# Using Auctions as Coordination Mechanisms for Planning Perishable Crop Production

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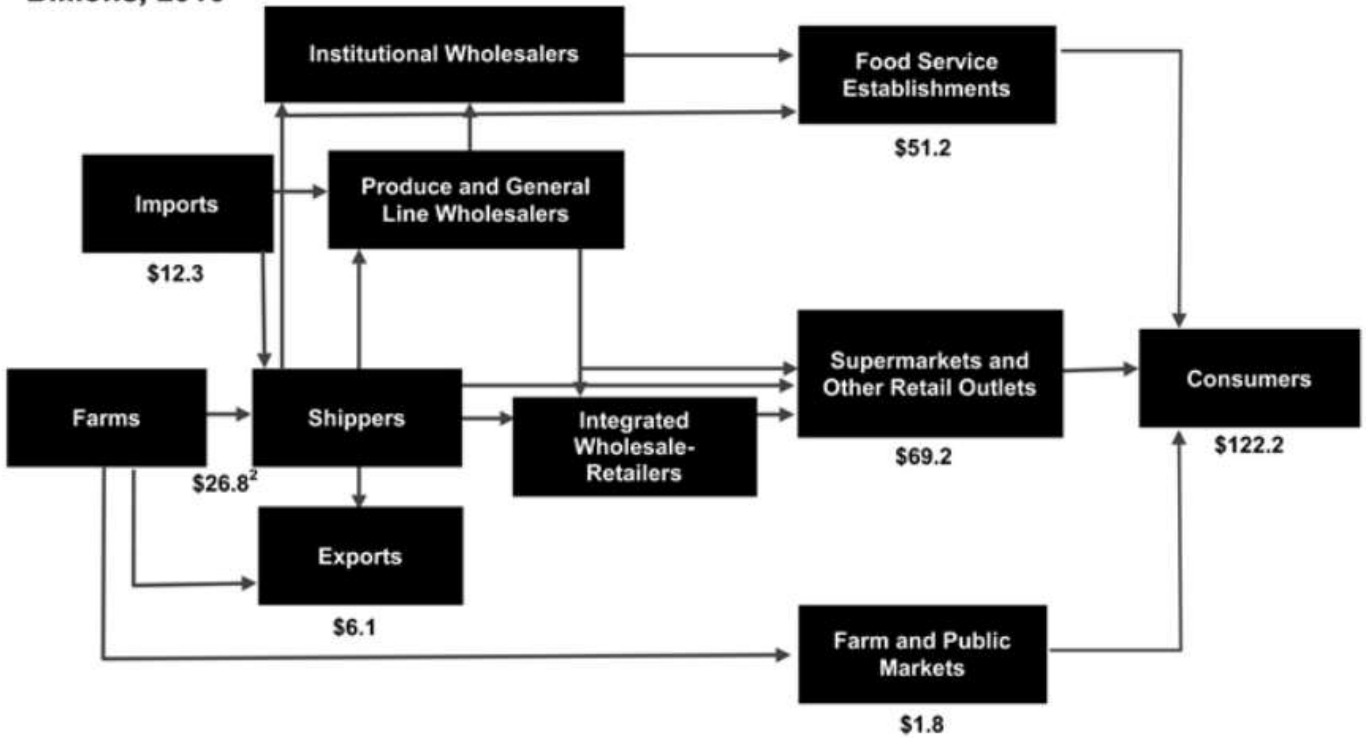
# Agenda:

- Problem background and motivation
- Description of the problem
- Literature review
- Solution approach
- Mathematical model
- Numerical results
- Further considerations

# Background:

- Consolidation in the industry is changing the balance of power to the detriment of producers who lag far behind (U.S. Case)

**Figure 1: U.S Fresh Fruit and Vegetable Value Chain, Estimated Dollar Sales, Billions, 2010**



# Background:

## Producer Impact Concerns:

- Long lead times, yield/price variability, weather uncertainty, **retailer requirements** and **short shelf lives**

## Environmental Concerns:

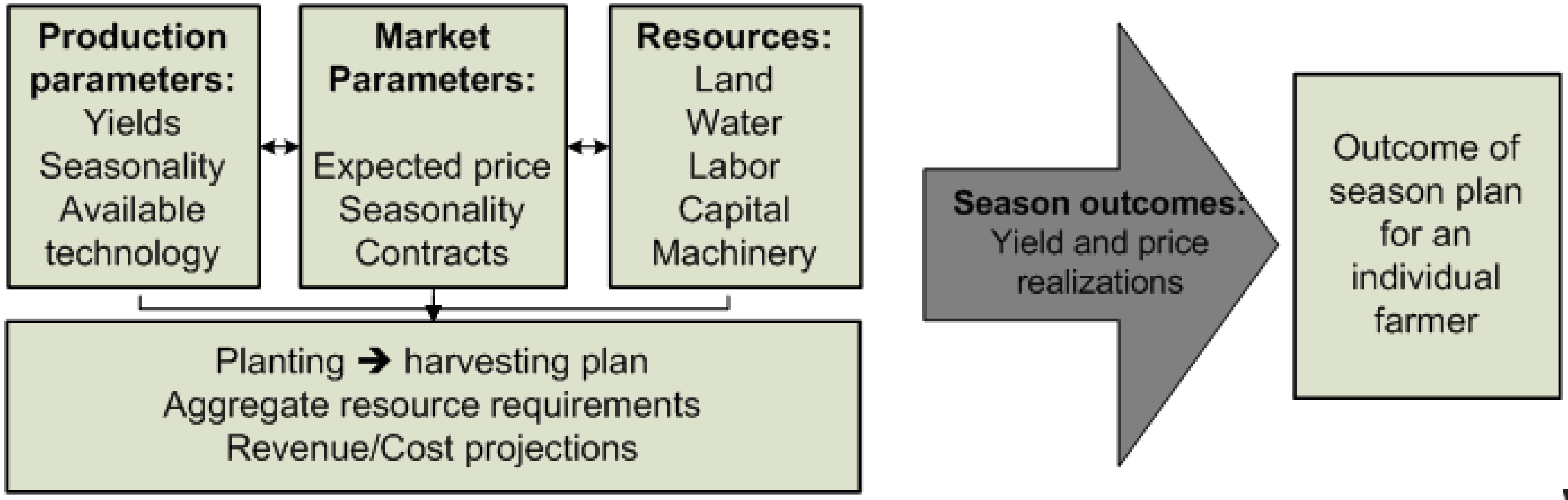
- Food consumption is set to double by 2050
- Current levels of food waste are significant
  - Over 50% for fruits and vegetables
  - 30% lost before reaching the consumer

Producers are responding by **forming cooperatives** and **joint consolidation centers**

# Description of the problem:

## Farmers:

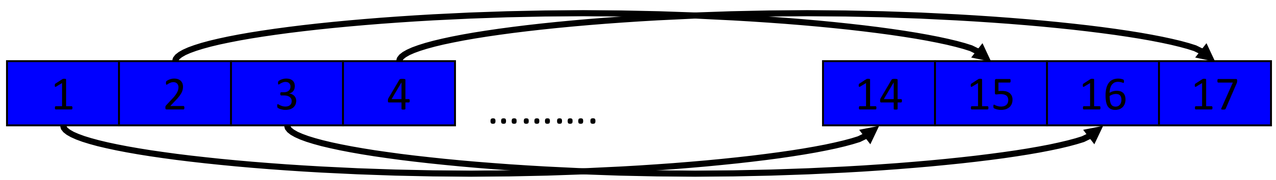
- Make critical tactical decisions which will influence their entire season
- Must account for many relevant variables, both certain and uncertain



# Description of the problem:

Planting Periods

Harvesting Periods

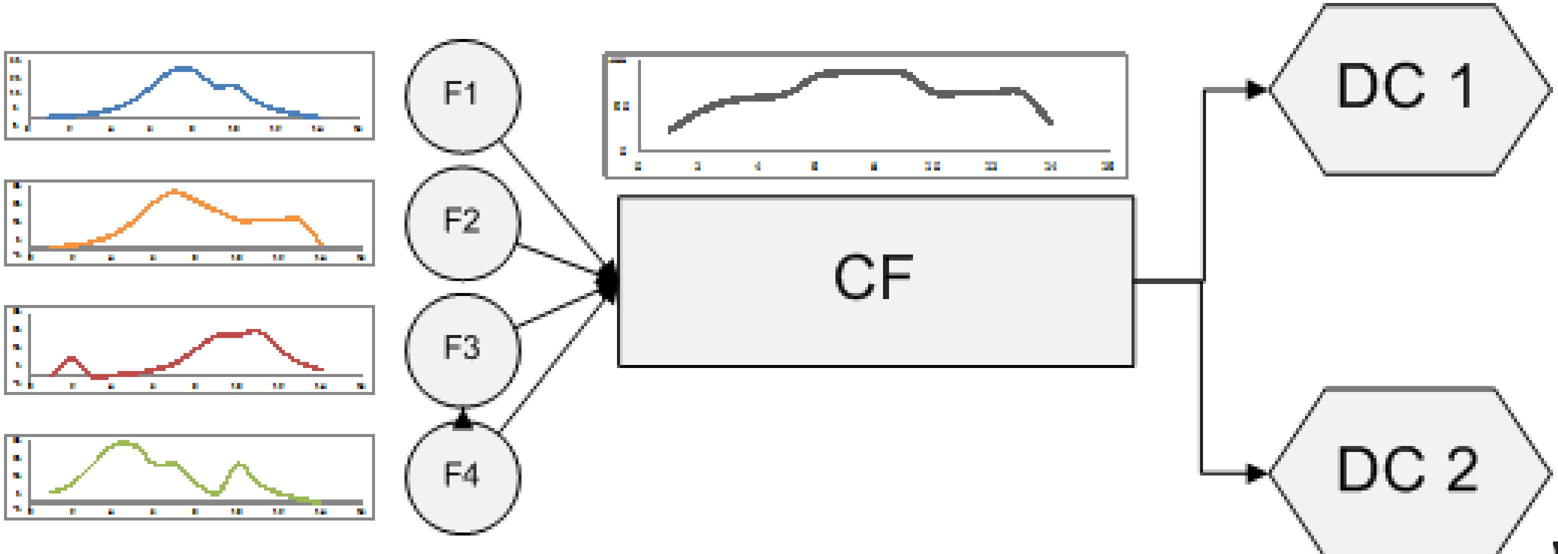



| | | Harvest by week | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | November | | | | December | | | | January | | | | February | | | | March | | | | April | | | | May | | | | June | | | | |
| Date of Plant | Production | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | % |
| 15-Aug | 1,662 | | | 5 | 5 | 10 | 10 | 10 | 10 | 9 | 9 | 8 | 8 | 8 | 8 | | | | | | | | | | | | | | | | | | | 100 |
| 30-Aug | 1,828 | | | | | 5 | 5 | 10 | 10 | 10 | 10 | 9 | 9 | 8 | 8 | 8 | 8 | | | | | | | | | | | | | | | | | 100 |
| 14-Sep | 2,373 | | | | | 5 | 5 | 6 | 10 | 10 | 10 | 10 | 10 | 9 | 9 | 8 | 8 | | | | | | | | | | | | | | | | | 100 |
| 29-Sep | 2,564 | | | | | | | 5 | 5 | 10 | 10 | 10 | 10 | 9 | 9 | 8 | 8 | 8 | 8 | | | | | | | | | | | | | | | 100 |
| 14-Oct | 2,698 | | | | | | | | | 5 | 5 | 10 | 10 | 10 | 10 | 9 | 9 | 8 | 8 | 8 | 8 | | | | | | | | | | | | | 100 |
| 29-Oct | 2,684 | | | | | | | | | | | 5 | 5 | 10 | 10 | 10 | 10 | 9 | 9 | 8 | 8 | 8 | 8 | | | | | | | | | | | 100 |
| 13-Nov | 2,896 | | | | | | | | | | | | | 5 | 5 | 10 | 10 | 10 | 10 | 9 | 9 | 8 | 8 | 8 | 8 | | | | | | | | | 100 |
| 28-Nov | 2,837 | | | | | | | | | | | | | | | 5 | 5 | 10 | 10 | 10 | 10 | 9 | 9 | 8 | 8 | 8 | 8 | | | | | | | 100 |
| 13-Dec | 2,337 | | | | | | | | | | | | | | | 5 | 5 | 10 | 10 | 10 | 10 | 9 | 9 | 8 | 8 | 8 | 8 | | | | | | | 100 |
| 28-Dec | 2,183 | | | | | | | | | | | | | | | | | 5 | 6 | 10 | 20 | 22 | 10 | 8 | 7 | 6 | 6 | | | | | | | 100 |
| 12-Jan | 1,794 | | | | | | | | | | | | | | | | | | | 4 | 5 | 10 | 15 | 22 | 10 | 9 | 9 | 8 | 8 | | | | | 100 |
| 27-Jan | 1,385 | | | | | | | | | | | | | | | | | | | | | 7 | 7 | 13 | 13 | 18 | 18 | 9 | 9 | 4 | 2 | | | 100 |
| 11-Feb | 1,200 | | | | | | | | | | | | | | | | | | | | | 7 | 7 | 21 | 21 | 15 | 15 | 5 | 4 | 3 | 2 | | | 100 |
| 26-Feb | 948 | | | | | | | | | | | | | | | | | | | | | | | 6 | 6 | 16 | 17 | 12 | 12 | 8 | 8 | 8 | 7 | 100 |

# Description of the problem:

## Consolidation Facility:

- Role of CF is to pool variance of production, achieve economies of scale and allow year-round availability of products
- Entry point to the cold-chain



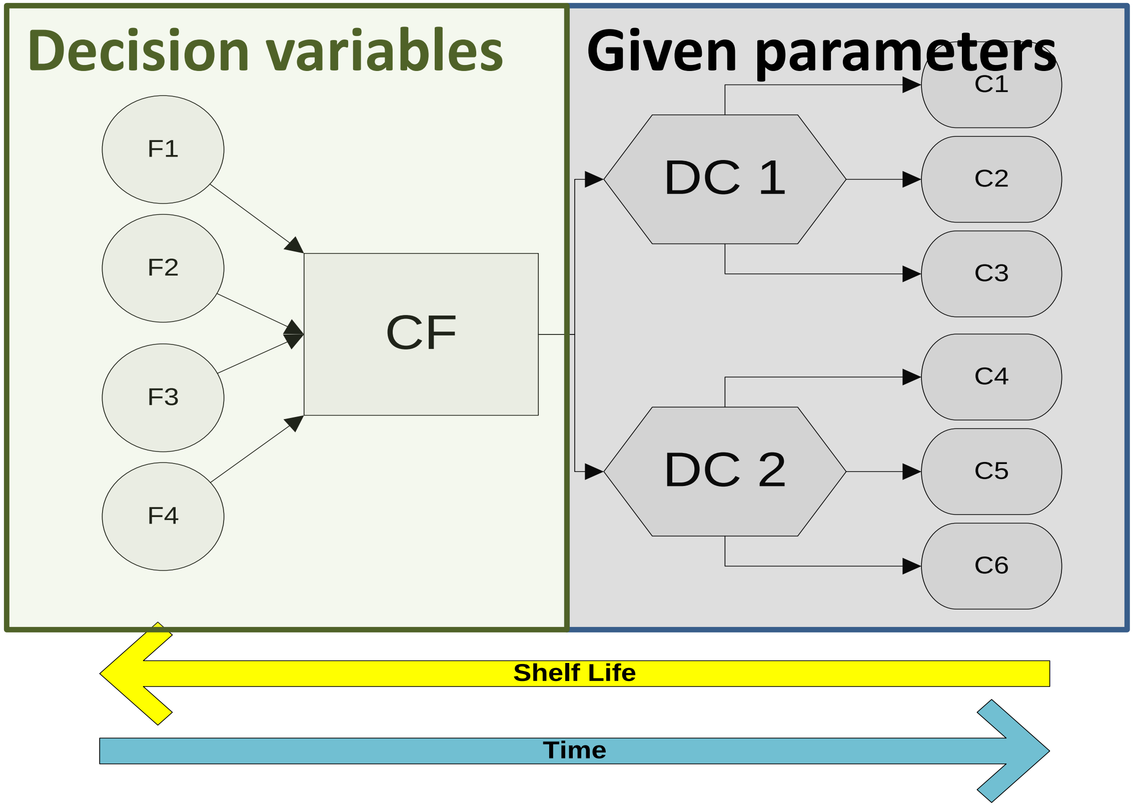
# Description of the problem:

We seek to **coordinate the supply chain** such that **optimal** production and marketing decisions are made **as if** they were taken by **a single, centralized, decision maker**

Must create the right **incentives, decision support technologies** and **collaboration frameworks**

# Description of the problem:

- First echelon of the supply chain
  - Producers and consolidation points
- Tactical decisions



# Key Problem Considerations:

- There should be transparency and fairness on contract allocation
- **Agents may act strategically** and attempt to influence allocation decisions
- ***Incentive Compatibility:*** No agent can be made better off by misrepresenting its information
- ***Individual Rationality:*** Agents cannot be forced to participate

# Related literature:

## Mechanism design and auctions:

- Auctions for price discovery and efficient allocation (Vickrey, 1961)
- Efficiency of auctions (Myerson, 1981)
- Auction mechanisms have been proposed as viable tools to achieve coordination (Vohra, 2011)
- For horizontal coordination, ***a marriage between auction mechanisms and supply contracts*** may be promising (Chen, 2003)

# Related literature:

## Supply chain coordination:

- Multiple proposals for SC coordinating auctions have been proposed (Karabuk & Wu, 2002; Fan, Stallaert, & Whinston, 2003; Mishra & Veeramani, 2007)
  - Few account for incentive compatibility
  - None exist for agriculture (in particular, for fresh produce)

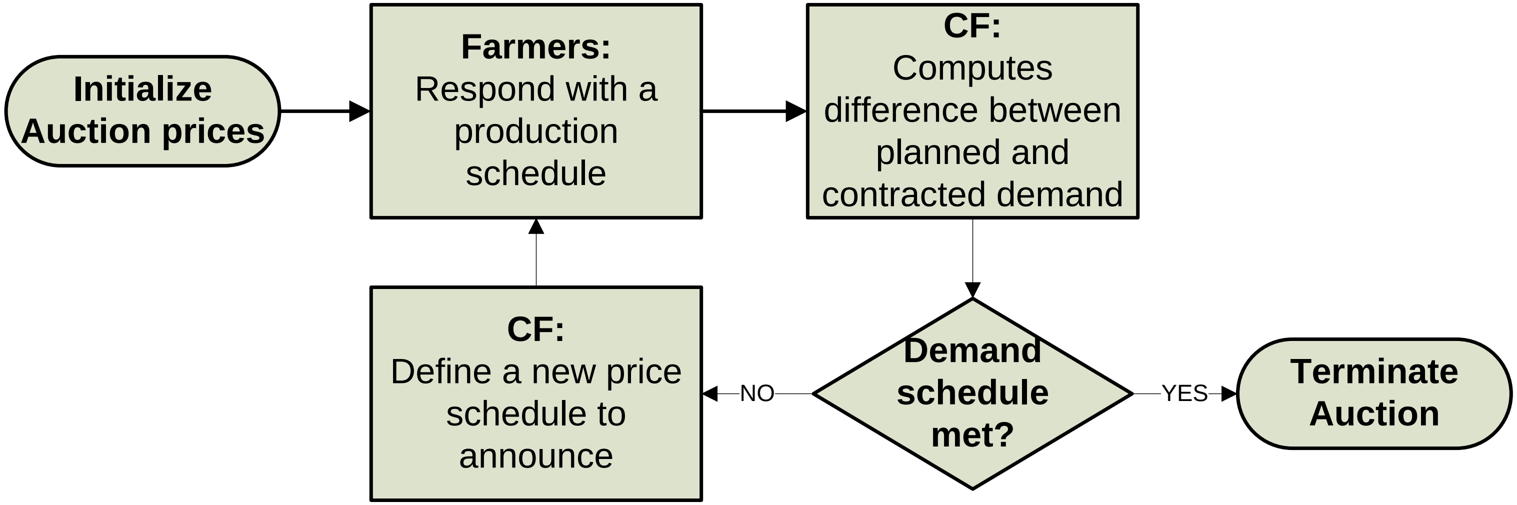
## Agricultural supply chains:

- Supply chain management is becoming increasingly important for fresh produce (Ahumada & Villalobos, 2009b; Zhang & Wilhelm, 2009)
- Must model relevant interactions, objectives and competitive behavior (A. J. Higgins et al., 2009)

# Solution Approach:

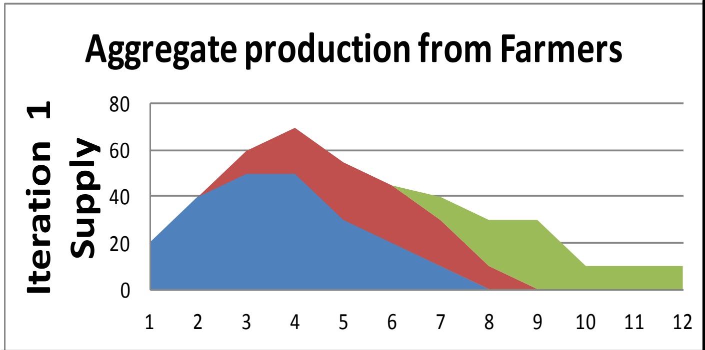
## Not the traditional auction for agricultural goods

- Allocates contracts before any production has been materialized
- Auctions multiple products/units simultaneously
- Agricultural planning may be **specially well suited** for such a mechanism



# Solution Approach:

## Decentralized optimization with auctions:



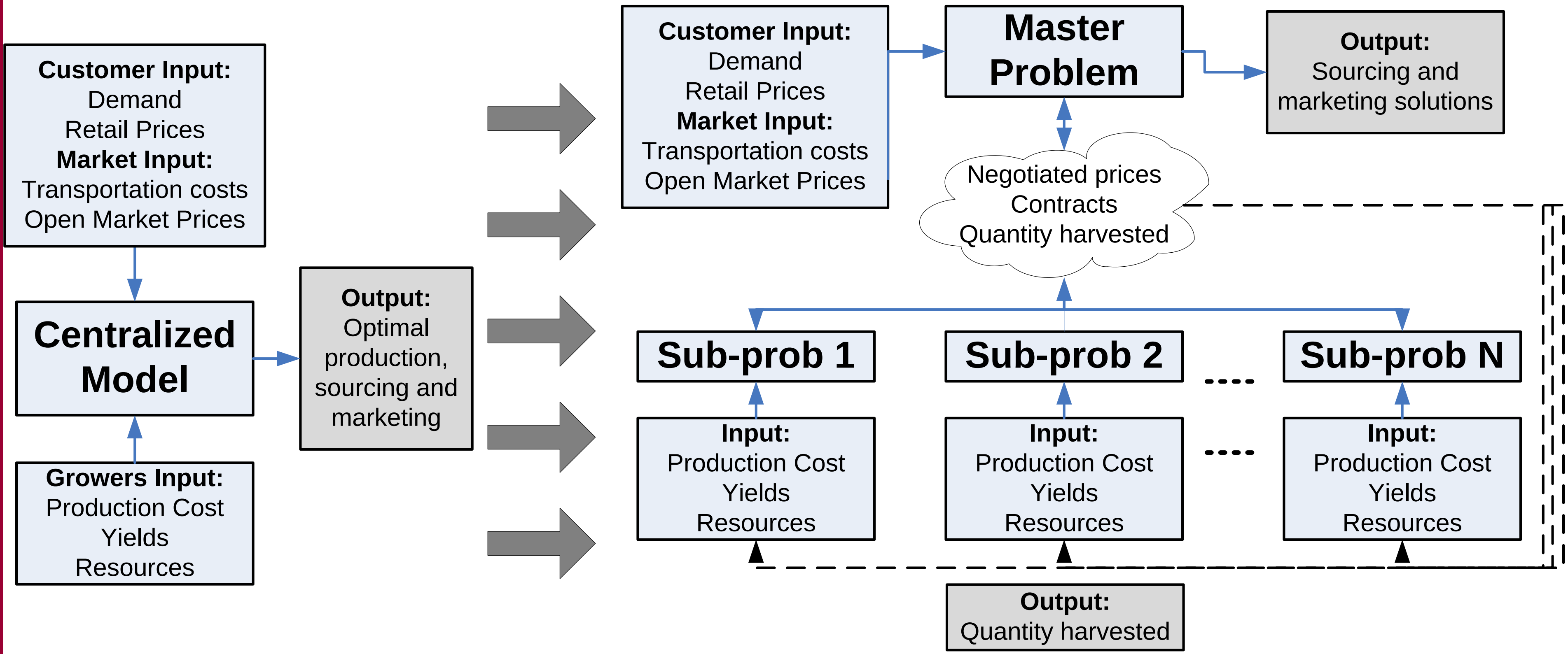

1st Consolidation

2nd Iteration

3rd Iteration

# Models Proposed:

## Centralized and decentralized models:



# Mathematical Formulation:

**Indexes:**

$t \in T$ : Planning **periods** (weeks)

$p \in P,\ P(j,l) \subseteq \mathrm{T}$ : Set of feasible **planting weeks** for crop **j** in location **l**

$h \in H,\ H(j,l) \subseteq \mathrm{T}$ : Set of feasible **harvesting weeks** for crop **j** in location **l**

$j \in J$ : Potential **crops** to plant

$q \in Q$ : **Quality states** of crops

$l \in L$ : **Locations** available for planting

**General Parameters (CF):**

$MaxDem_{hj}$ : Maximum demand of crop *j* at time *h* (Maximum open market)

$MinDem_{hj}$ : Minimum demand of crop *j* at time *h* (Contracted demand)

$qmin_j$ : Minimum quality accepted for crop ***j***

$WHCap$ : Total capacity of consolidation facility

$\Delta q_j$ : Change in quality for product ***j*** stored one week at CF

# Mathematical Formulation:

**General Parameters (Farmer):**

$Land_l$ : Land available at location *l* (in acres)

$LaborP_{ptj}$ : Workers needed at period *t* for **cultivating** crop *j* planted at period *p* (Men-week/ Acre)

$LaborH_j$ : Workers needed for **harvesting** crop *j* (Men-week/Acre)

$MaxLab_l$ : Max number of workers that can be hired in location l

$Yield_{phj}$ : Expected yield of crop *j* at time *p* and harvested in week *h* (%/Week)

$Total_{jl}$ : Expected total production of crop *j* planted in location *l* (Cartons/Acre)

$MaxL_j$ : Maximum allowed amount to plant of crop *j* during one week (in Acre)

$MinL_j$ : Minimum allowed amount to plant of crop *j* during one week (in Acre)

$QualD_{jql}$ : Quality distribution ***q*** for crop ***j*** for farmer *l*

$\Delta tl_l$ : Travel time from location ***l*** to facility

$\Delta ql_{lj}$ : Change in quality for product ***j*** traveling from location ***l*** to facility

# Mathematical Formulation:

**Cost parameters (Farmers):**

$Cplant_{jl}$ : Cost per acre of **planting** and cultivating for crop *j* (exclude labor)

$Charv_{jl}$ : Cost per acre of **harvesting** for crop *j* (exclude labor)

$Chire_t$ : Fixed cost to **hire** a seasonal worker at time *t*

$Clab_t$ : Variable cost to **hire** a seasonal worker at time *t*

$Ctrans_{jl}$ : Cost of transportation form location ***l*** to facility

**Cost parameters (CF):**

$Cinv_j$ : Inventory cost for crop ***j***

$Cover_j$ : Cost of overage for product ***j***

$Cunder_j$ : Cost of underage for product ***j***

$Price_{hj}$ : Expected price for crop ***j*** at time ***h***

# Mathematical Formulation:

**Decision variables (Farmers):**

$Vplant_{pjl}$ : Area to plant of crop *j* in period *p* at location *l*

$Vharv_{hjl}$ : Harvest quantity of crop *j* in period *h* at location *l*

$Vlab_{tl}$ : Seasonal laborers employed at location *l* at time *t*

$VHire_{tl}$ : Seasonal laborers **hired** for location *l* at time *t*

$VFire_{tl}$ : Seasonal laborers **dismissed** from location *l* at time *t*

$Y_{jpl}$ (Binary) : **1** If crop $j$ is planted at period $p$ at location $l$ **0** otherwise

$Vtrans_{hjql}$ : Amount to transport from location ***l*** of crop ***j*** with quality ***q*** at time ***h***

**Decision variables (CF):**

$Vinv_{hjq}$ : Amount to store of crop ***j*** with quality ***q*** at time ***h***

$Vsell_{hjq}$ : Amount of crop ***j*** to sell with quality ***q*** at time ***h***

$Vover_{hj}$ : Overage of crop ***j*** at time ***h***

$Vunder_{hj}$ : Underage of crop ***j*** at time ***h***

# Mathematical Formulation:

## Objective Function:

CF Master

**Objective Function:**

| | |
|---|---|
| $Max\ Z_{CP} = \sum_{hj,qmax_j \geq q \geq qmin_j} Vsell_{hjq} * Price_{hj}$ | Revenue from selling crops |
| $- \sum_{hjq} Vinv_{hjq} * Cinv_j$ | Cost of inventory |
| $- \sum_{hjq} Vover_{hj} * Cover_j$ | Cost of Overage/waste |
| $- \sum_{hjq} Vunder_{hj} * Cunder_j$ | Cost of Underage |
| $- \sum_{ljqt} Vtrans_{hjql} * Ctrans_{jl}$ | Costs of transportation |
| $- \sum_{tl}(VHire_{tl} * Chire_t) - \sum_{tl}(Vlab_{tl} * Clab_t)$ | Labor costs |
| $- \sum_{pjl}\left(VPlant_{pjl} * Cplant_j\right) - \sum_{hjl}\left(Vharv_{hjl} * Charv_j\right)$ | Planting/harvesting costs |

Farmer Sub-P

# Mathematical Formulation:

## Farming Constraints:

**Farming Constraints:**

$\sum_j \sum_p Vplant_{pjl} \leq Land_l \qquad \forall\, l \in L$

$Min_j * Y_{jpl} \leq Vplant_{pjl} \leq Max_j * Y_{jpl} \qquad \forall\; j \in J,\; p \in P, l \in L$

$Vharv_{hjl} \leq \sum_p Vplant_{pjl} * Yield_{phj} * Total_{jl} \qquad \forall\, h \in H,\; j \in J,\; l \in L$

$Vharv_{hjl} * QualD_{hjql} = Vtrans_{lj\,(q-\Delta ql_{lj})(h+\Delta tl_l)} \qquad \forall\;\; h, j, q, l$

**Farming Labor Constraints:**

$Vlab_{tl} \geq \sum_p \sum_j Vplant_{pjl} * LaborP_{ptj} + \sum_{h=t} \sum_j Vharv_{hjl} * LaborH_j \qquad \forall\, t \in T, l \in L$

$VHire_{tl} - VFire_{tl} = Vlab_{tl} - Vlab_{(t-1)l} \qquad \forall\, t \in T,\;\; l \in L$

$\sum_t VHire_{tl} \leq MaxLab_l \qquad \forall\;\; l \in L$

# Mathematical Formulation:

## Consolidation Facility (Master) Constraints:

**Coupling Constraint:**

$$\sum_l Vtrans_{hljq} = PVarr_{h,j,q} \qquad \forall \ \ j, q, h$$

**Inventory balance and quality tracking:**

$$PVarr_{h,j,q} + Vinv_{h-1,jq+\Delta q_j} - Vsell_{hjq} - Vwaste_{hjq} = Vinv_{h,j,q} \qquad \forall \ \ j, q, h$$

**Demand Constraints:**

$$MinDem_{hj} - Vunder_{hj} \le \sum_{qmax_j \ge q \ge qmin_j} Vsell_{hjq} \le MaxDem_{hj} + Vover_{hj} \quad \forall \ \ j, h$$

**Warehouse Capacity Constraint:**

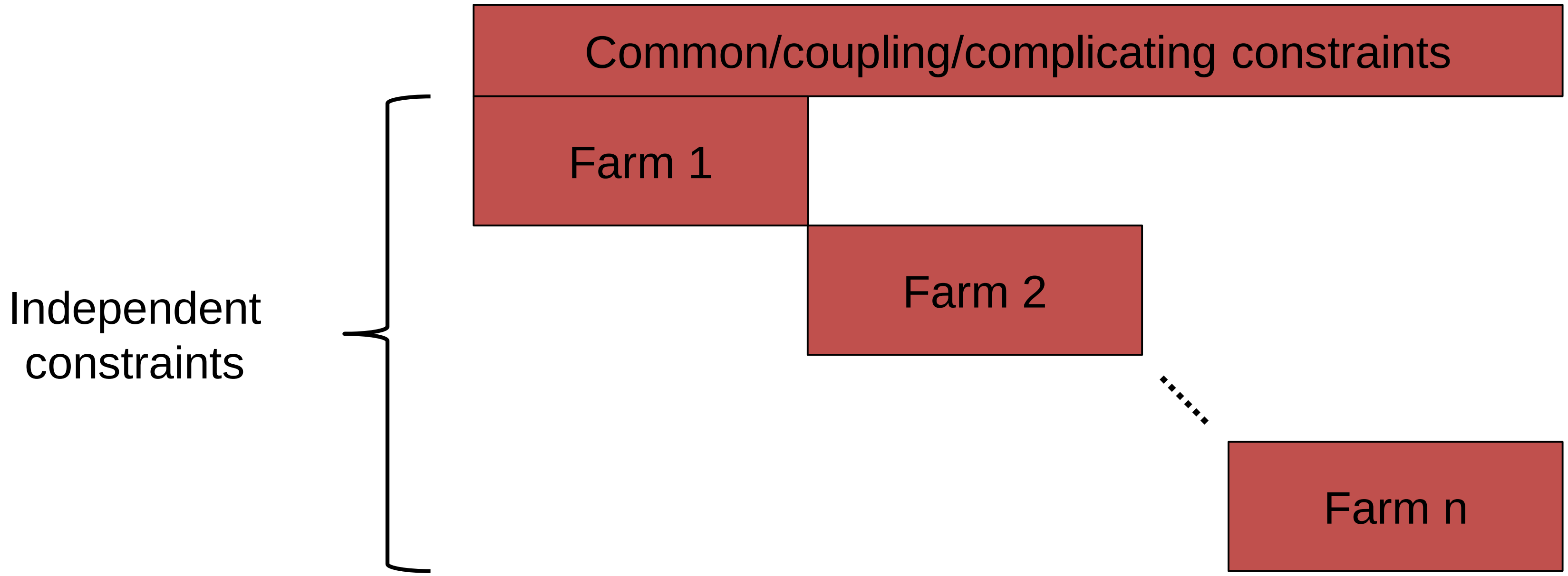
$$\sum_{jq} Vinv_{hjq} \le WHCap \qquad \forall \ \ h$$

# Mathematical Decomposition:

## Problem has a block-angular structure:

**Coupling Constraint:**

$$\sum_l Vtrans_{hljq} = PVarr_{h,j,q} \qquad \forall \; j, q, h$$



# Mathematical Decomposition:

## Possible Decentralized Reformulations:

- **Dantzig-Wolfe Decomposition**
  - Dual decomposition
  - Master problem recombines local solutions
  - Less appealing to stakeholders

- **Subgradient optimization**
  - Dual decomposition
  - Master problem creates a price tatonement/bidding process
  - More intuitive, transparent and of apparent fairness

**Reformulate through Sub-Gradient optimization and use vector for transfer prices**

# Mathematical Decomposition:

## Master (CF) Constraints:

Relax this constraint to make all problems separable

**Coupling Constraint:**

$\sum_l Vtrans_{hljq} = PVarr_{h,j,q} \quad \forall \;\; j, q, h$

**Inventory balance and quality tracking:**

$PVarr_{h,j,q} + Vinv_{h-1,jq+\Delta q_j} - Vsell_{hjq} - Vwaste_{hjq} = Vinv_{h,j,q} \quad \forall \;\; j, q, h$

**Demand Constraints:**

$MinDem_{hj} - Vunder_{hj} \leq \sum_{qmax_j \geq q \geq qmin_j} Vsell_{hjq} \leq MaxDem_{hj} + Vover_{hj} \quad \forall \;\; j, h$

**Warehouse Capacity Constraint:**

$\sum_{jq} Vinv_{hjq} \leq WHCap \quad \forall \;\; h$

# Mathematical Decomposition:

## Modified Objective function:

$$Max\ Z_{SG} = \sum_{hj,qmax_j \geq q \geq qmin_j} Vsell_{hjq} * Price_{hj}$$
$$- \sum_{hjq} Vinv_{hjq} * Cinv_j$$
$$- \sum_{hjq} Vover_{hj} * Cover_j$$
$$- \sum_{hjq} Vunder_{hj} * Cunder_j$$

$$- \sum_{ljqt} Vtrans_{hjql} * Ctrans_{jl}$$
$$- \sum_{tl}(VHire_{tl} * Chire_t) - \sum_{tl}(Vlab_{tl} * Clab_t)$$
$$- \sum_{pjl}(VPlant_{pjl} * Cplant_j) - \sum_{hjl}(Vharv_{hjl} * Charv_j)$$

$$+ \sum_{hjq} \lambda_{hjq}\left(PVarr_{h,j,q} - \sum_l Vtrans_{hljq}\right)$$

Prices for contracts

# Mathematical Decomposition:

## Modified Objective function:

$$
\begin{aligned}
Max\ Z_{SG} \ = \ & \textstyle\sum_{hj,qmax_j \geq q \geq qmin_j} Vsell_{hjq} * Price_{hj} \\
& - \textstyle\sum_{hjq} Vinv_{hjq} * Cinv_j \\
& - \textstyle\sum_{hjq} Vover_{hj} * Cover_j \\
& - \textstyle\sum_{hjq} Vunder_{hj} * Cunder_j \\
& - \textstyle\sum_{hjq} \boldsymbol{\lambda_{hjq}} \left( \boldsymbol{PVarr_{h,j,q}} \right) \\
& - \textstyle\sum_{ljqt} Vtrans_{hjql} * Ctrans_{jl} \\
& - \textstyle\sum_{tl} (VHire_{tl} * Chire_t) - \sum_{tl} (Vlab_{tl} * Clab_t) \\
& - \textstyle\sum_{pjl} \left( VPlant_{pjl} * Cplant_j \right) - \sum_{hjl} \left( Vharv_{hjl} * Charv_j \right) \\
& + \textstyle\sum_{hjq} \boldsymbol{\lambda_{hjq}} \left( \sum_l \boldsymbol{Vtrans_{hljq}} \right)
\end{aligned}
$$

Cost for CF

Revenue for Farmers

# Validation of the Mechanism:

## Data used:

- Production data for **four crops** was used: *(Broccoli, cauliflower, romaine lettuce and iceberg lettuce)*
- Information from **Yuma, AZ** representing a **typical farm** from the region was used.
- Data used includes:
  - **Production costs**
  - **Yields and seasonality**
  - **Labor costs and productivity**
  - **Perishability of crops**
  - **Historical market prices**

# Validation of the Mechanism:

**Differences between agents (farms):**

- Numerous factors can influence a farmers comparative advantage and decision processes

- Size of farm → bargaining power /costs
- Soil types → seasonality/yields/costs
- Microclimates → seasonality/yields/costs
- Technology → seasonality/yields/costs
- Preferences → product offerings
- Access to water → product offerings
- Simple know-how

# Validation of the Mechanism:

## Data manipulation:

- In order to test the mechanism, the "typical farm" framework was adjusted to induce diversity among decisionmakers.
  - Land/Labor: [U~(0.5,1.5)]*(35 workers/200 acres)
  - Yield: [U~(0.75, 1.35)]* Base yield
  - Production costs: [U~(0.75, 1.35)]* Base cost

- Parameters of farmers remained hidden from one another. Only prices are communicated

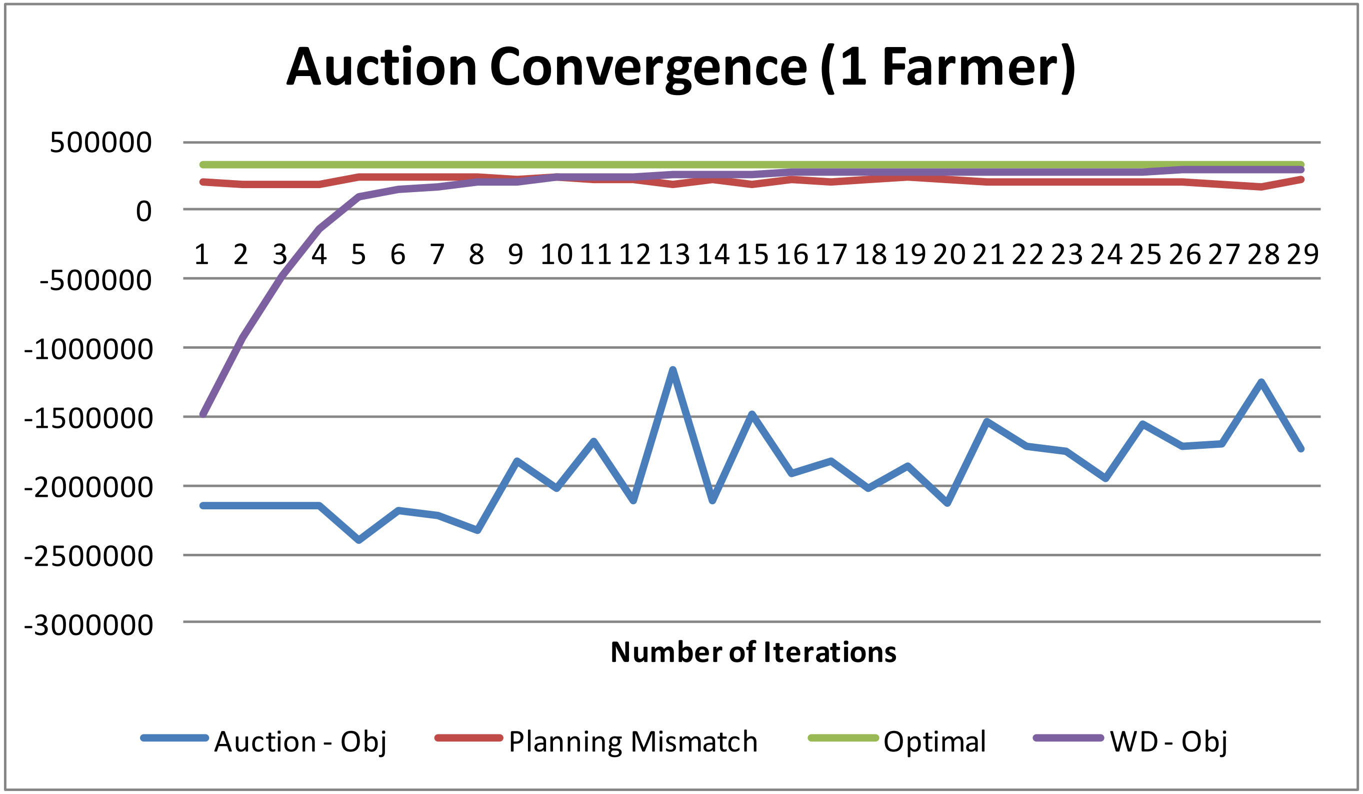
# Convergence and Efficiency:

## Convergence of formulation for various problem sizes

- **Auction – Obj:** Current auction objective function value
- **Planning Mismatch:** $\cdot \sum_{hjq} \left(PVarr_{h,j,q} - \sum_{l} Vtrans_{hljq}\right)$
- **Optimal:** Centralized, optimal solution
- **WD–Obj:** Solution obtained through Wolfe Dantzig decomposition

# Convergence and Efficiency:

**Convergence of formulation for various problem sizes**



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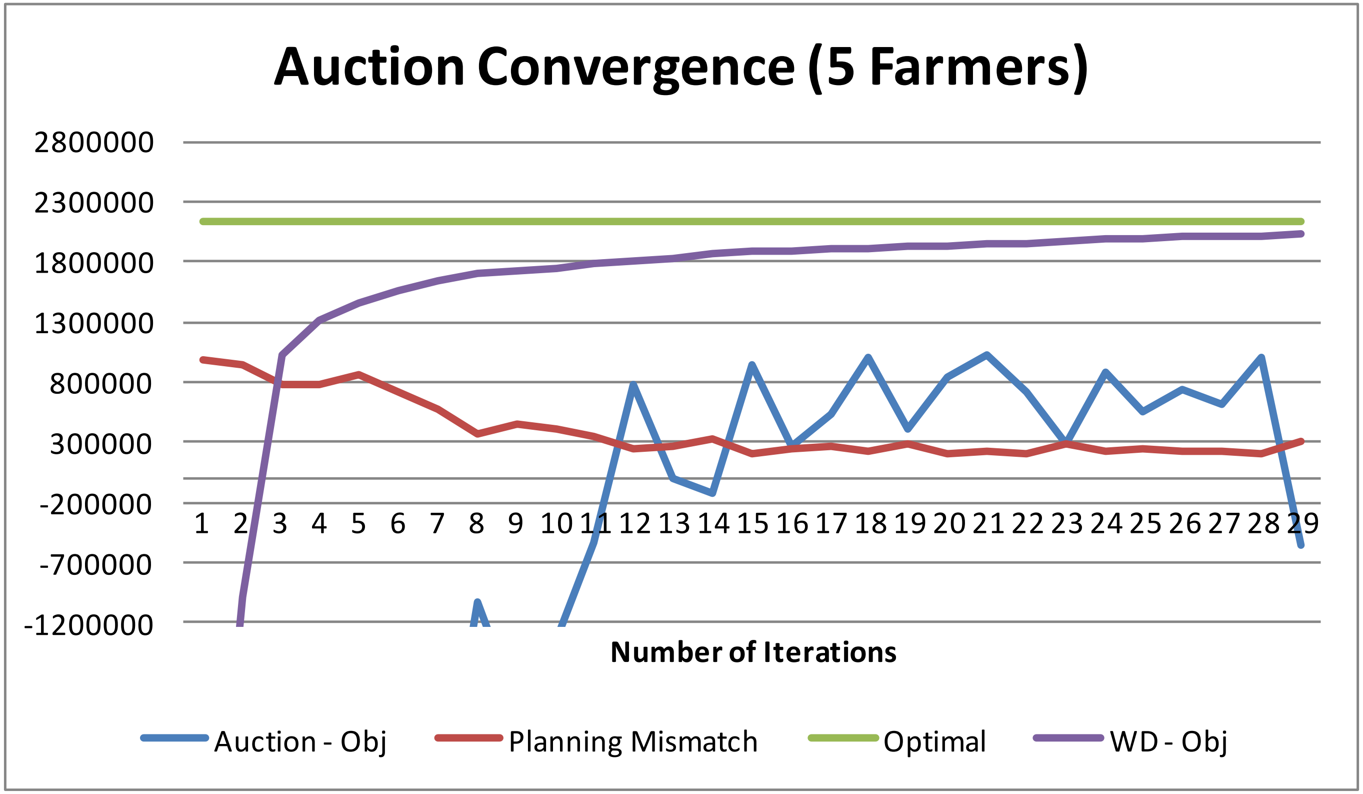
## Convergence of formulation for various problem sizes



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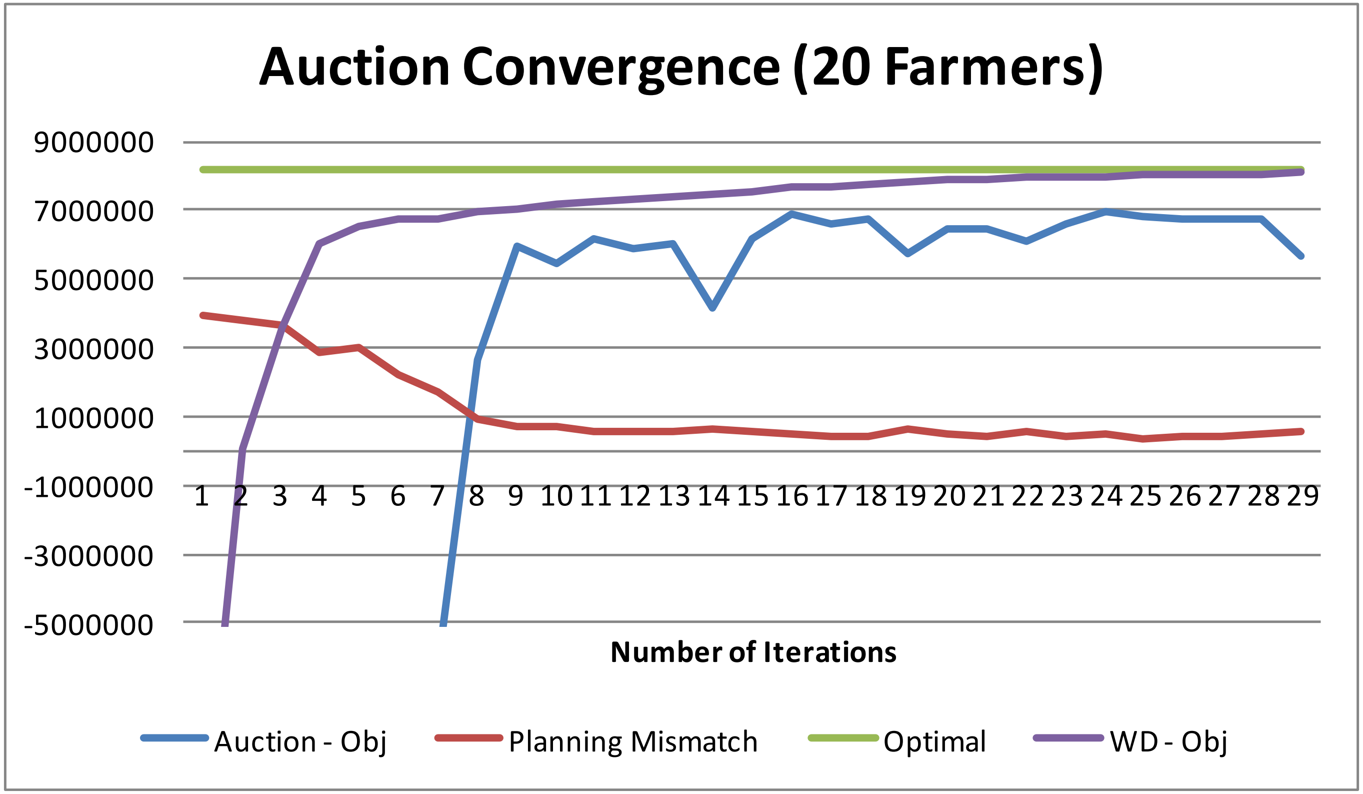

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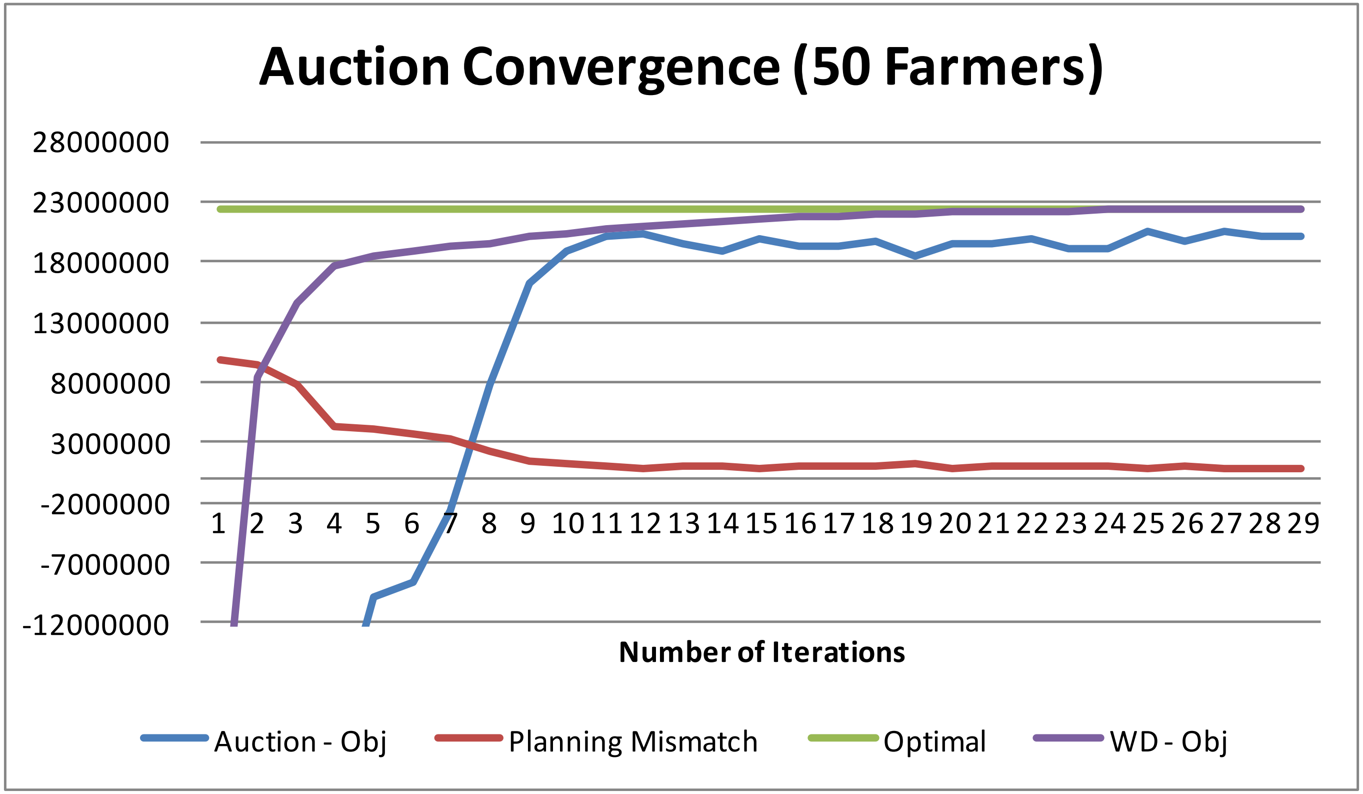

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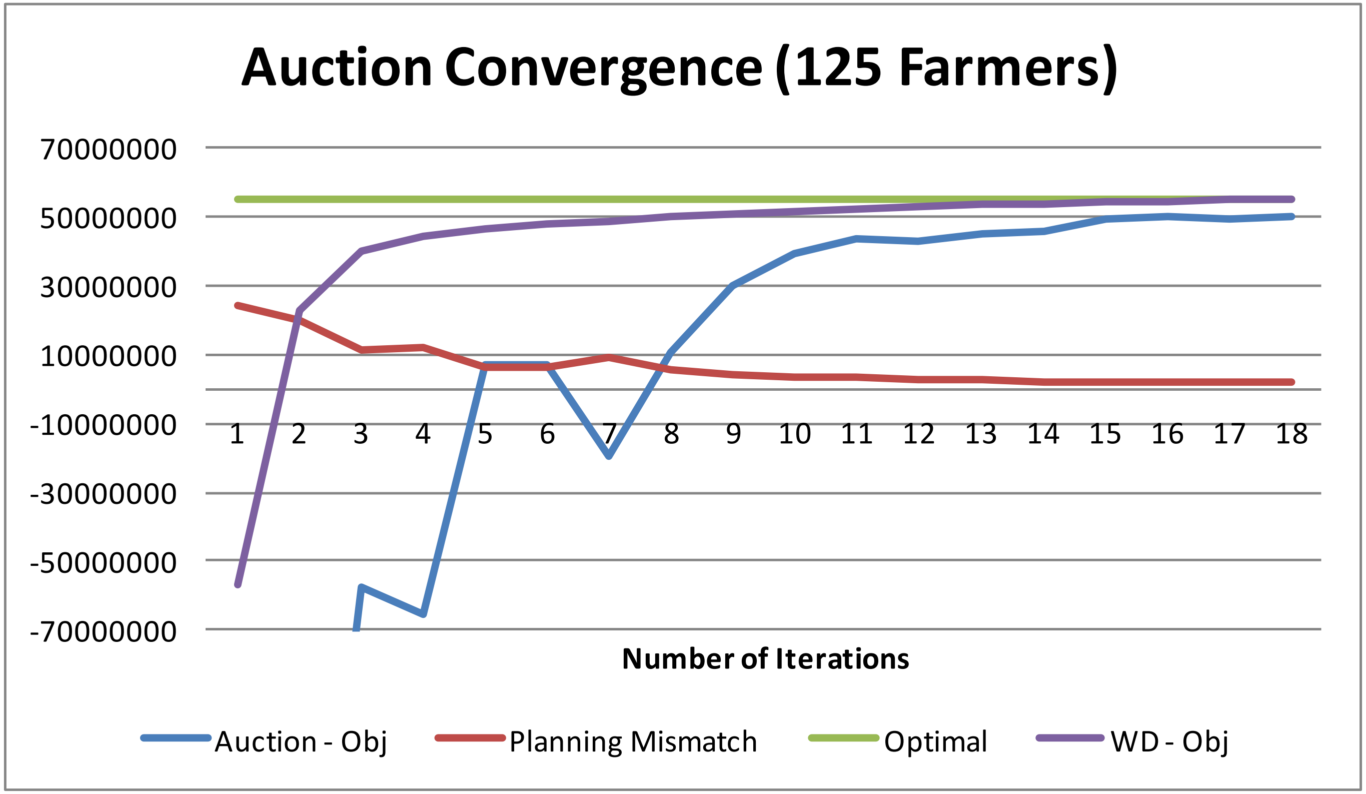
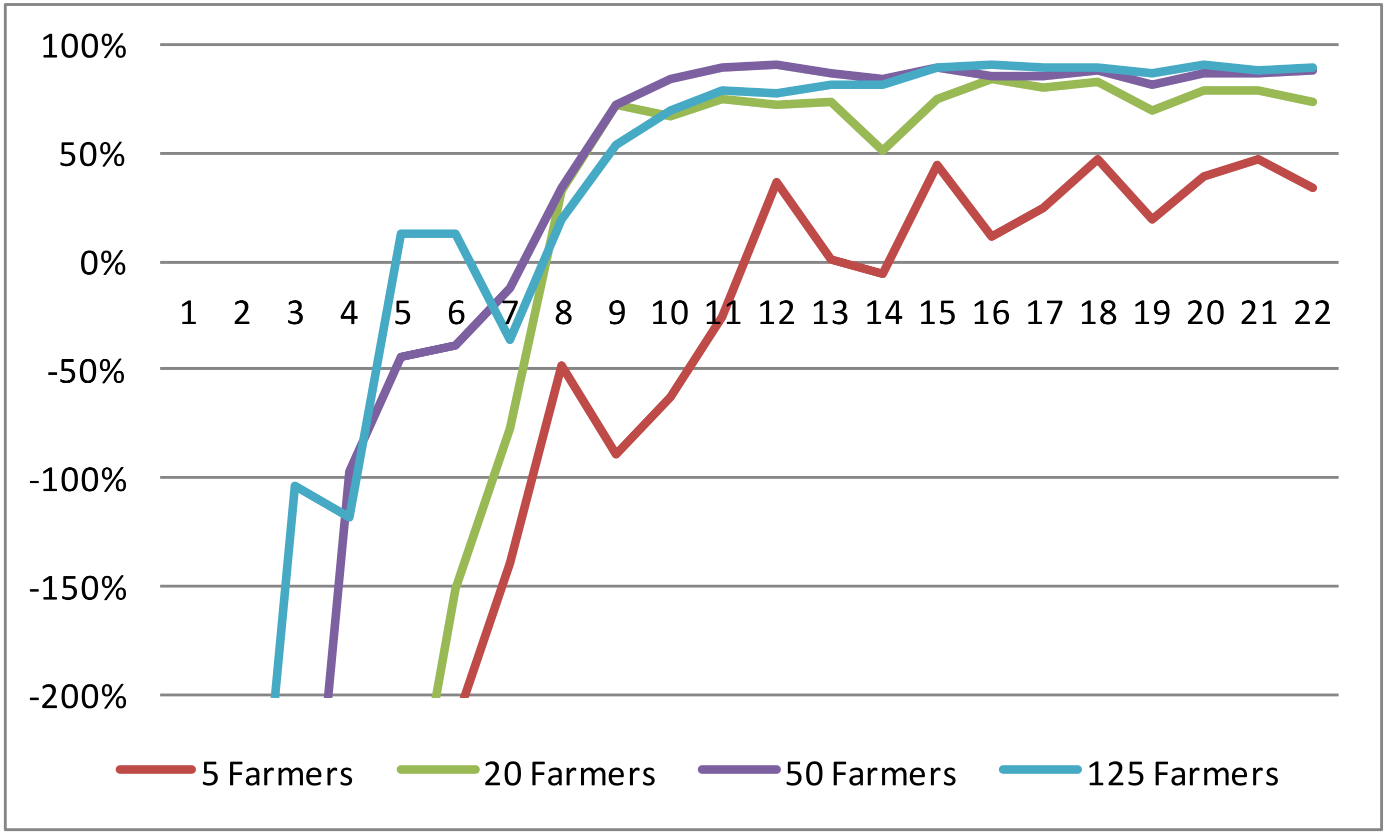
## Convergence of formulation for various problem sizes



# Convergence and efficiency:

## Relative Optimality Gap



# Convergence and Efficiency:

## Convergence Summary:

- Convergence is faster at larger problem instances
- Smaller optimality gap is achieved with more players
- A reduced number of players leads to high supply elasticity
  - Few players have more control over relative supply/demand equilibrium
  - Consistent with economic theory

| Number of participants | Optimal Solution | Best Auction Solution | % Planning Mismatch | % Optimality | Iteration # | Iterations to 80% |
|---|---|---|---|---|---|---|
| 1 Farm | $ 324,269 | $ (1,161,669) | 106% | -358% | 13 | - |
| 5 Farms | $ 2,136,136 | $ 1,020,037 | 25% | 48% | 21 | - |
| 20 Farms | $ 8,156,519 | $ 6,930,982 | 14% | 85% | 24 | 17 |
| 50 Farms | $ 22,395,199 | $ 20,601,215 | 8% | 92% | 27 | 10 |
| 125 Farms | $ 55,567,789 | $ 50,863,300 | 8% | 92% | 20 | 11 |

# Final considerations:

## Benefits

- Coordination mechanism is intuitive
- Ample theoretical backing to support optimality
- Attractive for large organizations

## Pitfalls

- Sub gradient optimization may yield infeasible solutions
- Must define penalties for demand overage/underage
- Bidders may lie to gain strategic advantage

# Final Considerations:

- There should be **transparency and fairness** on contract allocation ✓
- Reasonable convergence ✓
- **Agents may act strategically** and attempt to influence allocation decisions ?
- ***Incentive Compatibility:*** No agent can be made better off by misrepresenting its information ?
- ***Individual Rationality:*** Agents cannot be forced to participate ✓

# Final considerations:

**Further work**

- Refine sub-gradient step sizes for convergence
- Reformulate a more flexible demand fulfillment
- Perform case study
- **Quantify and minimize impact of strategic bidding**

# Solution Approach:

## Analysis of efficiency:

- Optimal allocation for each agent ***i*** (Truth)

$$Max \quad z^{*} = c^{i}x^{i}$$
$$st: Ax^{i} = b$$
$$x^{i} \geq 0$$

- Best response (Not necessarily truth)

$$Max \quad z^{BR} = c^{i}x^{i} + \sum_{k=i}^{K-1} c^{k+1}_{(c^{k},\ x^{i}, w^{i})} x^{k+1}$$
$$st: Ax^{i} = b$$
$$x^{i} \geq 0$$

**BR. Includes consideration of multiple iterations "K"**

ASU

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