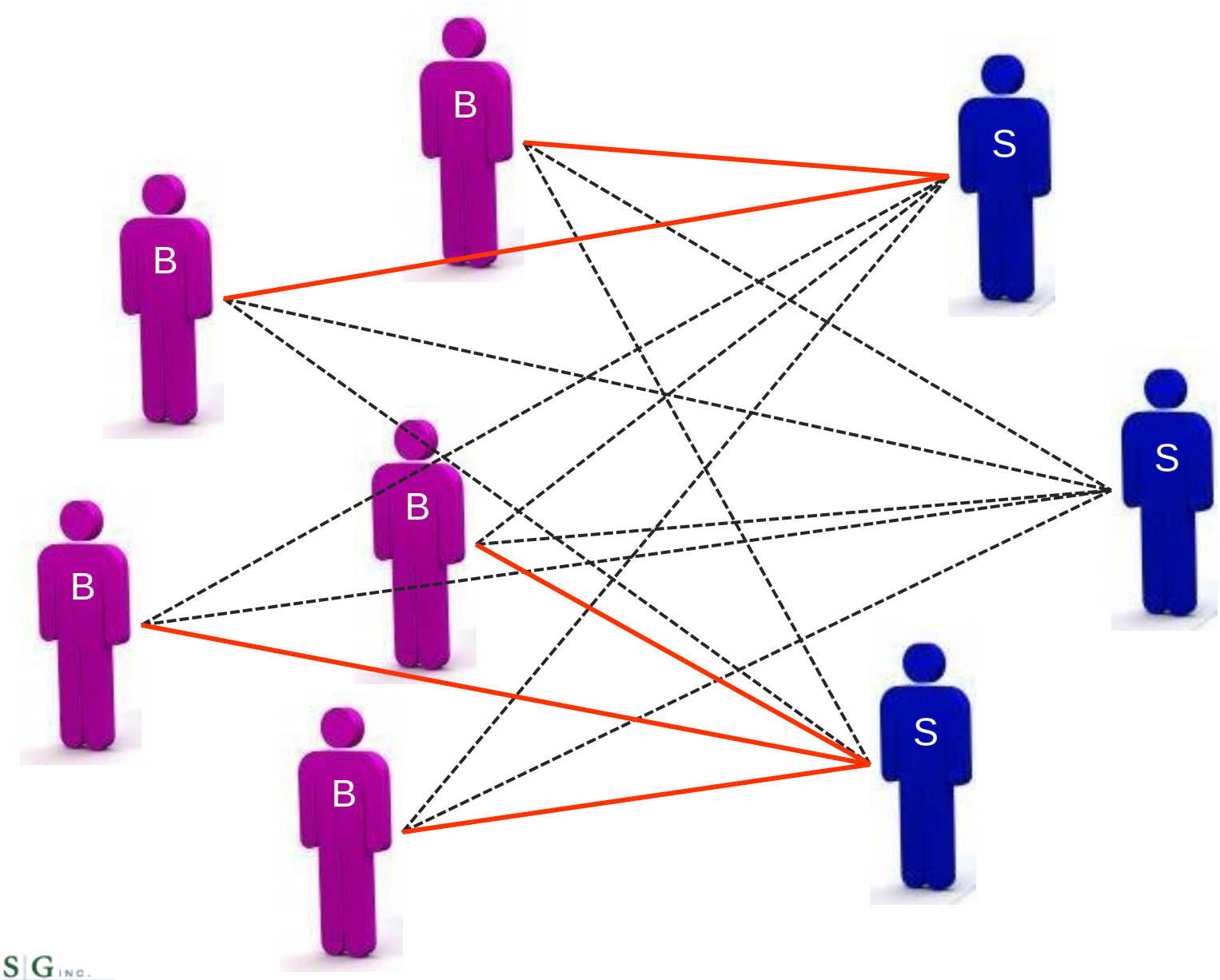
*Seller Cost-Service Bundle*

- Shipment sizes
- Average shipping times
- Distribution centers
- Mode
- Cost

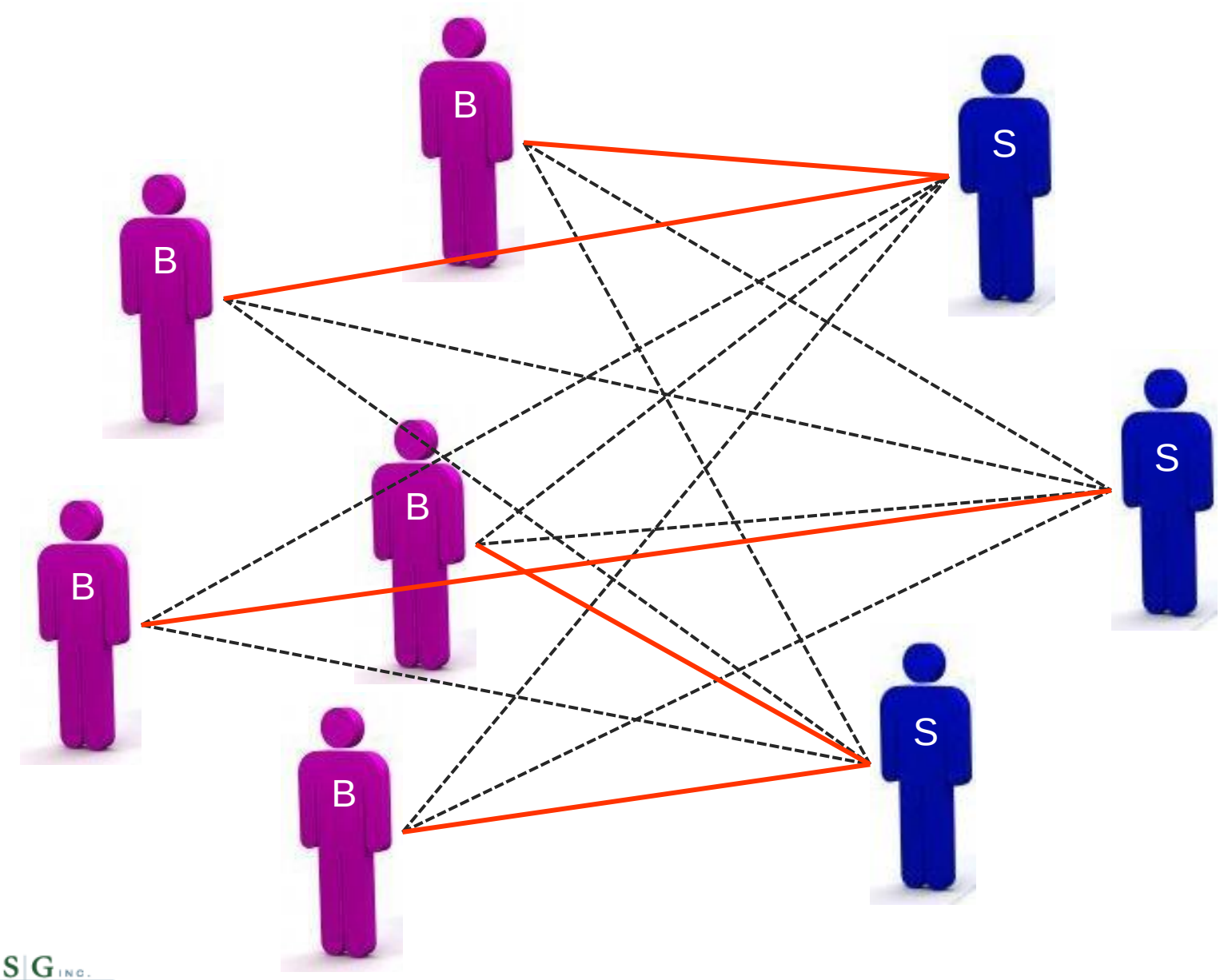
# Round 1



# Round 2



# Round 3



# Example PMG: Trade Scenario "A"

- Large buyer "L" and a small buyer "S" who are both in the packaged foods industry, commodity code, CC=1
- Each buyer needs to purchase a quantity of an input commodity, seafood, commodity code, CC=2. Both buyers are in the geographic zone, GZ=1
- Three sellers: foreign ('F"), domestic ("D"), and local ("L"), each offering different bundles of unit costs and shipping time

**First Buyer**

| | CC | GZ | Size | Cost Wght. | Time Wght. | Order Size |
|---|---|---|---|---|---|---|
| Buyer "L" | 1 | 1 | L | -0.2 | -0.8 | 20 |

| | CC | GZ | Unit Cost | Ship Time | Utility | Order Cost |
|---|---|---|---|---|---|---|
| Seller "F" | 2 | 3 | $ 0.95 | 7 | -5.79 | $ 19.00 |
| Seller "D" | 2 | 2 | $ 2.00 | 3 | -2.80 | $ 40.00 |
| Seller "L" | 2 | 1 | $ 3.00 | 1 | -1.40 | $ 60.00 |

**Second Buyer**

| | CC | GZ | Size | Cost Wght. | Time Wght. | Order Size |
|---|---|---|---|---|---|---|
| Buyer "S" | 1 | 1 | S | -0.4 | -0.6 | 5 |

| | CC | GZ | Unit Cost | Ship Time | Utility | Order Cost |
|---|---|---|---|---|---|---|
| Seller "F" | 2 | 3 | $ 0.95 | 7 | -4.58 | $ 4.75 |
| Seller "D" | 2 | 2 | $ 2.00 | 3 | -2.60 | $ 10.00 |
| Seller "L" | 2 | 1 | $ 3.00 | 1 | -1.80 | $ 15.00 |

| | |
|---|---|
| Opportunity Cost Constant (Failed Trade): | -7.0 |

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# Pairwise Trade L-F

- Large Buyer and Foreign Seller

***Should Buyer "L" and Seller "F" form a trading alliance? (Assuming mutual exclusivity)***

*(Sourcing decision for purchase of Commodity Code #2 "Meat/Seafood")*

| **Expected Payoffs to Buyer** | | |
|---|---|---|
| ***Yes*** | -5.79 | <--Utility of Transaction |
| ***No*** | -2.10 | <--Expected Utility if another supplier must be chosen (assuming even odds among remaining sellers and zero risk of no trade)[1] |

| **Payoffs to Seller** | | | |
|---|---|---|---|
| ***Yes*** | $ | 19.00 | <--Revenue of Transaction |
| ***No*** | $ | 1.58 | <--Expected Revenue of holding out for another (more lucrative) buyer (assuming 1/3 chance of success competing against two other sellers)[1] |

| | |
|---|---|
| **Outcome:** | ***Buyer says "no" (holding out for a better contract); Seller says "yes"*** |
| | ***We don't know the actual payoffs, yet! (pending outcomes of other pairwise trading games)*** |
| [1] | **Update expected probabilities over repeated trading games** |

# Pairwise Trade S-D

- Small Buyer and Domestic Seller

***Should Buyer "S" and Seller "D" form a trading alliance? (Assuming mutual exclusivity)***

*(Sourcing decision for purchase of Commodity Code #2 "Meat/Seafood")*

| **Expected Payoffs to Buyer** | | |
|---|---|---|
| ***Yes*** | -2.60 | <--Utility of Transaction |
| ***No*** | -3.19 | <--Expected Utility if another supplier must be chosen (assuming even odds among remaining sellers)[1] |

| **Payoffs to Seller** | | |
|---|---|---|
| ***Yes*** | $ 10.00 | <--Revenue of Transaction |
| ***No*** | $ 13.33 | <--Expected Revenue of holding out for another (more lucrative) buyer (assuming 1/3 chance of success competing against two other sellers)[1] |

| | | |
|---|---|---|
| **Outcome:** | ***Buyer says "yes"; Seller says "no" (holding out for a better contract)*** | |
| | ***We don't know the actual payoffs, yet! (pending outcomes of other pairwise trading games)*** | |

# Pairwise Trade L-L

- Large Buyer and Local Seller

***Should Buyer "L" and Seller "L" form a trading alliance? (Assuming mutual exclusivity)***

*(Sourcing decision for purchase of Commodity Code #2 "Meat/Seafood")*

| **Expected Payoffs to Buyer** | | |
|---|---|---|
| ***Yes*** | -1.40 | <--Utility of Transaction |
| ***No*** | -4.30 | <--Expected Utility if another supplier must be chosen (assuming even odds among remaining sellers)[1] |

| **Expected Payoffs to Seller** | | |
|---|---|---|
| ***Yes*** | $ 60.00 | <--Revenue of Transaction |
| ***No*** | $ 5.00 | <--Expected Revenue of holding out for another (more lucrative) buyer (assuming 1/3 chance of success competing against two other sellers)[1] |

| | |
|---|---|
| **Outcome:** | ***Buyer says "yes"; Seller says "yes"*** |
| | ***We don't know the actual payoffs, yet! (pending outcomes of other pairwise trading games)*** |

# Scenario A Resolution

- And so on… All pairwise combinations (2 x 3 = 6) are calculated and expected payoffs for each game are updated based on these pairwise outcomes

| *Actual Payoffs for Round 1* | | | | | | |
|---|---|---|---|---|---|---|
| **Pairwise Games:** | **L-F** | **S-D** | **L-D** | **S-L** | **S-F** | **L-L** |
| ***Buyer--Yes*** | -5.79 | -7.0 | -2.80 | -7.0 | -7.0 | -1.40 |
| ***Buyer--No*** | -1.40 | -7.0 | -1.40 | -7.0 | -7.0 | -2.80 |
| ***Seller--Yes*** | $ - | $ 10.00 | $ - | $ 15.00 | $ - | $ 60.00 |
| ***Seller--No*** | $ - | $ - | $ - | $ 60.00 | $ - | $ 15.00 |

- Only partnership formed was between Buyer L ("large") and Seller L ("local").
- Under an assumption of mutual exclusivity, an initially favorable L-D match was superseded by L-L (slightly better for the buyer)
- Buyer S ("small") was outbid after holding out for the preferred provider ("local").
- Buyer S was rejected by all of the sellers, who were holding out for Seller L ("large").
- During the second round, buyers and sellers would update their beliefs about the probability of a successful trade, which should result in a second alliance forming between Buyer S and Seller D ("domestic").
- Seller F ("foreign") is priced out of this market for fish, but could become competitive in a different scenario if cost structures or preferences were to change.

# Expectations of PMG

- Replicating what actually goes on in a procurement market is challenging
- Different payoff matrices may be defined to capture different styles and assumptions on the bilateral trade, resulting in different emergent behavior
- We may create 3-5 general types of games to represent commodity markets of similar types
- Buyers will outnumber sellers in the majority of markets
- Pair-feasibility criteria will be developed
- Stopping criteria to be determined, but providing suppliers to fulfill every buyer's input needs will be minimum—convergent solutions preferred
- Sellers will have capacity constraints
- Some buyers will want to spread risk and choose multiple sellers
- Cost structure assumptions and parameters, and utility preference weights will be highly influential, thus a large part of the development time
- FAF$^3$ flows will be used for benchmarking and calibration of aggregate results

# Planned Scenario Testing

- Impacts of full implementation of Chicago's CREATE program
- Impacts of implementation of Midwest Intermodal Hub in Iowa
- Impacts of expansion of Port of Prince Rupert, BC
- Impacts of reduction/increase in U.S. Trade with China


Source: http://www.createprogram.org/linked_files/ProjectMap_print.pdf

# Next Steps

- **Development of PMG test bed (ongoing)**
  - Incremental testing of variables, algorithms and assumptions
- **Assess convergence properties, reasonableness of results, computational time, realism of portrayed competition**
  - Start with single commodity procurement market; gradually try additional markets, look for commonalities and generalizability
  - Start with simpler single-cost variables in payoffs, gradually add other variables
  - Test different utility weighting parameter values
  - Test full combinatorial treatment vs. filtering and sampling
  - Experiment with assumptions information known to agents
  - Experiment with other algorithmic assumptions


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# Reserve Slides for Q & A

# Firm Synthesis

Firms are synthesized for the entire U.S. with a high level of industrial sector detail, and across several employment size categories

| NAICS Groups | 1-19 | 20-99 | 100-249 | 250-499 | 500-999 | 1,000-2,499 | 2,500-4,999 | Over 5,000 | Total |
|---|---|---|---|---|---|---|---|---|---|
| Agriculture | 631,703 | 83,328 | 11,941 | 2,897 | 954 | 382 | 46 | 13 | **731,264** |
| Mining\Construction | 774,697 | 73,607 | 10,090 | 3,711 | 2,363 | 1,900 | 1,744 | 1,716 | **869,828** |
| Manufacturing | 228,381 | 74,451 | 18,942 | 6,170 | 2,384 | 828 | 143 | 49 | **331,348** |
| Transportation\ Wholesale\Retail | 1,518,135 | 214,956 | 34,082 | 7,305 | 1,536 | 393 | 71 | 34 | **1,776,512** |
| Information\Finance\ Professional Services | 2,094,868 | 186,140 | 32,431 | 10,141 | 4,336 | 1,737 | 295 | 97 | **2,330,045** |
| Education\ Healthcare | 731,344 | 110,504 | 20,120 | 4,523 | 2,168 | 1,748 | 435 | 157 | **870,999** |
| Entertainment\ Recreation\Food | 558,052 | 186,140 | 11,069 | 1,522 | 576 | 269 | 43 | 15 | **757,686** |
| Other Services | 694,640 | 45,377 | 3,409 | 548 | 163 | 40 | 12 | 3 | **744,192** |
| **Total** | **7,231,820** | **974,503** | **142,084** | **36,817** | **14,480** | **7,297** | **2,789** | **2,084** | **8,411,874** |

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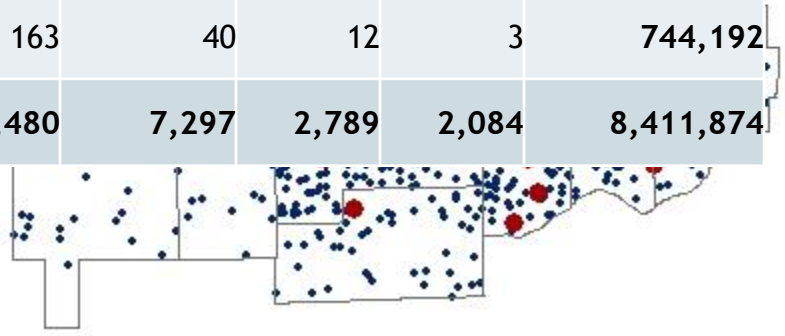

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# Application Development in R

- **Scripting Software**
  - R version 2.14
- **Runtime**
  - Total run time is 80-90 minutes
- **Hardware**
  - Manufacturer: HP Z200 Workstation
  - Processor: Intel Core i7 CPU 870 @ 2.93 GHz
  - Installed RAM: 12.0 GB
  - OS: Windows 7 Professional (64-bit)

| Model Component | Run Time (minutes) | Notes |
|---|---|---|
| Firm synthesis | 13 | Synthesize 8 million firms and choose buyers (7.5 million) and suppliers firm types (1.4 million) for CMAP simulation |
| Supplier selection | 24 | Match supplier firm types for about 3 million firms |
| Supply chain and goods demand | 19 | Apportion FAF flows for 3 million buyer supplier pairs and locate 8 million firms to mesozones |
| Distribution channel | 1.0 | Predict distribution channels for 3 million buyer-supplier pairs using logit shares |
| Shipment size | 1.5 | Estimates annual shipment size and frequency |
| Mode-Path selection | 20 | Evaluation of annual logistics and transport costs for 54 mode-paths |
| Vehicle choice and tour pattern | 1.5 | Daily simulation for 300k deliveries\pick-ups from warehouses |
| Stop clustering and sequencing | 1.5 | Clusters and sequences stops on tours |
| Stop duration | 0.2 | Estimates stop duration |
| Time of day | 1.5 | Constructs tours from start time and stop duration |

# Cost Function *(Current Mesoscale mode, improved equation)*

$$G_{mnql} = \beta_{0ql} + \beta_1 \times \left(\frac{Q}{q}\right) + T_{mnql} + \beta_2 \times j \times v \times Q + \beta_3 \times t_{mnl} \times v \times \frac{Q}{365} + (\beta_4 + \beta_5 \times v) \times \frac{q}{2} + \beta_5 \times v \times a \times \sqrt{(LT \times \sigma_Q{}^2) + (Q^2 + \sigma_{LT}{}^2)}$$

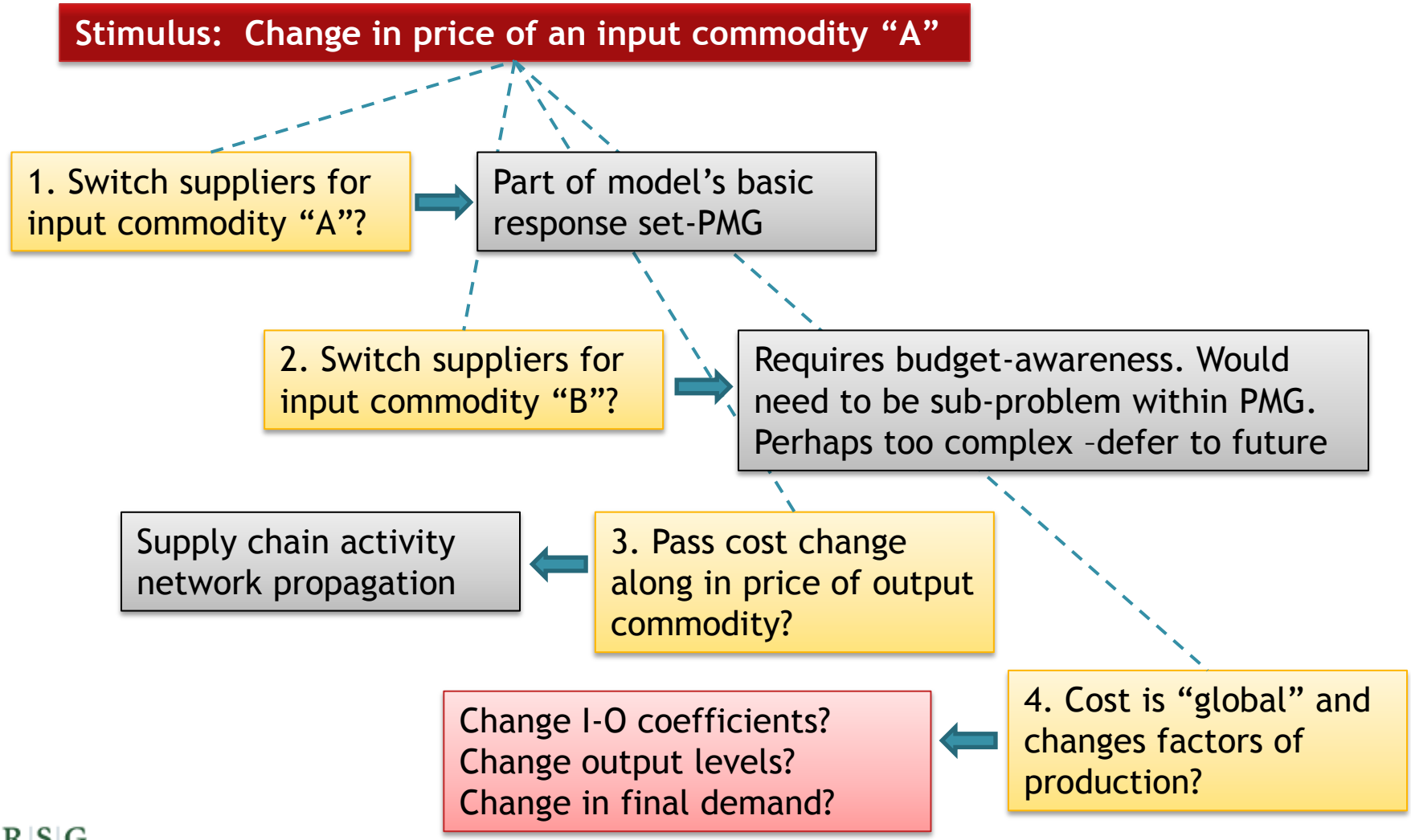
Ordering Cost | Transport and Handling Cost | Damage Cost | Inventory in-transit cost | Carrying Cost | Safety Stock Cost

| Variable or Parameter | Description or Interpretation (of Parameters) | Source |
|---|---|---|
| $G_{mnql}$ | Logistics cost (shipper m and receiver n with shipment size q and logistics chain l) | Calculated in the model |
| Q | Annual flow in tons | FAF |
| q | Shipment size in tons | Variable |
| $\beta_{0ql}$ | Alternative-specific constant | Parameter to be estimated |
| $\beta_1$ | Constant unit per order | Parameter to be estimated |
| T | Transport and intermediate handling costs | network skims, survey data |
| $\beta_2$ | Discount rate | Parameter to be estimated |
| j | Fraction of shipment that is lost or damaged | Survey data or assumed value |
| v | Value of goods (per ton) | FAF data |
| $\beta_3$ | Discount rate of goods in transit | Parameter to be estimated |
| t | Average transport time (days) | Lookup table (or skims), survey data |
| $\beta_4$ | Storage costs per unit per year | Parameter to be estimated |
| $\beta_5$ | Discount rate of goods in storage | Parameter to be estimated |
| a | Constant, set safety stock a fixed prob. of not running out of stock | Survey data or assumed value |
| LT | Expected lead time (time between ordering and replenishment) | Lookup table (or skims) , survey data |
| $\sigma_Q$ | Standard deviation in annual flow (variability in demand) | Survey data, assumed value |
| $\sigma_{LT}$ | Standard deviation of lead time | Lookup table (or skims), survey data |

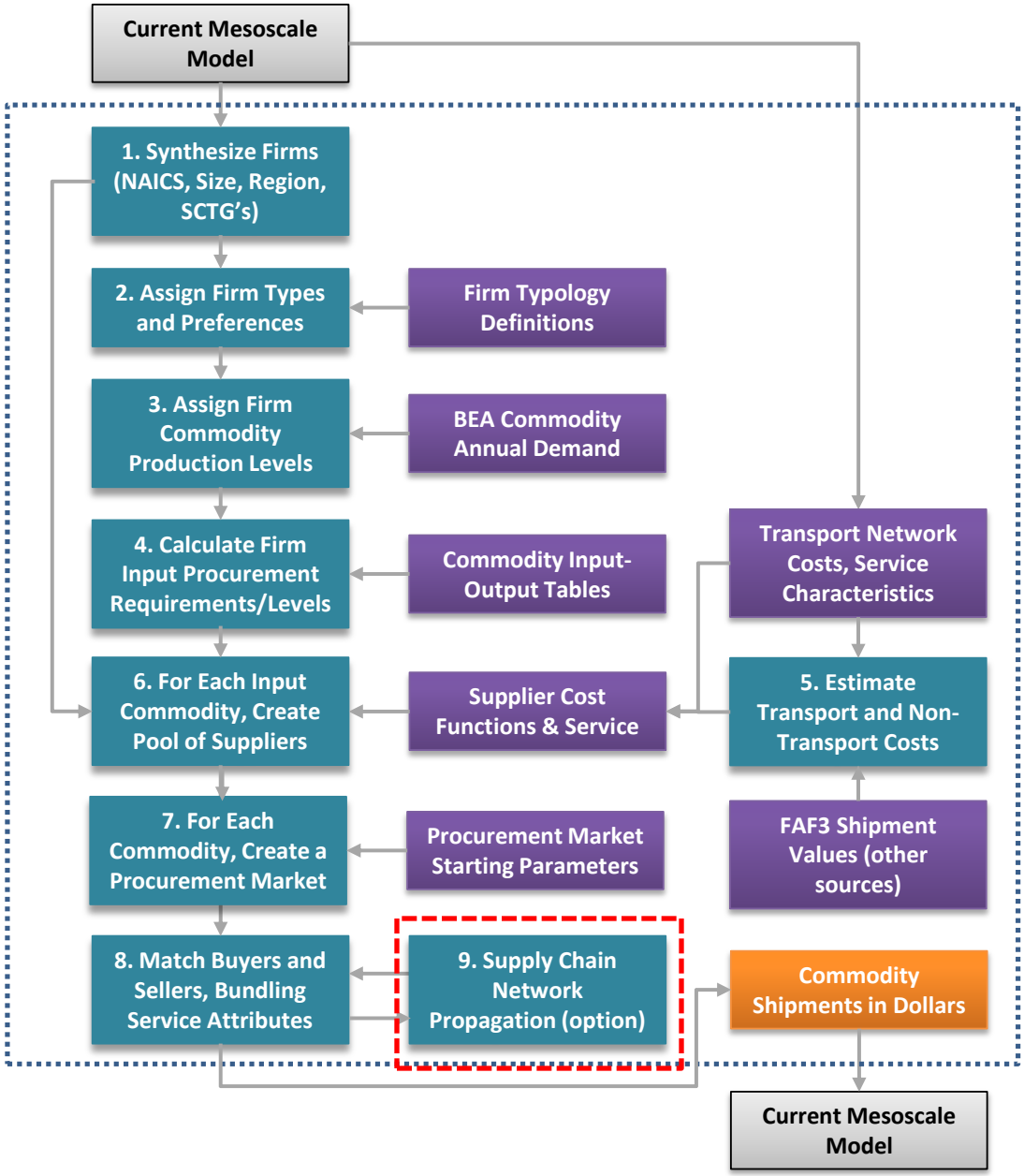
*(source: Cambridge Systematics, 2011)*

# Levels of Response Sensitivity in Forecasting

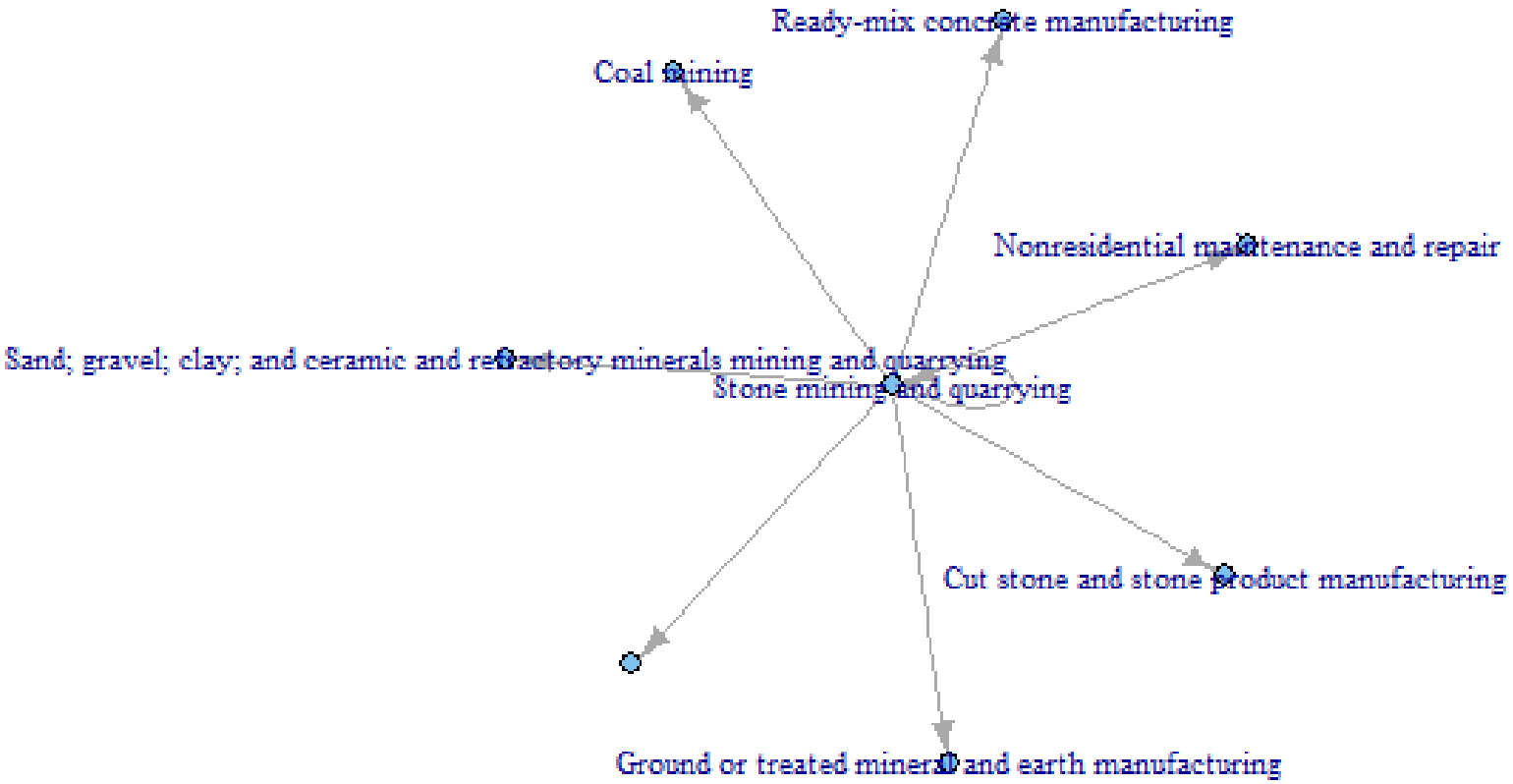
- Different levels of response sensitivity can be incorporated in the model design (not mutually exclusive)



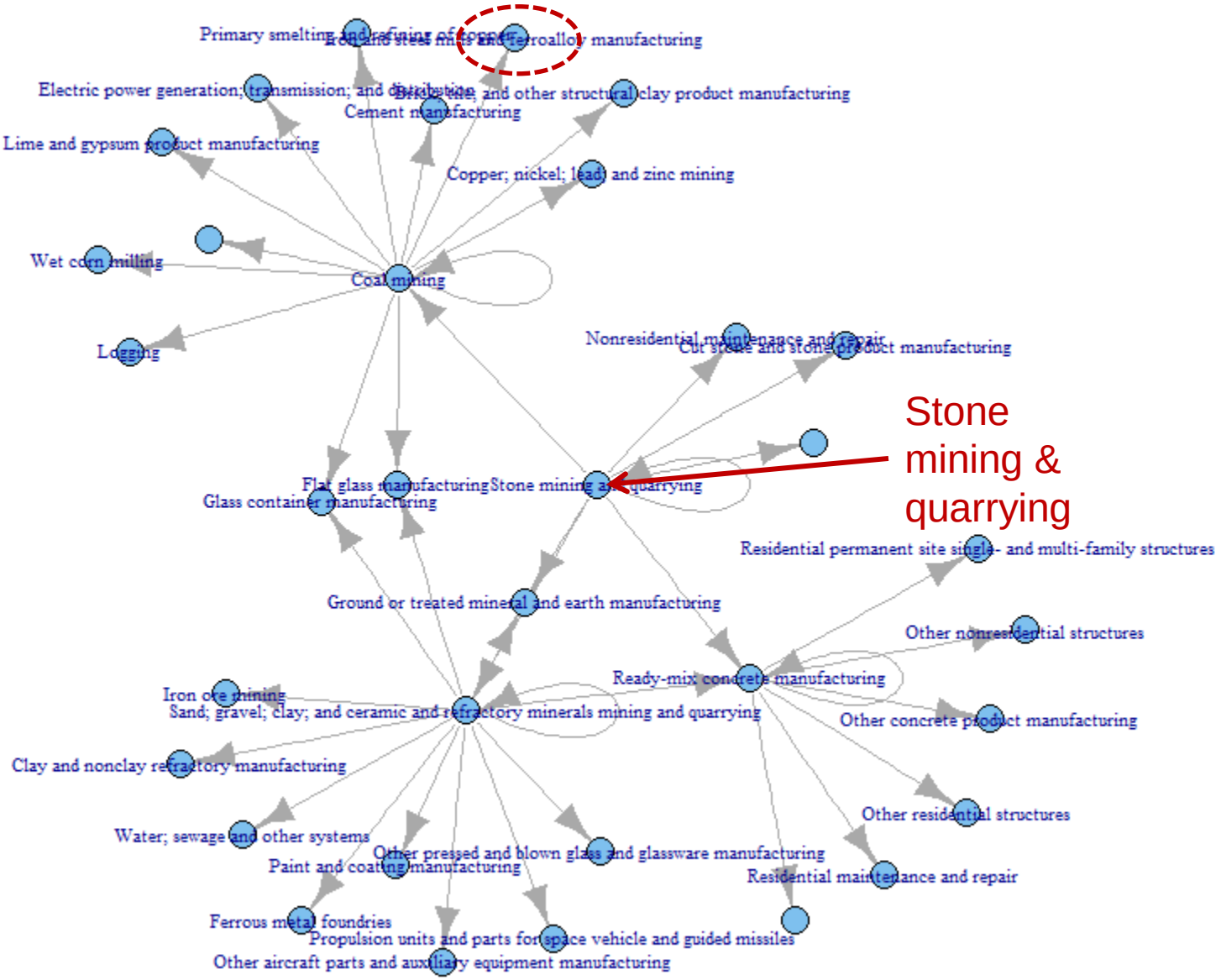
# Model Design Overview and Integration



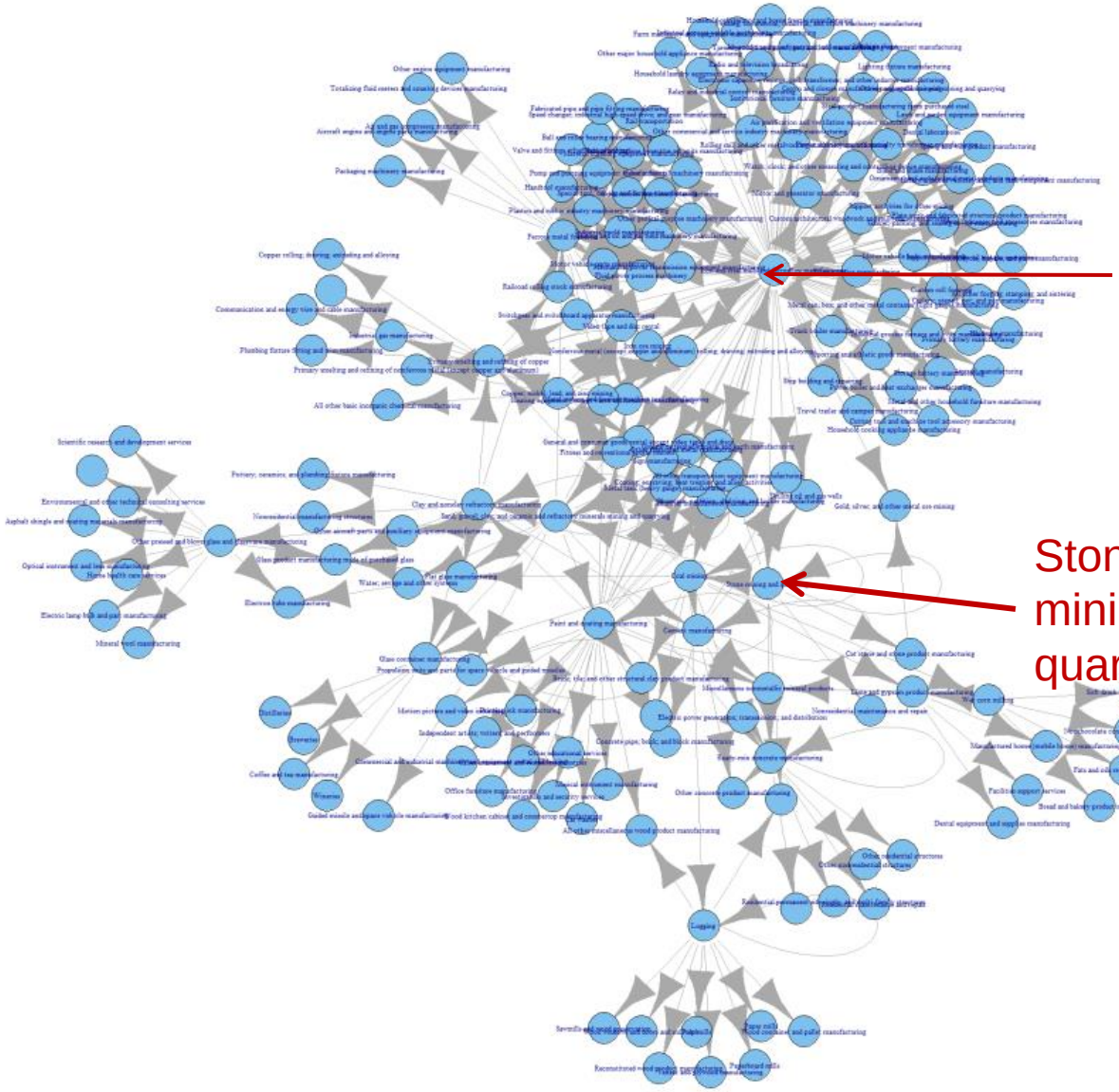
# “Stone mining/quarrying” (supplier perspective)



# “Stone mining/quarrying” (1st, 2nd order ties)



# “Stone mining/quarrying” (1st, 2nd, 3rd order ties)

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