OPERATIONS MANAGEMENT IN THE FRUIT INDUSTRY

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PRESENTATION OUTLINE

- Introduction
- Argentinean Fruit Industry Supply Chain Optimization
- Frutas & Jugos ARG Co.: Case Study
- Optimal Operation of a Packaging Plant
- A Novel Method to Reduce Event Variables in Continuous-time Formulation for Short-term Scheduling

ARGENTINE IN THE WORLD

Supply Chain Optimization in the Fruit Industry

Noemí Petracci, Guillermo Massini, J. Alberto Bandoni

FOCAPO 2003, Florida, USA, January 12-15, 2003

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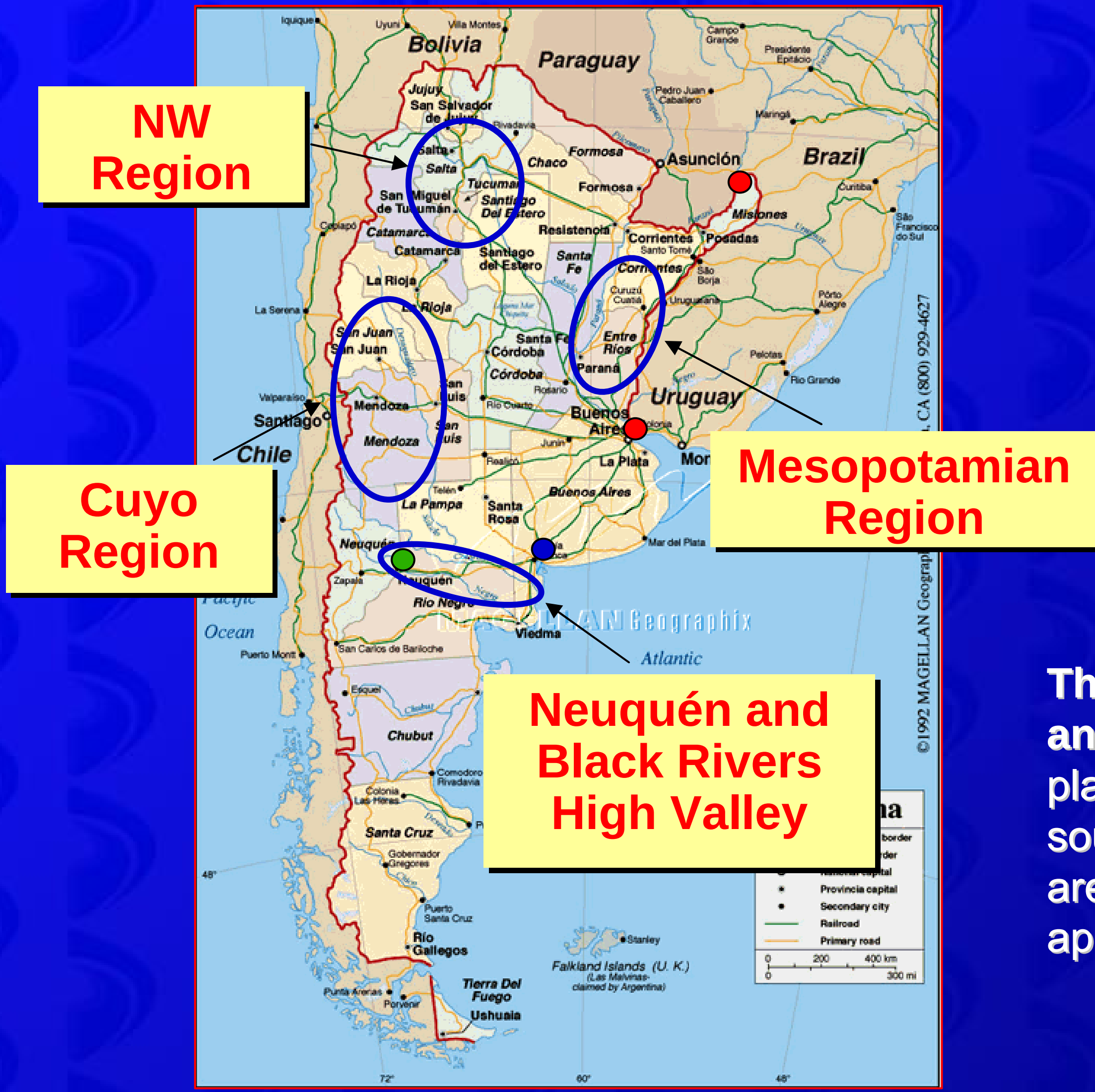
BLACK AND NEUQUEN RIVERS HIGH VALLEY FRUIT INDUSTRY



The High Valley of Río Negro and Río Neuquén, placed across two states southwest of the country, is the area of our country where the apples and pears are grown.

ARGENTINEAN FRUIT INDUSTRY IN FIGURES

Argentinean fruit industry relevant figures

- **Fruit Industry** : 700.000.000 u$s/year export value
- **Apples and Peers** : 350.000.000 u$s (50 %)
- **HV Region** : 330.000.000 u$s (95 %)

Apples:
10.086.000 tns

23 % for industrialization (concentrate juice)

Pears:
520.000 tns

50 % apples for industrialization (concentrate juice)

ARGENTINEAN FRUIT INDUSTRY DESCRIPTION

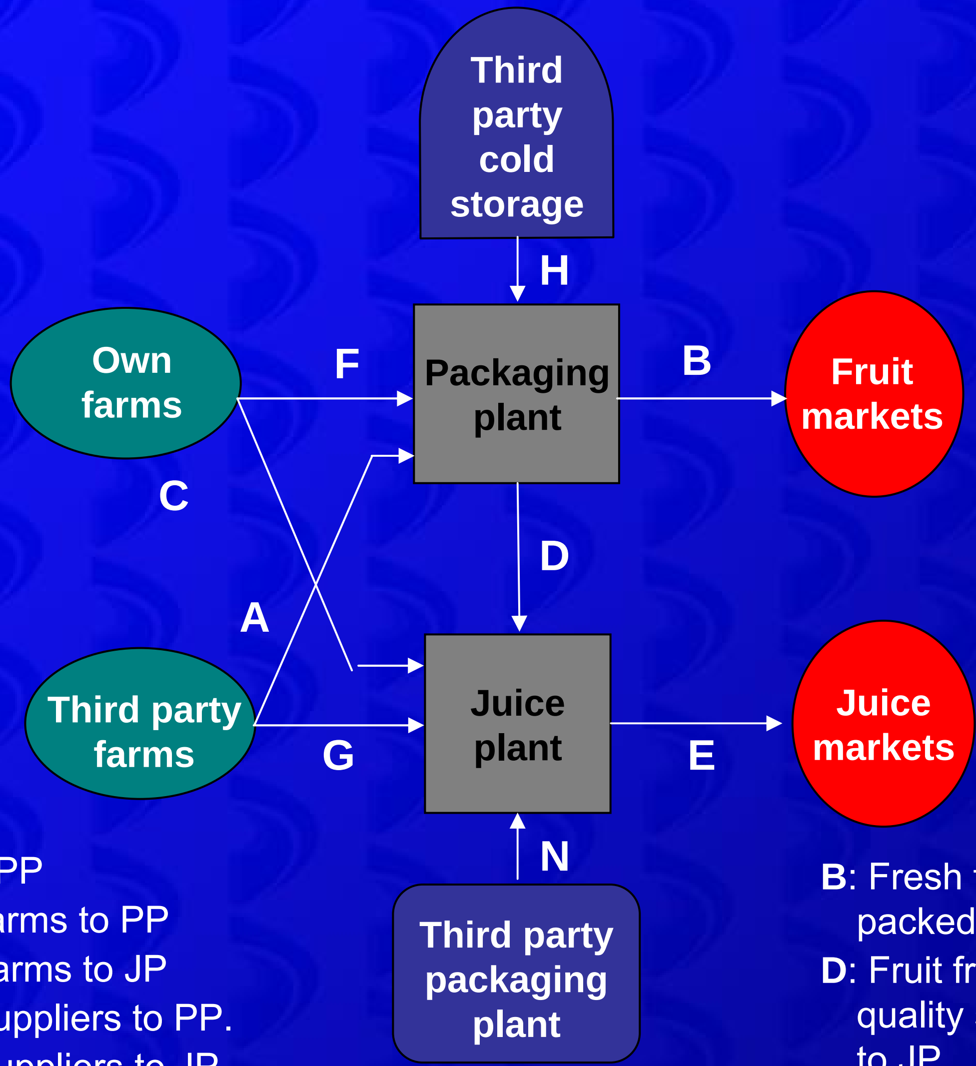
During the 90's, companies made important capital investments on new machinery for efficiency improvement.

In the last few years, due to new worldwide competitors from Asia South West, local economic problems and volatile international markets, companies are compelled to improve even more their competitiveness to keep on business.

In this context, they have a need for better decision tools to manage the whole supply chain.

There are a few large companies that operate along the entire fruit supply chain, and concentrate the largest part of the business in the HV region.

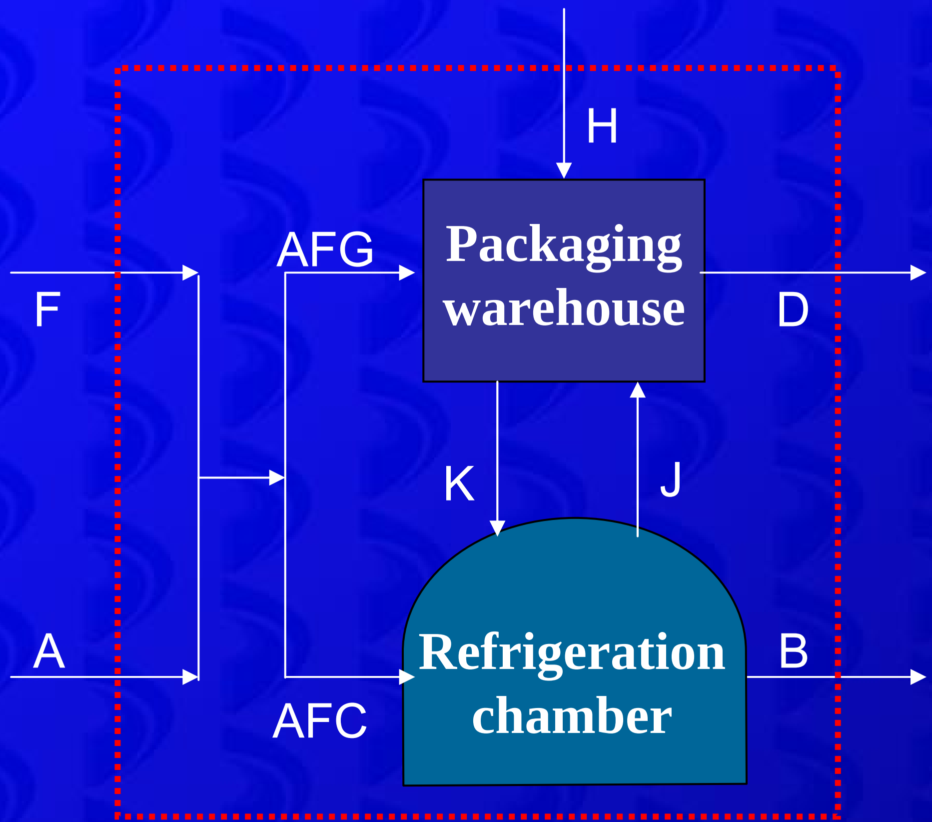
ARGENTINEAN FRUIT INDUSTRY SUPPLY CHAIN



H: Fruit from storage to PP
F: Fresh fruit from own farms to PP
C: Fresh fruit from own farms to JP
A: Fresh fruit from fruit suppliers to PP.
G: Fresh fruit from fruit suppliers to JP
N: Fruit from supplier's PP.

B: Fresh fruit prepared and packed in different ways.
D: Fruit from PP that do not fulfill quality specification transferred to JP
E: Product streams of Concentrate Juice of 72°Brix and aroma.

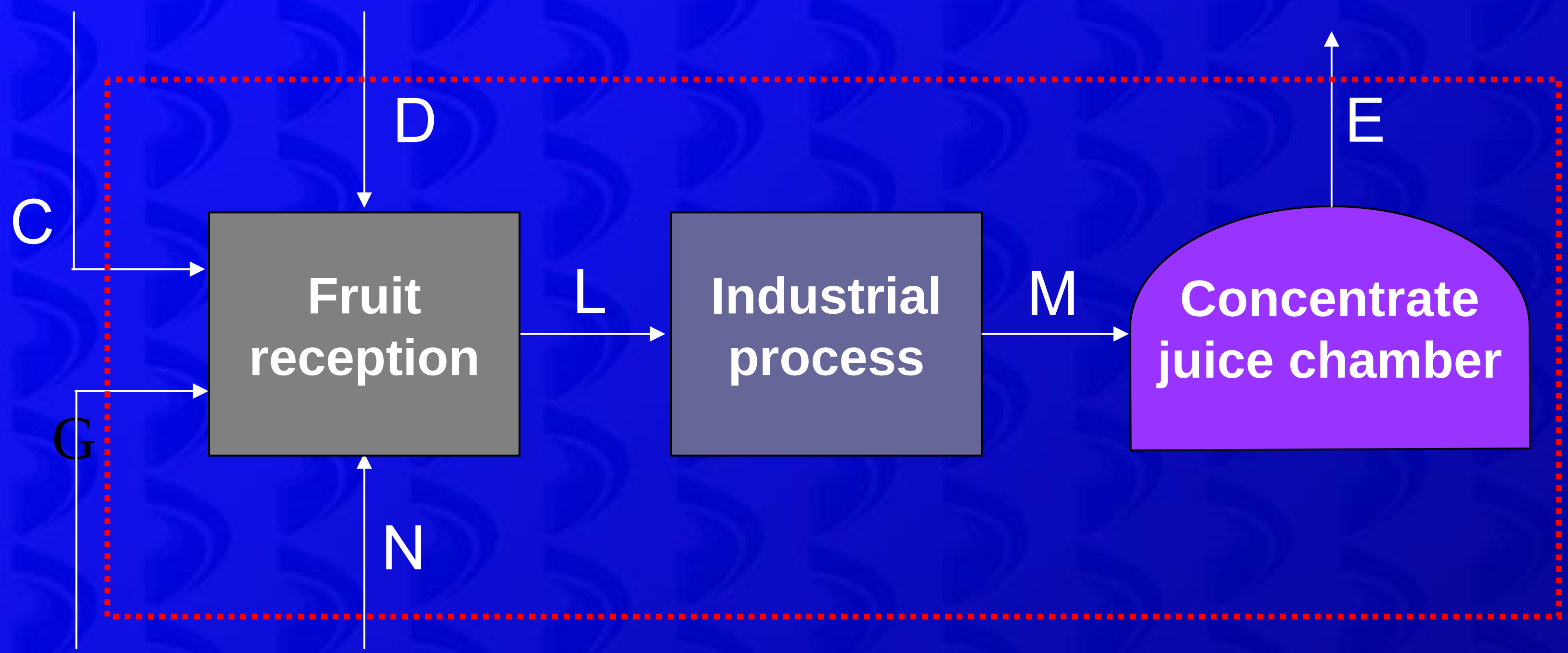
PACKAGING PLANT



H : Fruit from storage to PP
F : Fresh fruit from own farms to PP
A : Fresh fruit from fruit suppliers to PP
AFG : Fruit sent to the processing line.
AFC : Fruit directly sent to cold storage for later processing.
K : Fruit to keep in cold storage for later selling.

D : Fruit from PP that do not fulfill quality specification transferred to JP
J : Fruit from cold storage to processing line.
B : Fresh fruit prepared and packed in different ways.

CONCENTRATE JUICE PLANT



D : Fruit from PP that do not fulfill quality specification transferred to JP.
C : Fresh fruit from own farms to JP
G : Fresh fruit from fruit suppliers to JP
N : Fruit from supplier's PP.
E : Product streams of Concentrate Juice of 72°Brix and aroma.

FRUIT SUPPLY CHAIN PLANNING MODEL

Formulated as a midterm tactical planning problem, over one-year time horizon (divided in 12 monthly periods.

Time horizon coincides with the business cycle from harvest to harvest. During this cycle, many decisions have to be made along the SC.

Model parameters: cost of each variety of raw material, selling prices for each product, fruit production and fruit variety, distances, packaging and juice plant capacities, demands for each product and market, cooling storage of fresh fruit and final products, etc.

MTHEMATICAL MODEL: MILP

Model description:

Objective Function: max. of benefit along one-year operation.

Model equations : mass balance and production equations at farms, packaging plants and juice plants

Constraints : production limits at proprietary farms, bounds on fruit supply, bounds on internal processing capacities, demand satisfaction, stock limits at cold storage and storage at juice plants

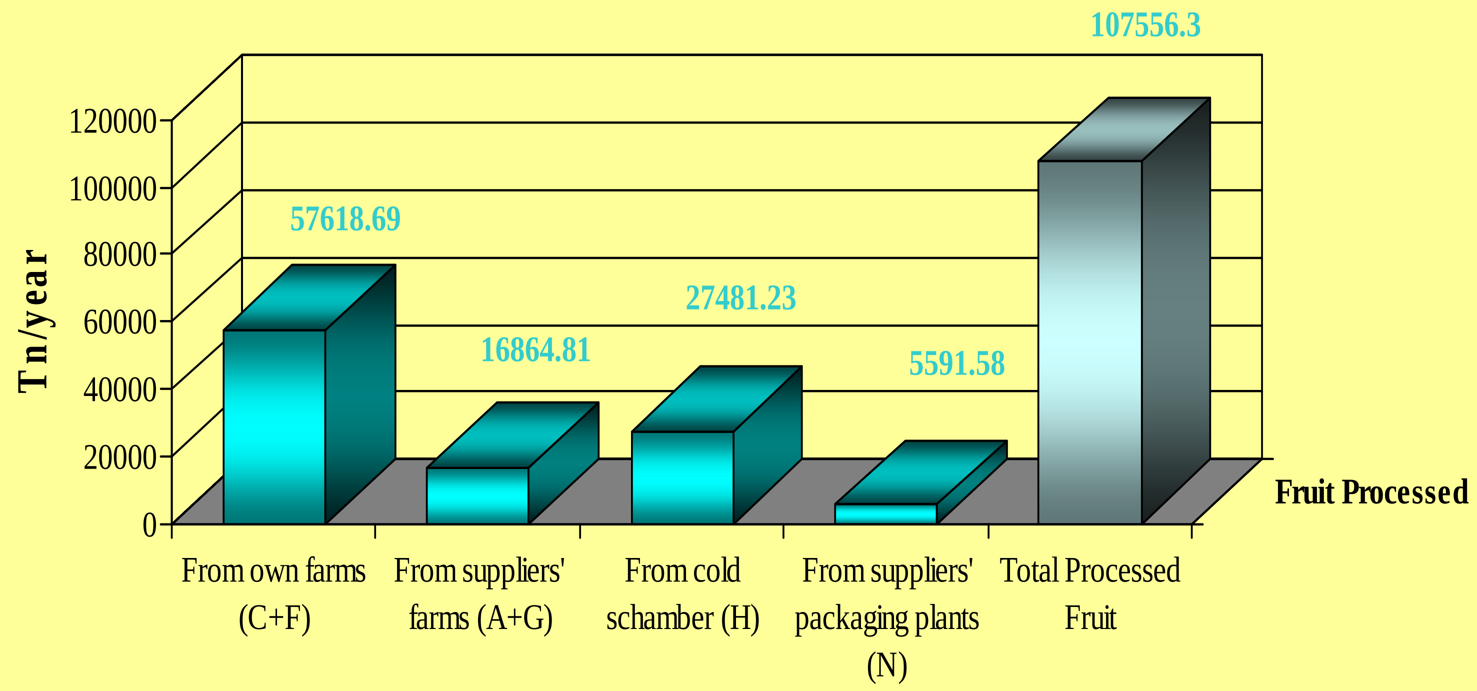
Model statistics:

14335 continuous variables and **3372** binary variables,
4421 equality and **7524** inequality constraints.

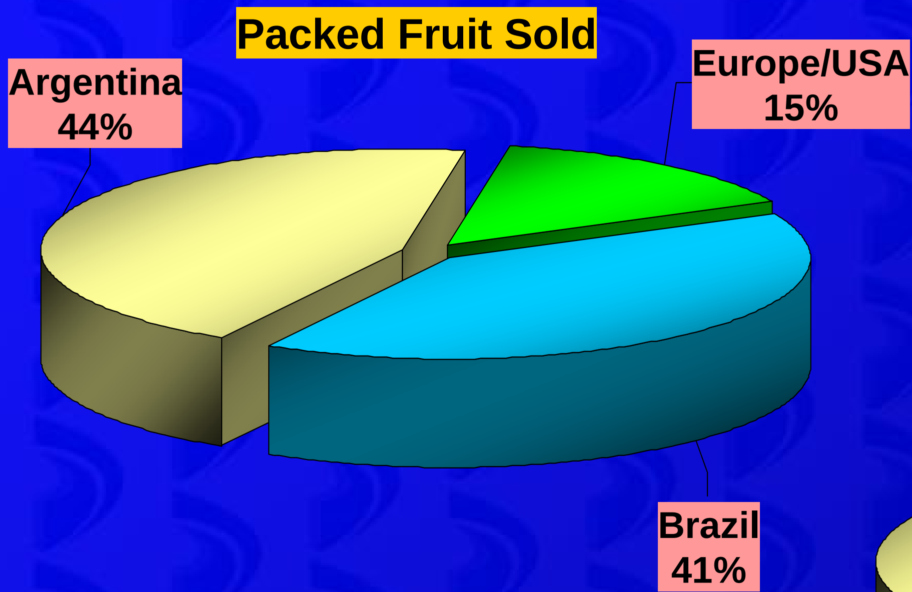
Implementation environment:

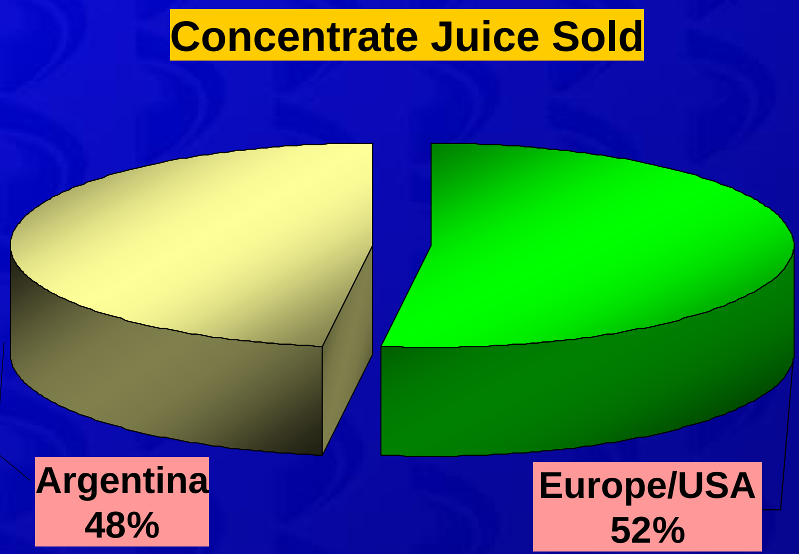
The GAMS (Brooke et al., 1998) was used in order to implement the MILP optimization model and generate their solutions.

NUMERICAL RESULTS: Total fruit processed

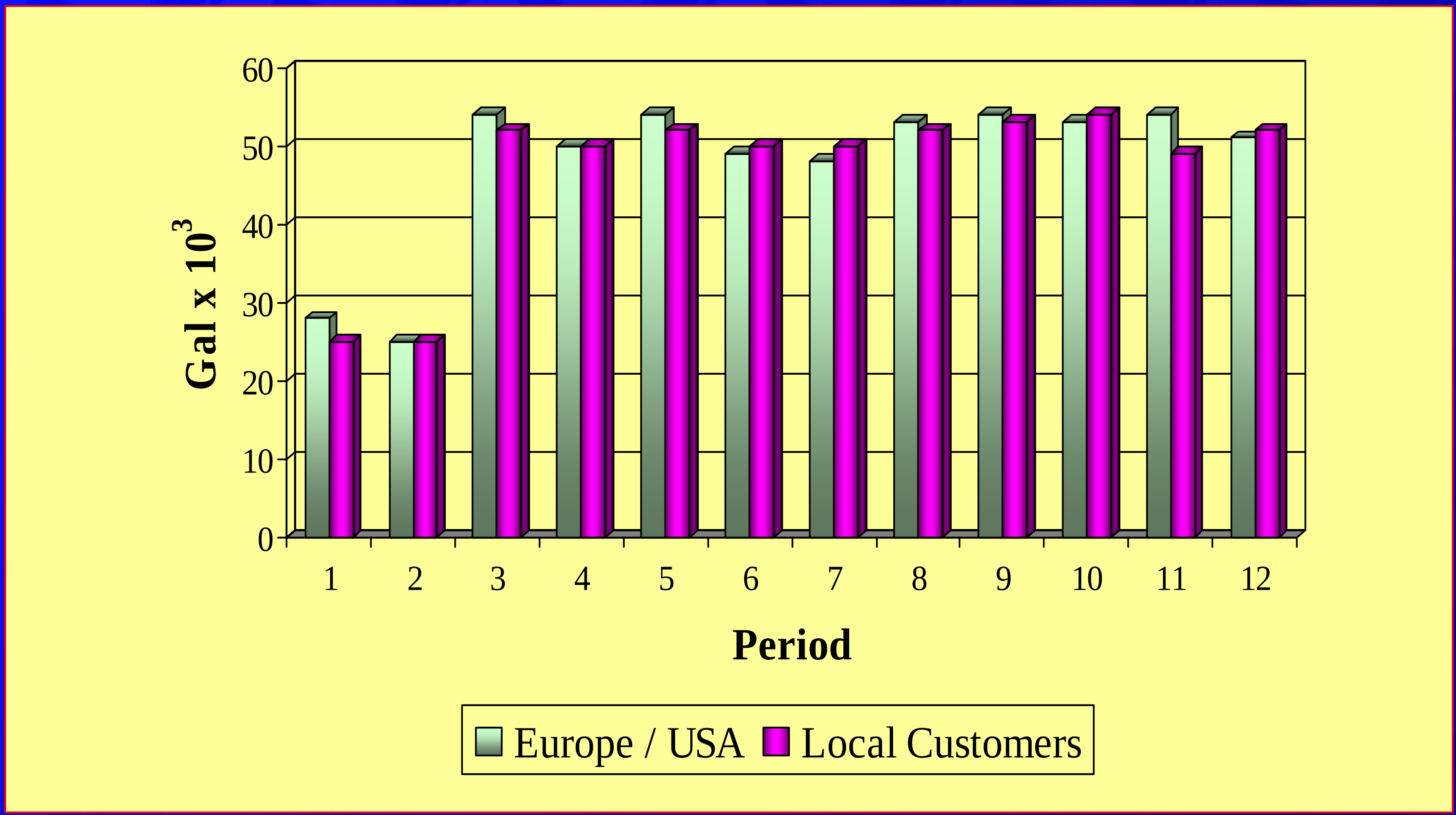


NUMERICAL RESULTS: Fruit and juice sold in different markets

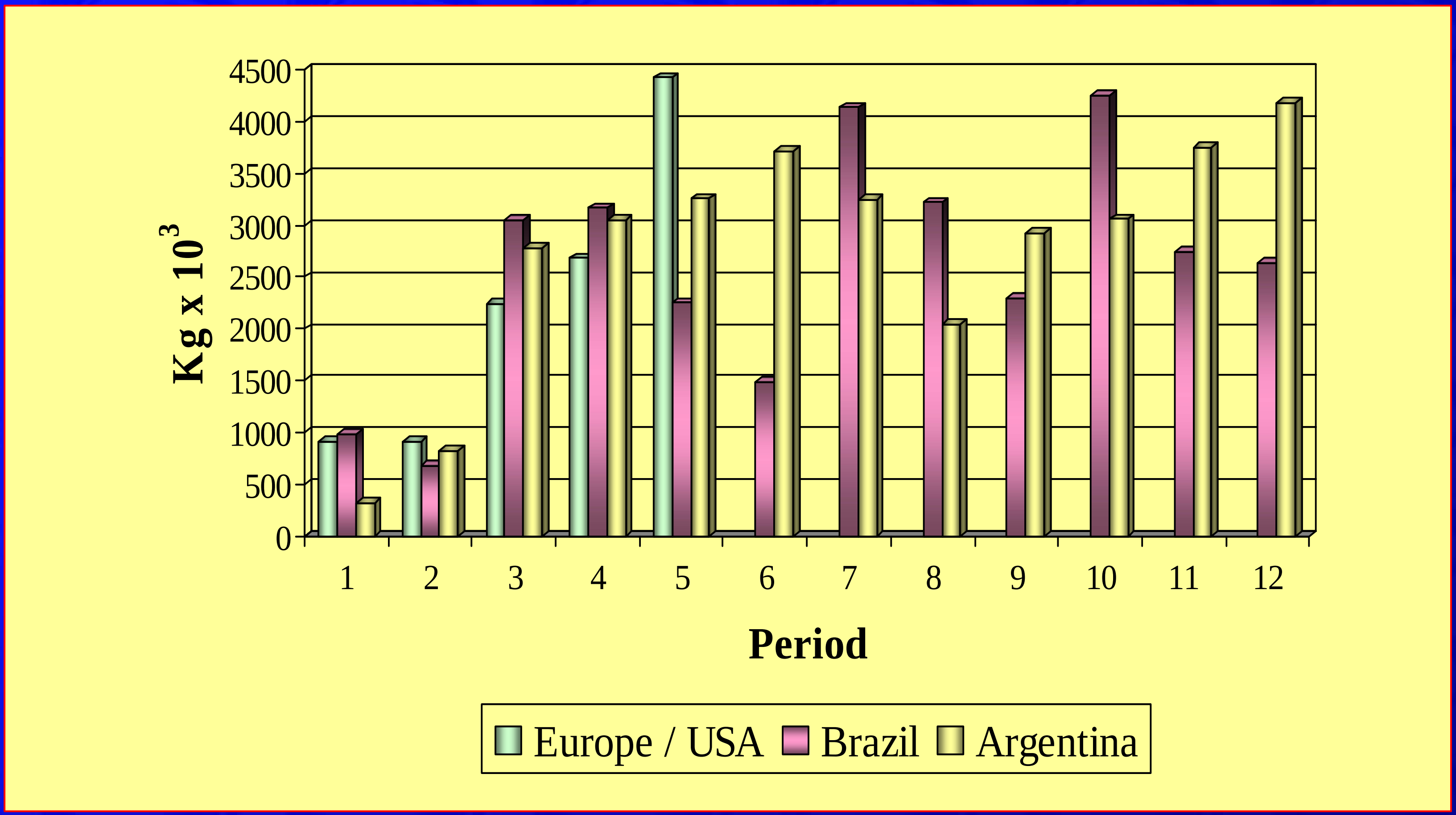




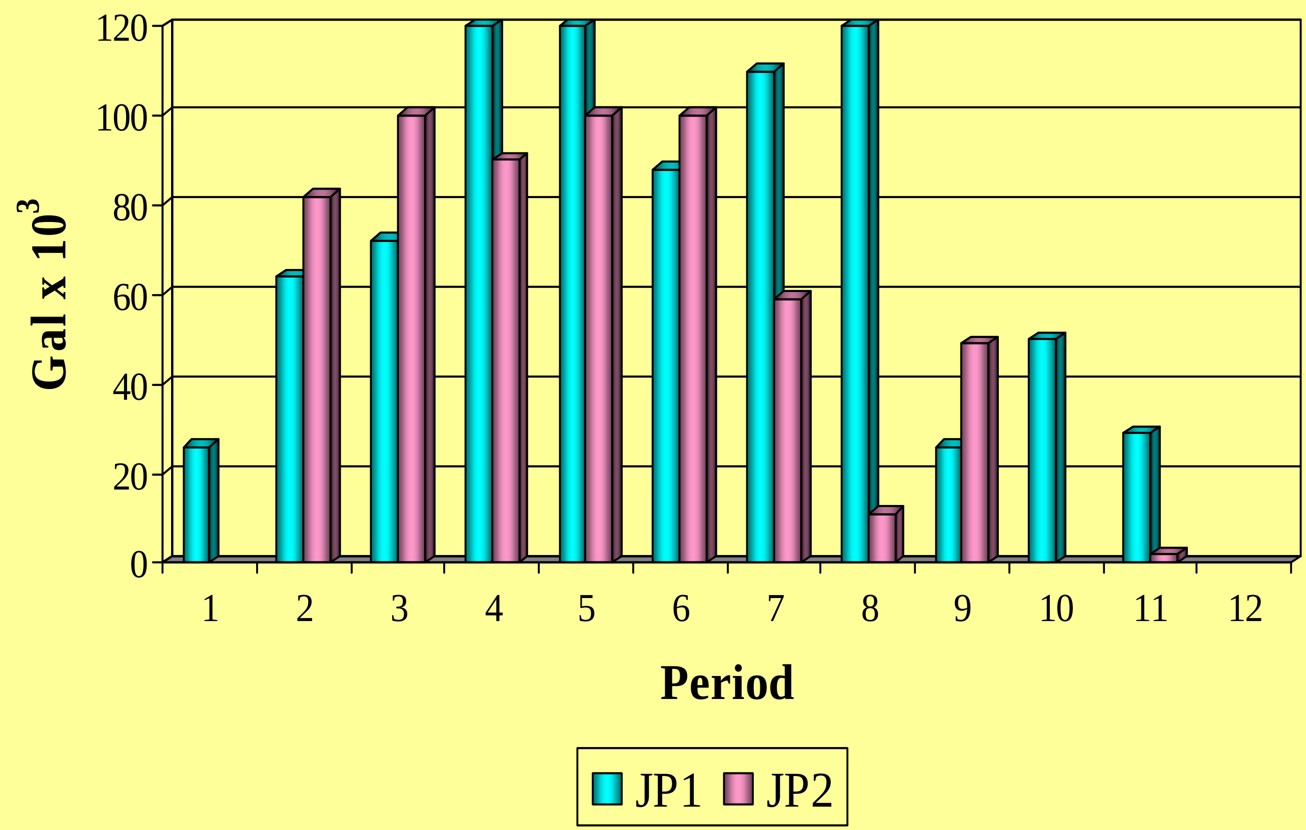
NUMERICAL RESULTS: Optimal plan for juice commercialization



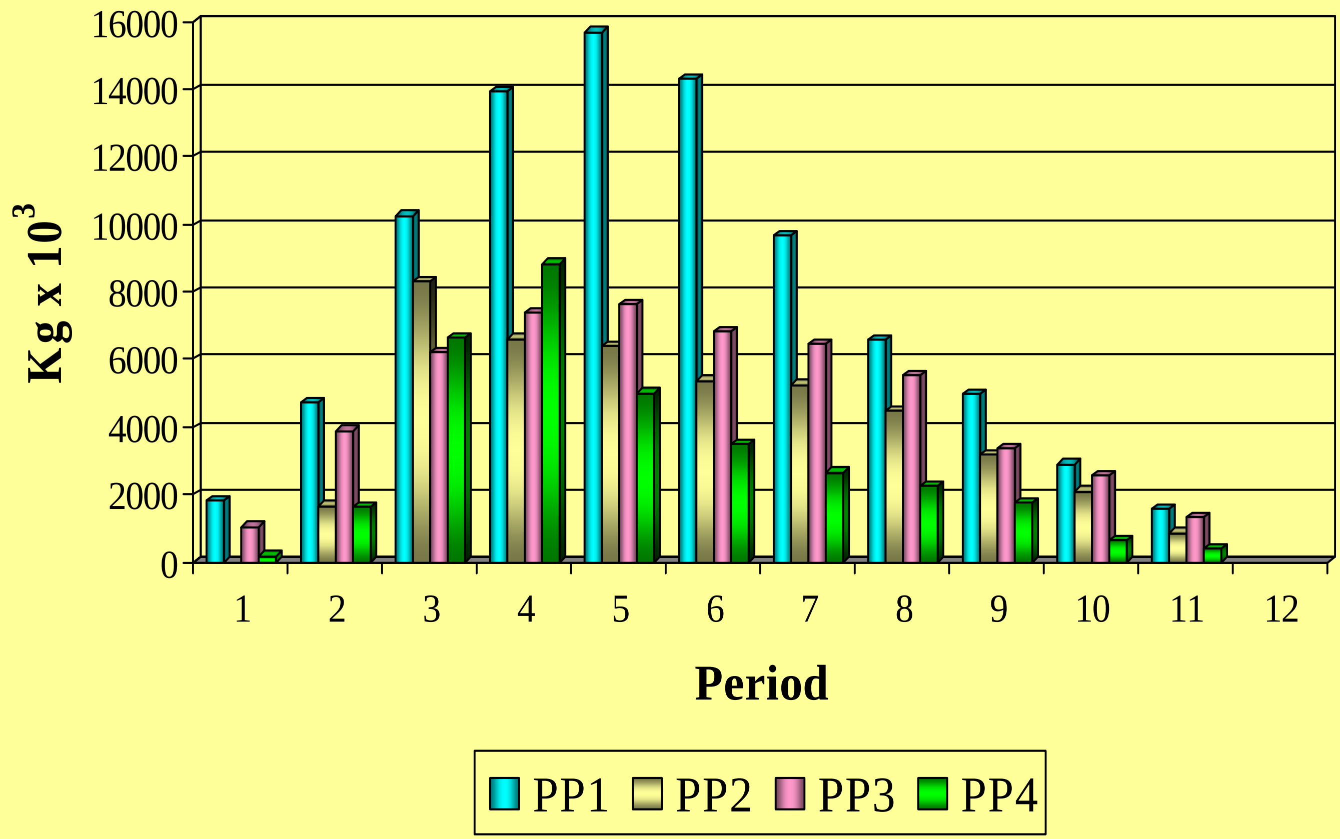
NUMERICAL RESULTS: Optimal plan for fresh fruit commercialization



NUMERICAL RESULTS: Optimal juice storage profile



NUMERICAL RESULTS: Optimal fresh fruit storage



NUMERICAL RESULTS: Optimal fresh fruit storage

- A model was developed to optimize the SC planning of a typical fruit company in the HV area of Argentina.
- It optimally decides production plans for fruit and juice to satisfy customer orders, while it optimally allocates sources or raw material, based on capacities and costs.
- The model realistically represents the current economic scenario in the country.
- Current research is under way to complete sensitivity analysis and incorporates uncertainties in demands and harvest estimations.

Case Study:

FRUTAS & JUGOS ARG co.

N. Petracci, A. Bandoni

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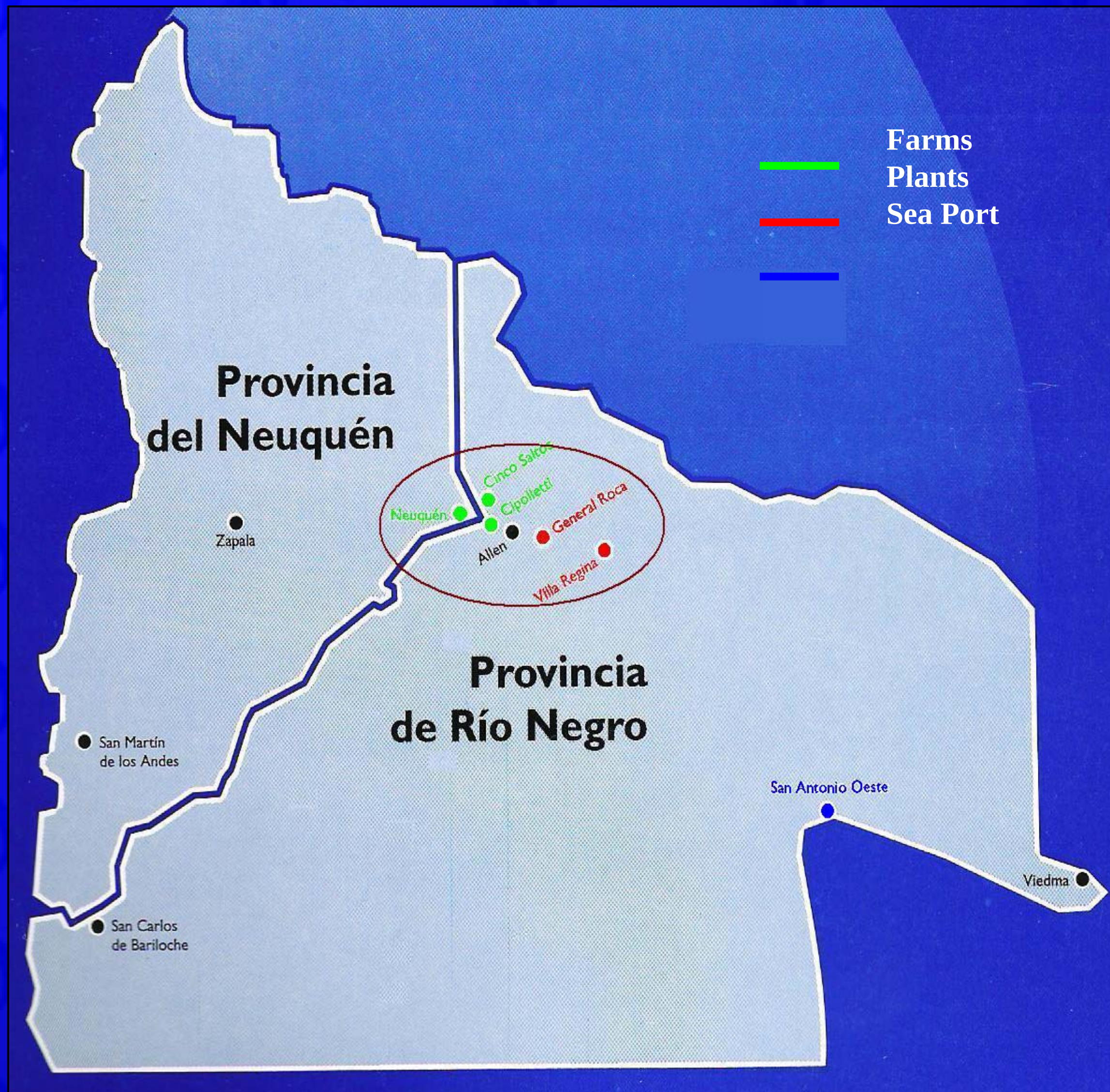
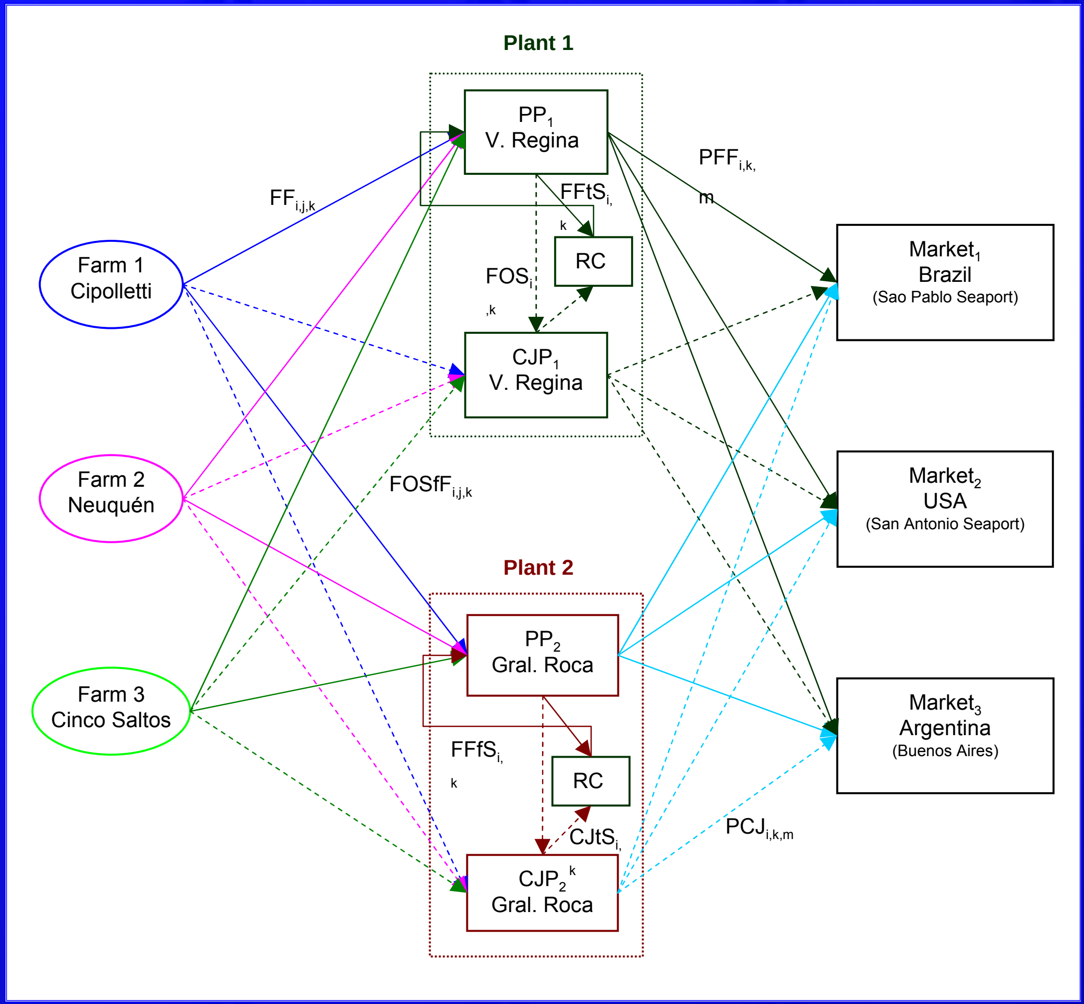
FRUTAS Y JUGOS ARG Co. : Supply Chain



FRUTAS Y JUGOS ARG Co. : Supply Chain

- *Villa Regina*
  - Packaging Plant, PP_1
  - Concentrate Juice Plant, CJP_1
- *Gral. Roca*
  - Packaging Plant, PP_2
  - Concentrate Juice Plant, CJP_2

FRUTAS Y JUGOS ARG Co. : Supply Chain Sketch



Goal of the study:

To design the supply chain that maximizes the gross benefit of the company, analyzing several possible scenarios.

FRUTAS Y JUGOS ARG Co. : Bases for the study

- ✓ Each site has a refrigeration chamber which may storage pre-classified fresh fruit and raw fruit to be processed by concentrated juice plant.
- ✓ Global mass balances of the plants (packaging and concentrate juice plants).
- ✓ The operating cost evaluation involves the complete supply chain, from farms to markets. Furthermore, terms like raw material cost, transportation cost, production cost, etc., must be considered
- ✓ The Plant's production may be split in different ways to satisfy the demands, so it must be considered at the time to evaluate sales.
- ✓ Company benefit is evaluated as a gross benefit (profit), i.e. the difference between sales and operating costs.

FRUTAS Y JUGOS ARG Co. : Possible scenarios

- To produce packed fresh fruit and/or concentrate juice after crop time to fulfill the unsatisfied demand, using as raw material fruit from refrigeration chambers.
- The Company is committed to receive all the farm production.
- Considering the farm production uncertainty. Analyze the supply chain profit when one, two or three farms loose a given maximum production percentage.
- According to the most important term of the total cost equation, suggest possible actions to improve the global profit
- Analyze the product price uncertainty.

FRUTAS Y JUGOS ARG Co. : SC Model

- A linear model has been developed to maximize the gross profit of the company along the harvest time, January to May.

- The model assign:

  - ✓ plant operation levels

  - ✓ amount and place where raw material should be obtained

  - ✓ and final product delivery

- Based on:
  - ✓ demands from three major markets
  - ✓ estimated fruit production
  - ✓
  - ✓ economic information
  - ✓ yield and availability of processing plants

FRUTAS Y JUGOS ARG Co. : SC Model

- Objective Function:
  - ✓ Maximize Gross Profit
- Model equations:
  - ✓ mass balance and production equations at farms, packaging plants and juice plants
- Constraints:
  - ✓ production limits at proprietary farms,
  - ✓ bounds on fruit supply,
  - ✓ bounds on internal processing capacities,
  - ✓ demand satisfaction.

FRUTAS Y JUGOS ARG Co. : SC Model

PP Mass Balance

PP global balance

$$FF_{i,k} = \frac{FFtS_{i,k} + PFF_{i,k} - FFfS_{i,k}}{\eta_{PP_{i,k}}}$$

$PP_{i,k}$ Initial Stock

$$FFfS_{i,k} = \eta_{ISL_{FF\,i,k}} * ISL_{FF\,i,k}$$

Fresh fruit send to stock

$$FFtS_{i,k} = \eta_{PFF_{i,k}} * MaxPFF_{i,k}$$

PP_k Yield

$$FOS_{i,k} = (1 - \eta_{PP_{i,k}}) * FF_{i,k}$$

PP_k Maximum Production

$$PFF_{i,k} = \eta_{MaxPFF_{i,k}} * MaxPFF_{i,k}$$

CJP Mass Balance

CJP global balance

$$FOSfF_{i,k} + FOS_{i,k} + FOSfS_{i,k} = \frac{1}{\eta_{CJP_{i,k}}} * PCJ_{i,k} + FOStS_{i,k}$$

$PCJ_{i,k}$ initial stock

$$FOSfS_{i,k} = \eta_{ISL_{CJ\,i,k}} * ISL_{CJ\,i,k}$$

Out of Spec. fruit to Stock

$$FOStS_{i,k} = \eta_{PCJ_{i,k}} * MaxPCJ_{i,k} / \eta_{CJP_{i,k}}$$

PCJ_k Maximum Production

$$PCJ_{i,k} = \eta_{MaxPCJ_{i,k}} * MaxPCJ_{i,k}$$

FRUTAS Y JUGOS ARG Co. : SC Model

Fruit Supplier's Distribution

Fresh fr. from farm j to PPk

$$FF_{i,j,k} = \alpha_{PP\,i,j,k} * FF_{i,k}$$

Fresh fr. out of Spec. from farm *j* to CJP_k

$$FOSfF_{i,j,k} = \alpha_{CJP\,i,j,k} * FOSfF_{i,k}$$

Normalization

$$\sum_j \alpha_{PP\,i,j,k} = 1$$

$$\sum_j \alpha_{CJP_{i,j,k}} = 1$$

Demand distribution

Packed fesh fr. delivered by plant *k* to market *m*.

$$PFF_{i,k,m} = \beta_{PP\,i,k,m} * PFF_{i,k}$$

Packed conc. juice delivered by plant *k* to market *m.*

$$PCJ_{i,k,m} = \beta_{CJP\,i,k,m} * PCJ_{i,k}$$

$$\sum_m \beta_{PP\,i,k,m} = 1$$

$$\sum_m \beta_{CJP_{i,k,m}} = 1$$

Unsatisfied demand of packed fresh fruit

$$usDPFF_{i,m} = \sum_k PFF_{i,k,m} - DPFF_{i,m}$$

Unsat. demand of conc. juice

$$usDPCJ_{i,m} = \sum_k PCJ_{i,k,m} - DPCJ_{i,m}$$

FRUTAS Y JUGOS ARG Co. : SC Model

Costs

Raw fruit cost

$$TRFC = TRFC_{FF} + TRFC_{FOS} = = \sum_{i,k}\left(cFF_i * FF_{i,k}\right) + \sum_{i,k}\left(cFOS_i * FOSfF_{i,k}\right)$$

Total production cost

$$TPC = TPC_{PP} + TPC_{CJP} = = \sum_{i,k}\left(pcPP_{i,k} * PFF_{i,k}\right) + \sum_{i,k}\left(pcCJP_{i,k} * PCJ_{i,k}\right)$$

Fruit from stock cost

$$TFfSC = TFfSC_{FF} + TFfSC_{FOS} = = \sum_{i,k}\left(cFFfS_{i,k} * FFfS_{i,k}\right) + \sum_{i,k}\left(cFOSfS_{i,k} * FOSfS_{i,k}\right)$$

Total refrigeration cost

$$TRC = TRC_{FF} + TRC_{CJ} = = \sum_{i,k}\left(rcFF * FFtS_{i,k}\right) + \sum_{i,k}\left(rcCJ * FOStS_{i,k}\right)$$

Farms to plants fruit trans. cost

$$TFPTrC = TFPTrC_{FF} + TFPTrC_{FOS} = = tcFF * \sum_{i,j,k}\left(dj_{j,k} * FF_{i,j,k}\right) + tcFF * \sum_{i,j,k}\left(dj_{j,k} * FOSfF_{i,j,k}\right)$$

Total plants to market products transport cost

$$TPMTrC = TPMTrC_{PFF} + TPMTrC_{PCJ} = = tcPFF * \sum_{i,k,m}\left(dm_{k,m} * PFF_{i,k,m}\right) + tcPCJ * \sum_{i,k,m}\left(dm_{k,m} * PCJ_{i,k,m}\right)$$

FRUTAS Y JUGOS ARG Co. : SC Model

Costs

Unsatisfied Demand PFF Cost

$$usDPFFC = \sum_{i,m} \left(usDPFF_{i,m} * pPFF_{i,m} * prf_{PFF} \right)$$

Unsatisfied Demand of Packed Conc. Juice

$$usDPCJC = \sum_{i,m} \left(usDPCJ_{i,m} * pPFF_{i,m} * prf_{PCJ} \right)$$

Total plant cost

$$Total\ Cost = TRFC + TFfSC + TFPTrC + TPC + TRC + TPMTrC + usDPFFC + usDPCJC$$

Sales

$$Sales = Sales_{PP} + Sales_{CJP} = \sum_{i,k,m} \left(pPFF_{i,m} * PFF_{i,k,m} \right) + \sum_{i,k,m} \left(pPCJ_{i,m} * PCJ_{i,k,m} \right)$$

Gross Profit

$$\text{Gross Profit} = \text{Sales} - \text{TotalCost}$$

Inequality constraints

$$PFF_{i,k} \le MaxPFF_{i,k}$$

$$PCJ_{i,k} \le MaxPCJ_{i,k}$$

$$FFfS_{i,k} \le ISL_{FF\,i,k}$$

$$FFtS_{i,k} \le MaxPFF_{i,k}$$

$$FOSfS_{i,k} \le ISL_{CJ\,i,k}$$

$$FOStS_{i,k} \le MaxPCJ_{i,k} / \eta_{CJP_{i,k}}$$

$$\sum_{k} PFF_{i,k,m} \le DPFF_{i,m}$$

$$\sum_{k} PCJ_{i,k,m} \le DPCJ_{i,m}$$

$$\sum_{k} \left(FF_{i,j,k} + FOSfF_{i,j,k} \right) \le \eta_{F_{i,j}} * MaxFP_{i,j}$$

Operations Management of a Packaging Plant in the Fruit Industry

A. Blanco , G. Masini, N. Petracci, A. Bandoni

Journal of Food Engineering 70, 297-307 (2005)

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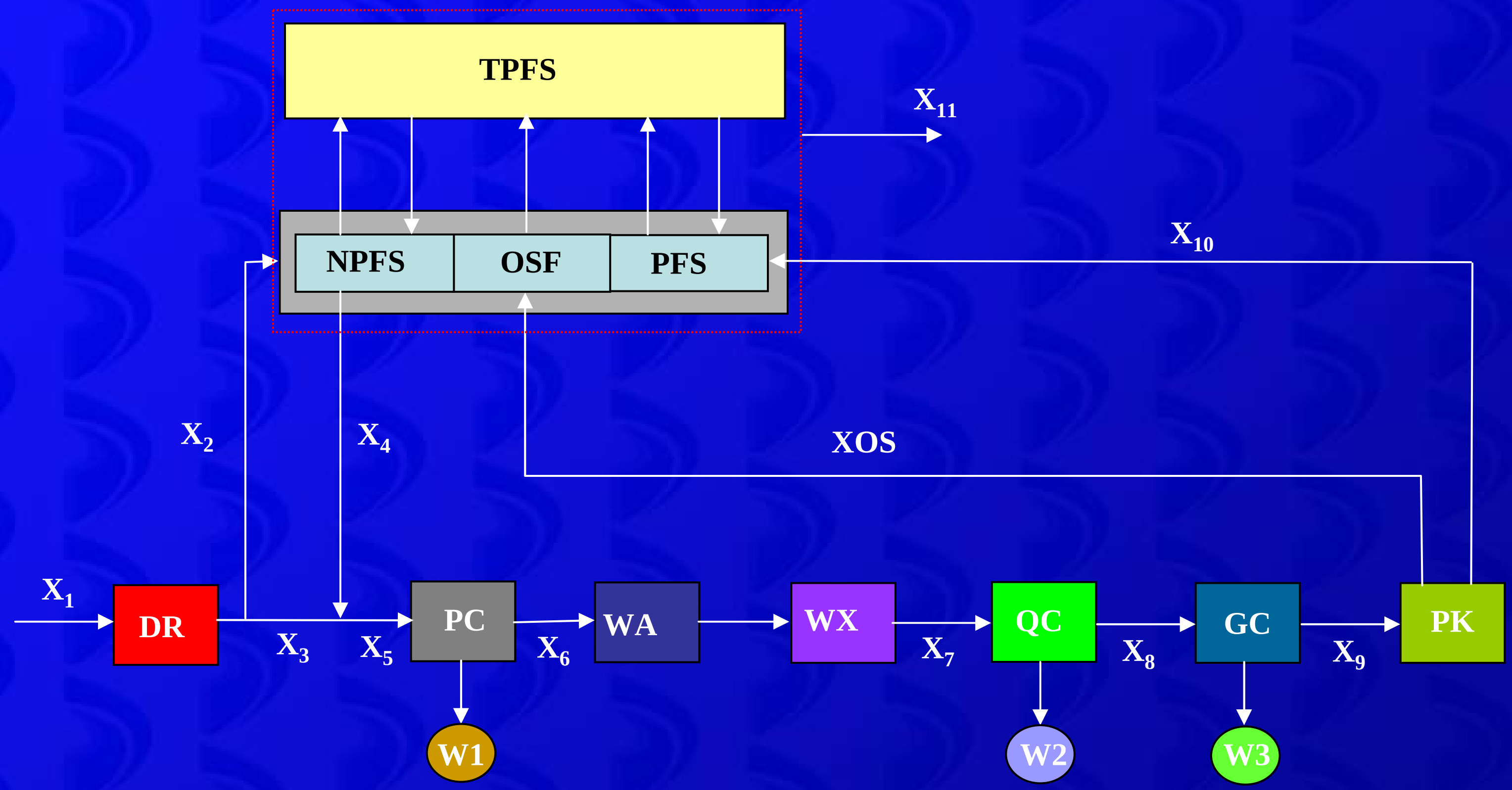
PACKAGING PLANT



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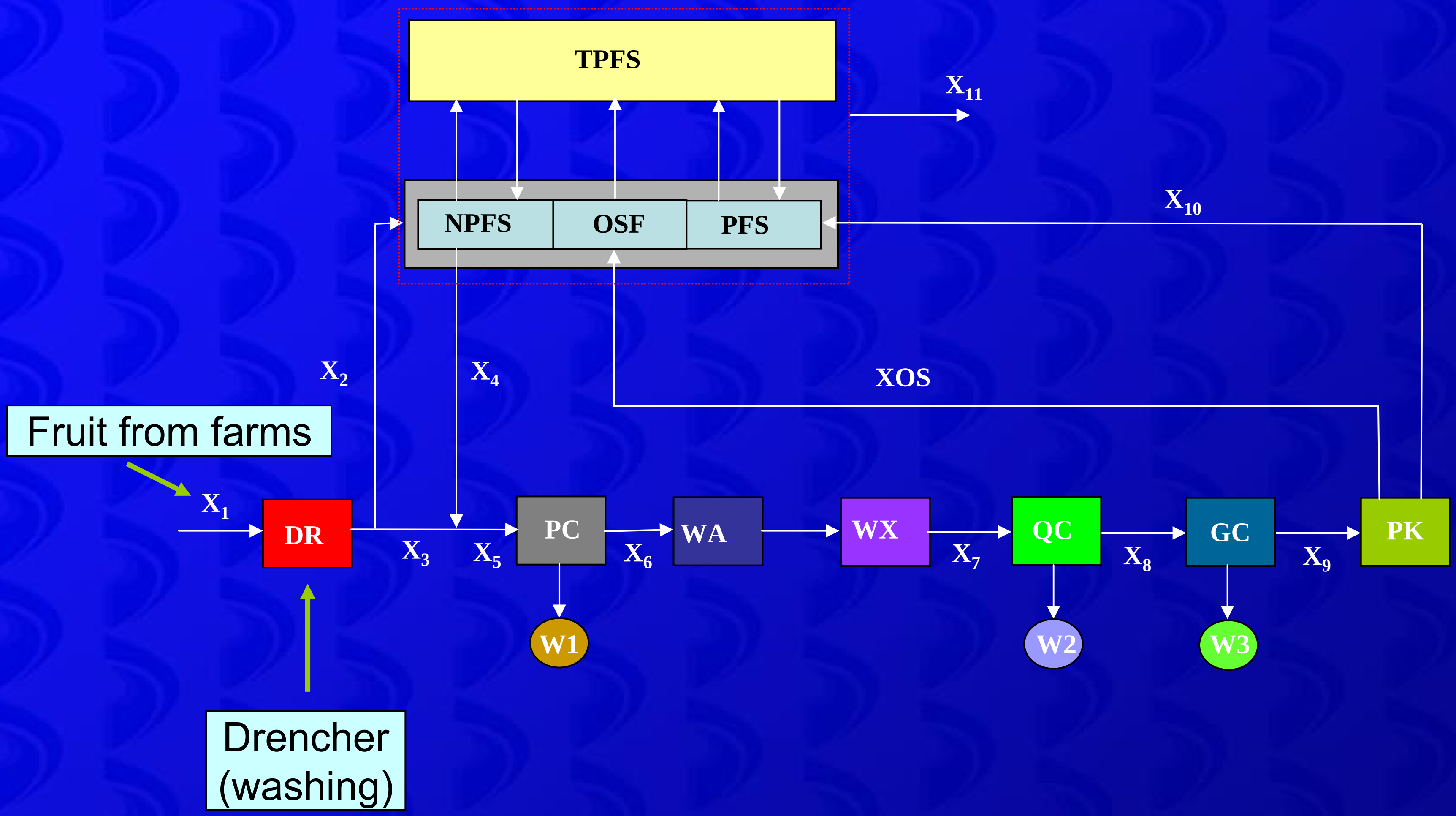

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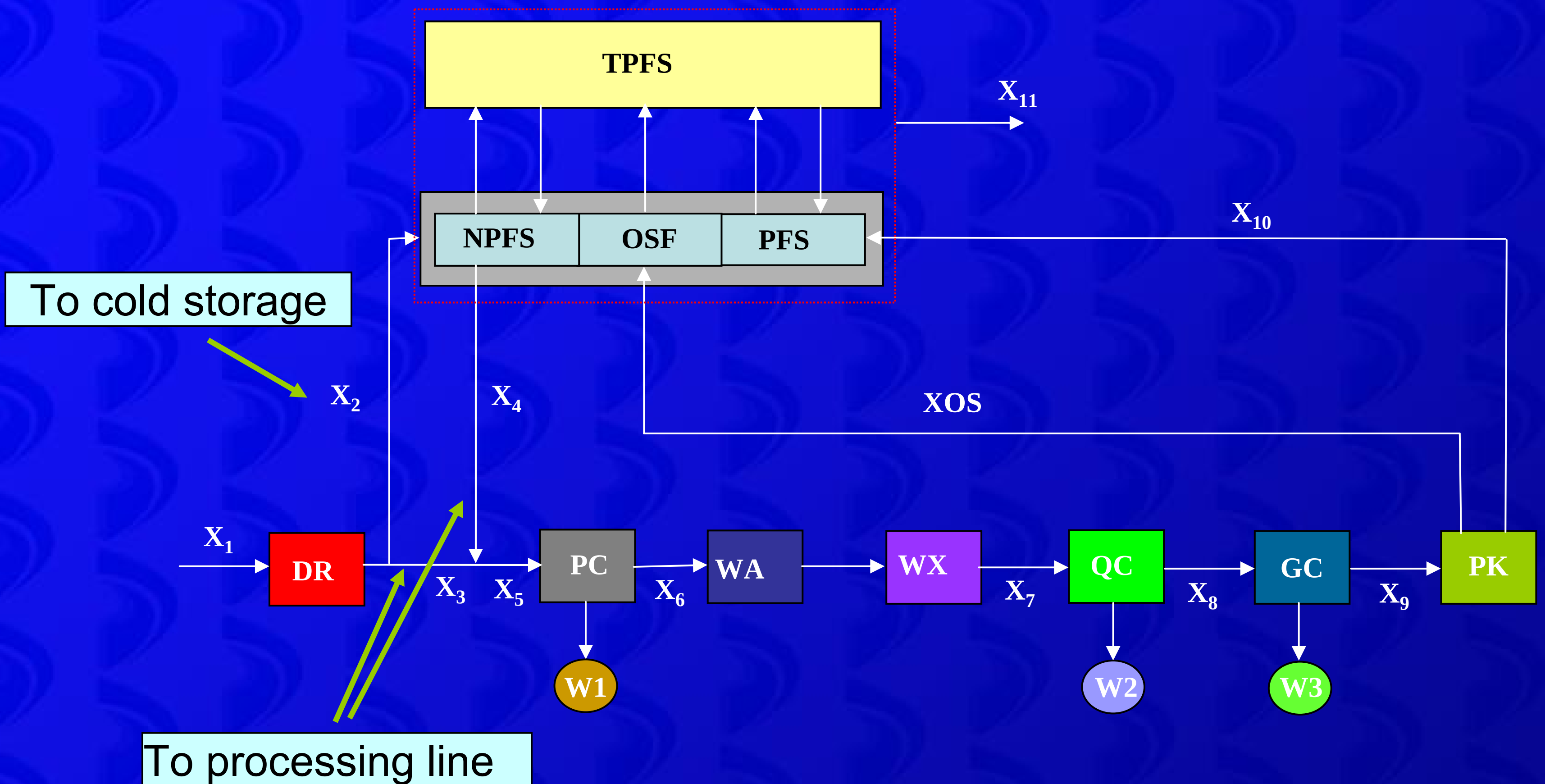

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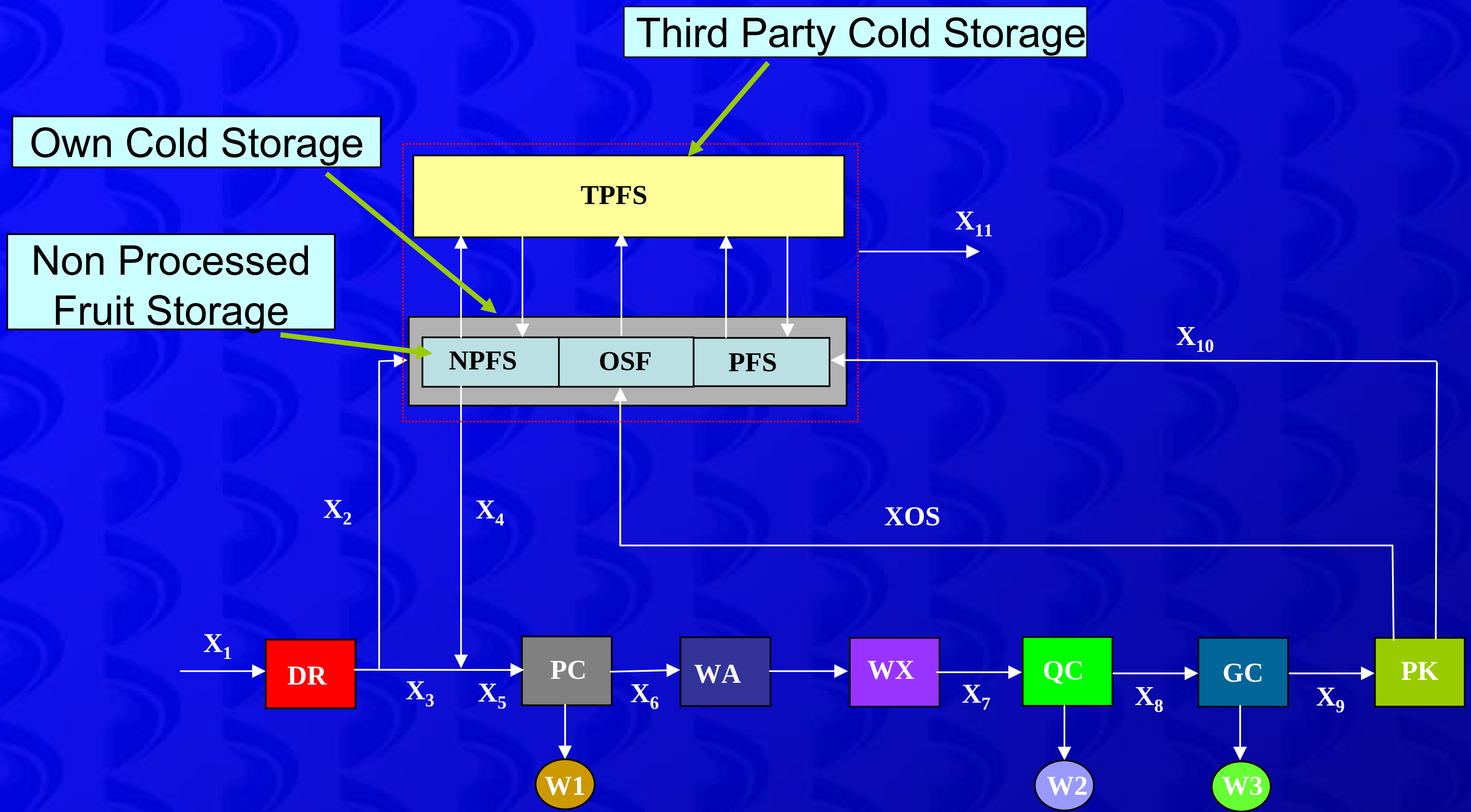

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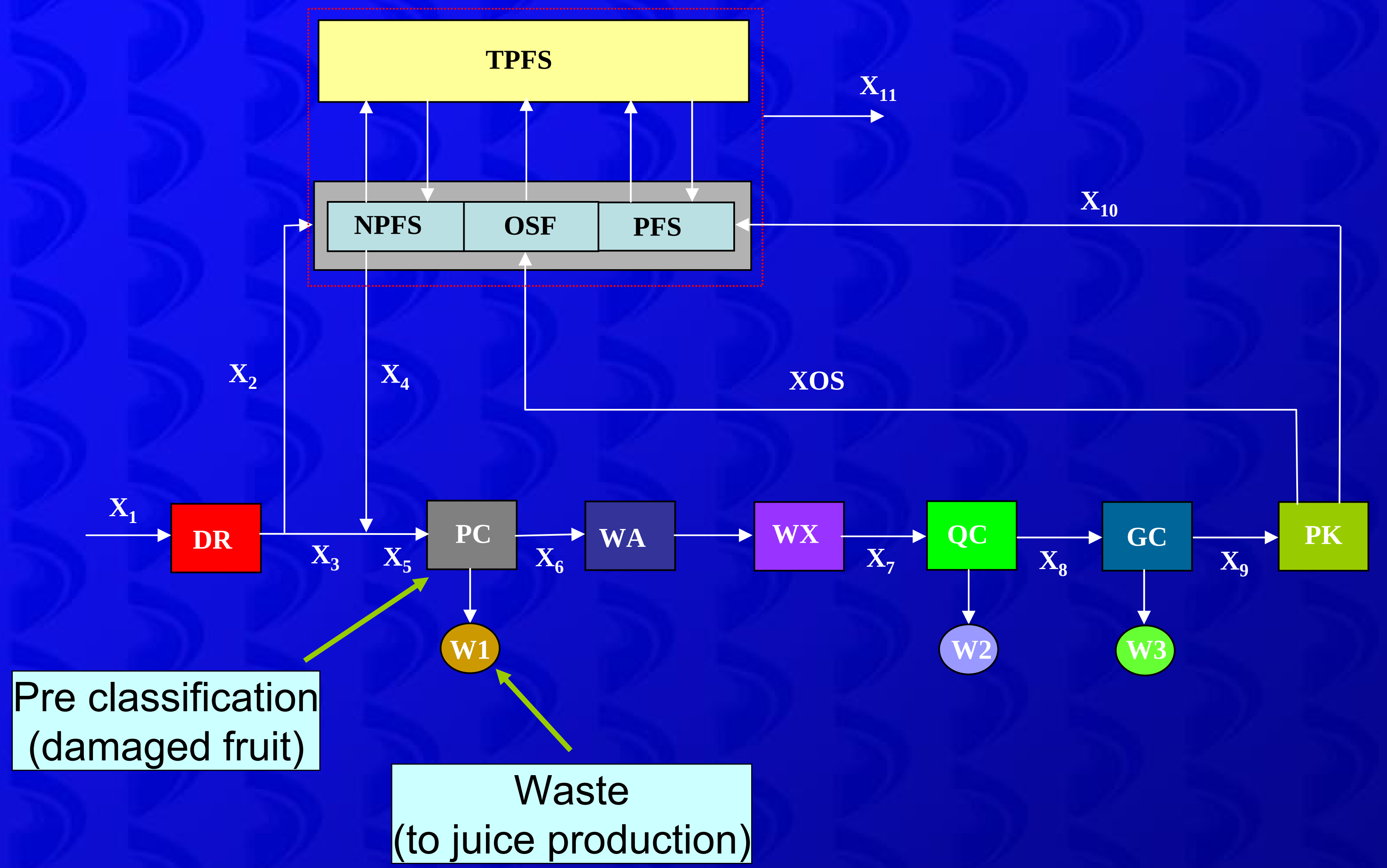

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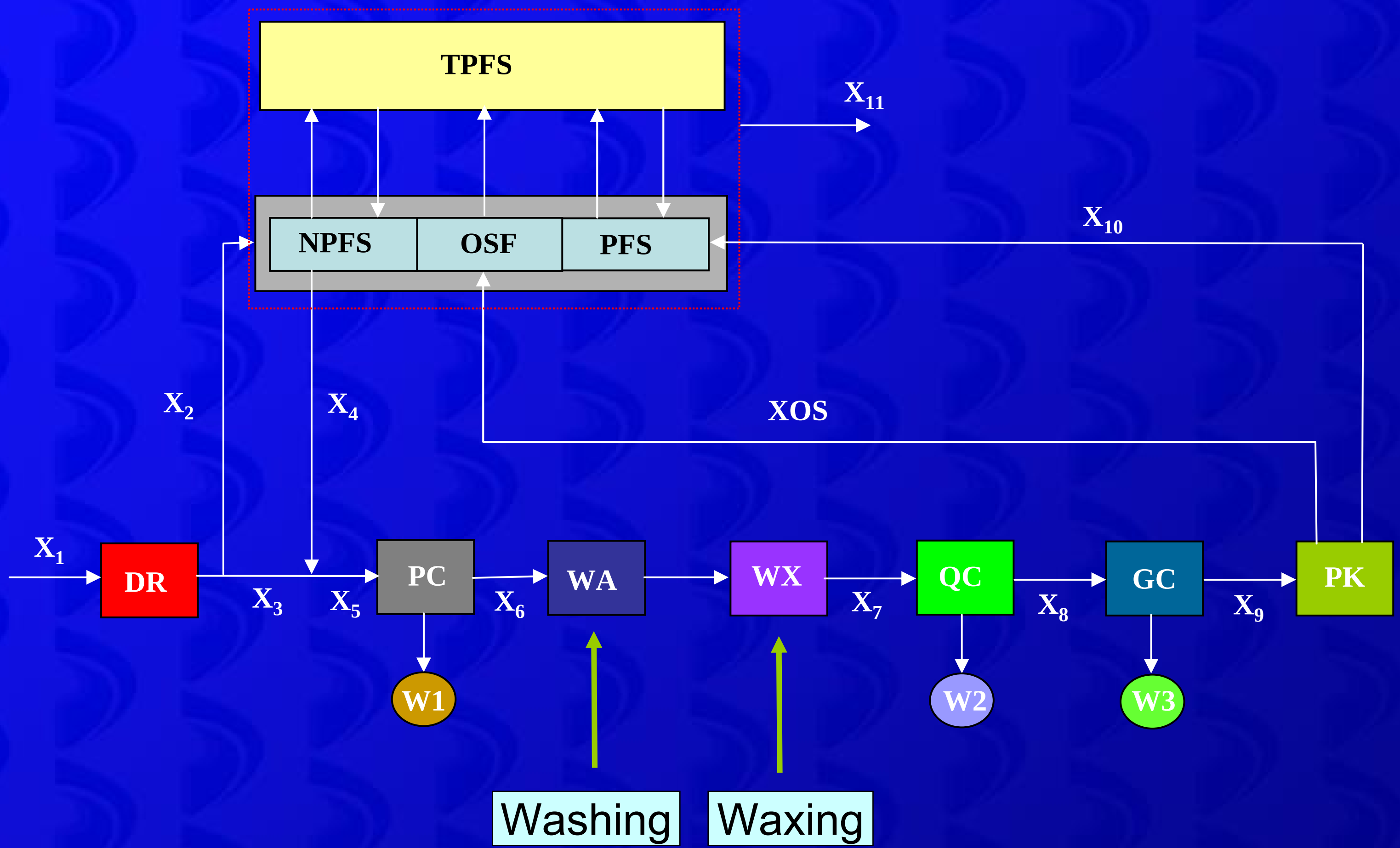

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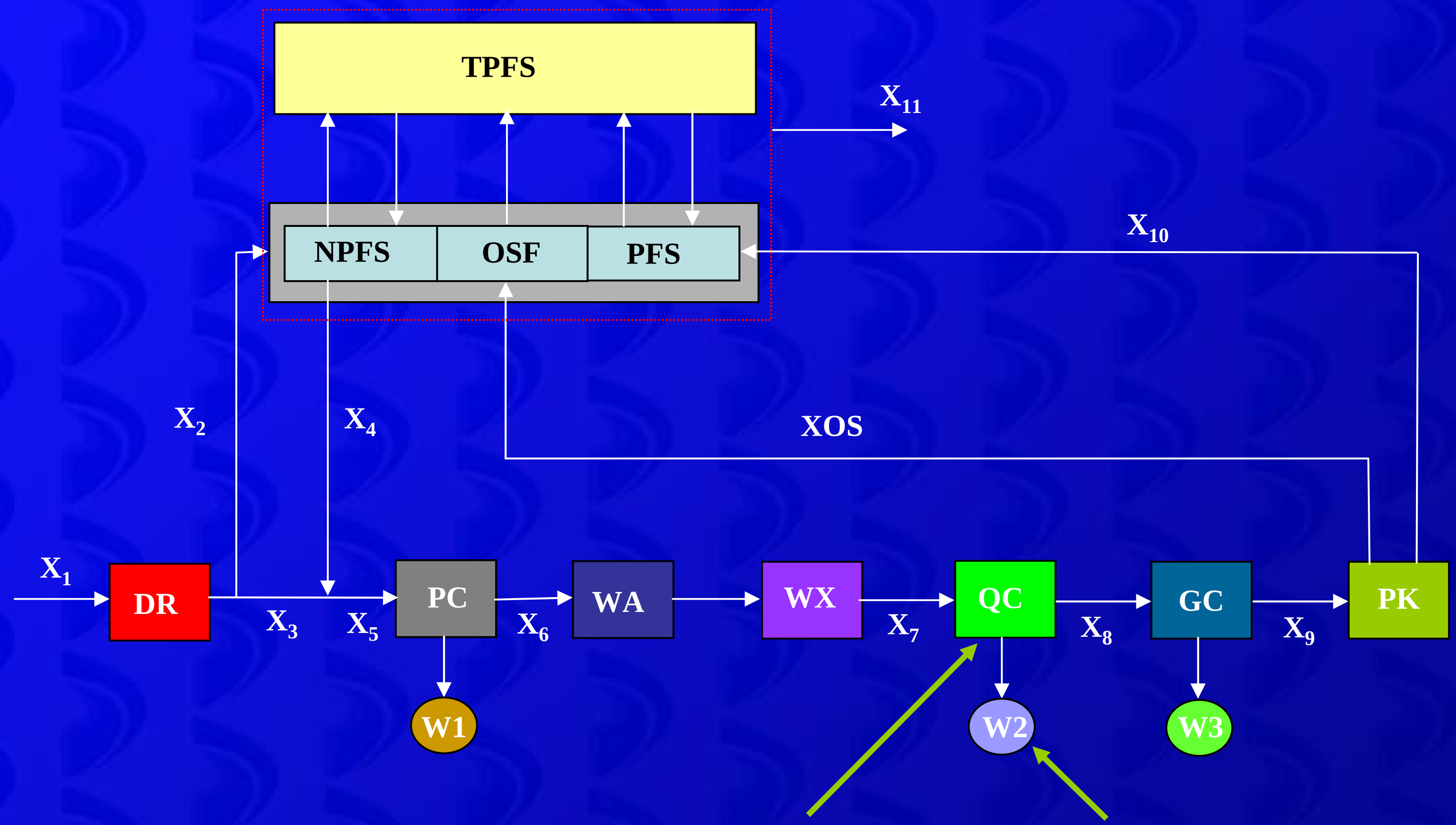
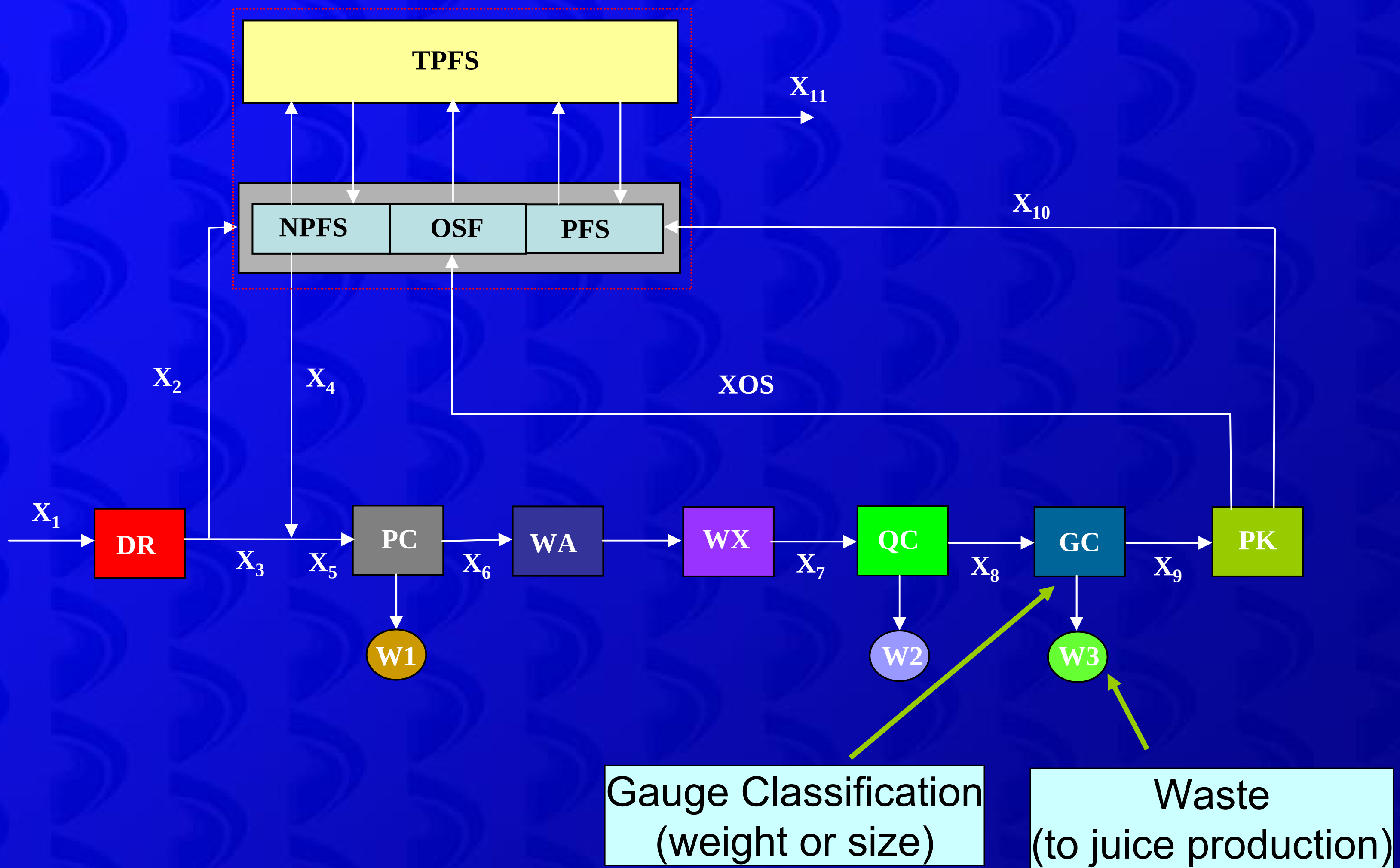


Quality Classification (1st, 2nd, 3rd quality)

Waste (to juice production)

PACKAGING PLANT



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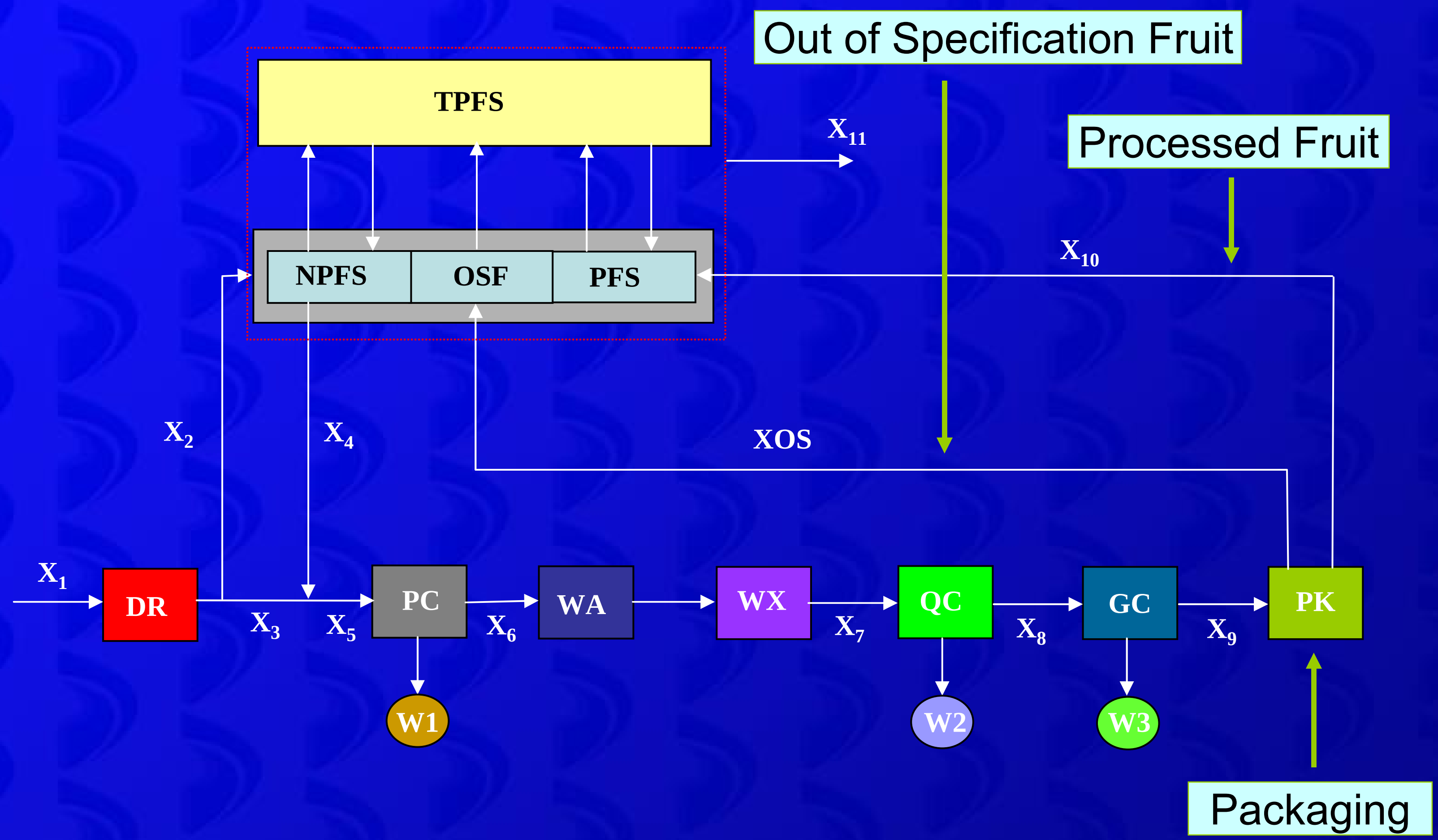

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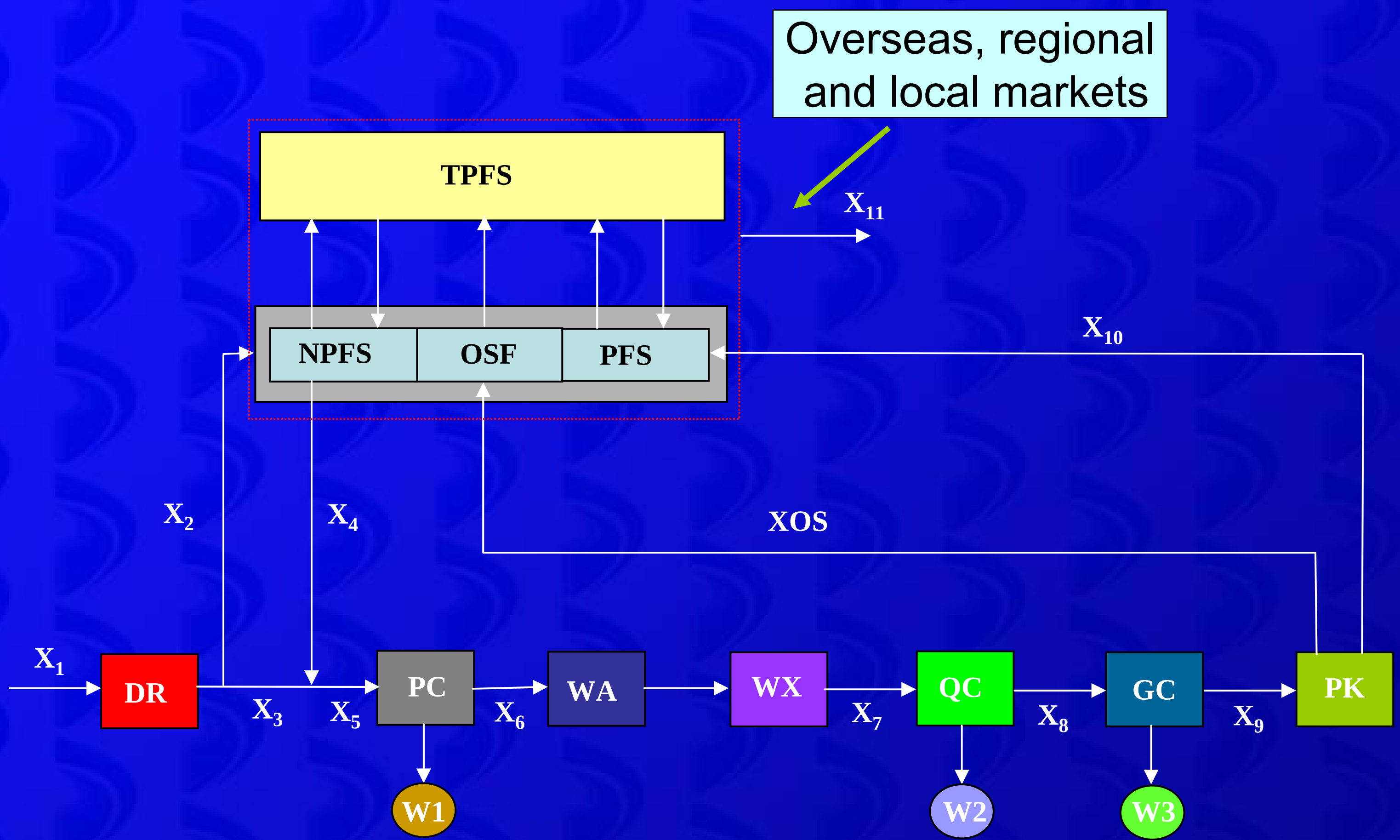


- Regular income of fruit (apples and pears) during the whole harvest period (day 12 to day 157)
- Based on historical records it is possible to forecast an income profile in terms of amount, quality, waste and gauge (average value and standard deviation)

FRUIT INCOME

v	Variety	SD	HP	A(kg/day)	SDev(kg/day)	CR($/kg)
v1	Williams pear	12	12 to 36	45560	2000	0.07
v2	Beurre D´Anjou pear	45	45 to 69	27400	1500	0.1
v3	Beurre Bosc pear	72	72 to 96	35960	2200	0.07
v4	Red apple 1	78	78 to 102	24240	780	0.08
v5	Packams Triumph pear	91	91 to 115	33200	2100	0.09
v6	Red Delicious apple	95	95 to 119	38600	3000	0.08
v7	Red apple 2	123	123 to 147	39040	2800	0.07
v8	Granny Smith apple	133	133 to 157	48360	3500	0.08

FRUIT QUALITY

v	A(%) q_1	A(%) q_2	A(%) q_3	SDev(%) q_1	SDev(%) q_2	SDev(%) Q_3
v1	0.58	0.27	0.15	0.063	0.045	0.025
v2	0.58	0.26	0.16	0.094	0.045	0.02
v3	0.5	0.35	0.16	0.077	0.045	0.019
v4	0.58	0.27	0.15	0.07	0.03	0.029
v5	0.58	0.34	0.08	0.106	0.057	0.013
v6	0.4	0.27	0.33	0.043	0.049	0.038
v7	0.58	0.29	0.13	0.092	0.041	0.023
v8	0.45	0.32	0.23	0.091	0.055	0.023

WASTE

		A(%)			SDev(%)	
v	**DPC**	**DQC**	**DGC**	**DPC**	**DQC**	**DGC**
v1	0.11	0.05	0.06	0.014	0.003	0.007
v2	0.14	0.03	0.06	0.011	0.004	0.006
v3	0.12	0.03	0.07	0.012	0.005	0.005
v4	0.13	0.04	0.06	0.014	0.004	0.007
v5	0.1	0.05	0.07	0.011	0.003	0.006
v6	0.11	0.04	0.07	0.011	0.005	0.006
v7	0.13	0.04	0.05	0.013	0.004	0.007
v8	0.12	0.03	0.07	0.013	0.003	0.006

GAUGE

	A(%)					SDev(%)				
v	g_1	g_2	g_3	g_4	g_5	g_1	g_2	g_3	g_4	g_5
v1	0.12	0.11	0.23	0.14	0.4	0.004	0.004	0.008	0.005	0.015
v2	0.11	0.16	0.19	0.24	0.3	0.005	0.008	0.009	0.009	0.012
v3	0.2	0.12	0.18	0.21	0.29	0.009	0.005	0.008	0.009	0.009
v4	0.18	0.12	0.22	0.22	0.26	0.008	0.005	0.008	0.009	0.012
v5	0.3	0.22	0.2	0.21	0.09	0.009	0.007	0.008	0.007	0.003
v6	0.21	0.26	0.12	0.26	0.16	0.01	0.012	0.005	0.011	0.007
v7	0.1	0.23	0.16	0.13	0.38	0.004	0.008	0.005	0.005	0.012
v8	0.27	0.16	0.16	0.14	0.28	0.012	0.007	0.005	0.005	0.011

- One permanent labor staff the whole year (eight hour working shift)
- Temporary labor staff may be required to cover two or three additional eight hour working shifts during certain periods in order to satisfy commercial commitments

- Different markets demand different products
- Products are classified according to:
  - Fruit variety (v1, …, v8)
  - Waxing (waxed or not waxed)
  - Fruit quality (1st, 2nd, 3rd))
  - Gauge (g1, …, g5)
  - Crate (only one in the present work)

PACKAGING PRODUCTS

	v_1	v_2	v_3	v_4	v_5	v_6	v_7	v_8	w_1	w_2	q_1	q_2	q_3	g_1	g_2	g_3	g_4	g_5	p_1	PP ($/kg)
P1	1									1	1			1					1	0.33
P2			1							1	1				1				1	0.39
P3		1							1				1			1			1	0.26
P4				1						1		1					1		1	0.28
P5					1					1			1					1	1	0.24
P6								1	1		1							1	1	0.34
P7						1			1			1						1	1	0.27
P8							1		1			1				1			1	0.29
P9	1									1	1				1				1	0.32
P10			1							1			1	1					1	0.36
P11						1			1				1	1					1	0.28
P12								1		1			1			1			1	0.31
P13		1							1			1				1			1	0.28
P14				1						1	1						1		1	0.29
P15							1			1	1					1			1	0.29
P16					1				1			1		1					1	0.29
P17		1								1		1		1					1	0.29
P18						1				1			1		1				1	0.26
P19	1								1		1						1		1	0.31
P20				1						1	1				1				1	0.31
Set				VP					WP			QP				GP			SP	

PRODUCTS AND DELIVERY DATES FOR DIFFERENT MARKETS

Overseas	P1, P2, P6, P9, P14, P15, P19, P20
Regional	P4, P7, P8, P13, P16, P17
Local	P3, P5, P10, P11, P12, P18

Overseas	Regional	Local
25	30	31
50	60	54
80	90	78
110	120	102
140	150	126
170	180	150
190	210	174
215	240	198
	270	222
	300	246
	330	270
	360	294
		318
		342
		360

PLANNING MODEL

- Deterministic income fruit scenario generation by means of Monte Carlo Simulation for each parameter:
  - amount of fruit per variety
  - quality of fruit per variety
  - gauge of fruit per variety
  - waste of fruit per variety

- Mass Balances
  - Packaging plant
    - Drencher
    - Preclassification
    - Waxing module
    - Quality classification module
    - Gauge classification module
    - Packaging stage
  - Cold storage
    - Non processed fruit (total and per variety)
    - Processed fruit (total and per product)
    - Out of specification fruit
    - Total mass balance
    - Third party storage

PLANNING MODEL

- Maximum Processing Capacity is given by the amount of fruit that can be handled at the Pre Classification module
- It depends on the number of working shifts and the processing capacity per shift
- Objective function : profit oriented mode

Total Profit = sales income - raw material cost - labor costs - cooling costs

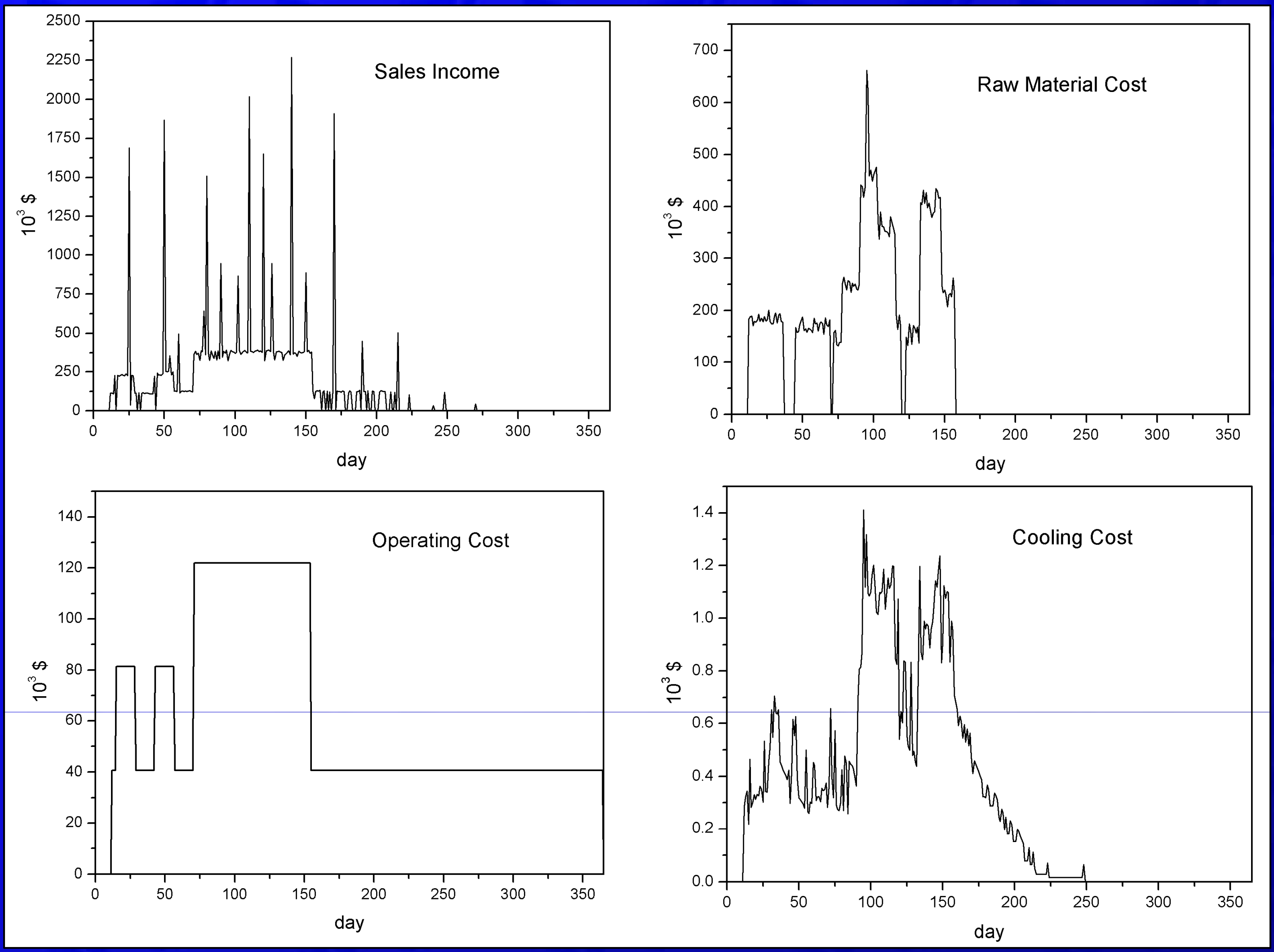
PLANNING MODEL: Profit oriented mode

- A plan that maximizes the production of each particular product is obtained

- The resulting plan constitutes a “forecast” of the processing capacity of the facility

- Valuable for managers to establish next year sales commitments

PLANNING MODEL: Results



PLANNING MODEL: Results

- Profit = $ 3,331,623
- Sales income = $ 58,423,785
- Raw material cost = $ 33,242,063
- Operating cost = $ 21,783,926
- Cooling cost = $ 111,171

PLANNING MODEL: Sales oriented mode

Provided a historical profile of fruit income and an established sales program, generate a processing plan in order to maximize total profit, while penalizing non satisfaction of sales commitments in terms of volume of fruit and delivery deadlines.

A Novel Method to Reduce Event Variables in Continuous-time Formulation for Short-term Scheduling

G. Durand, A. Bandoni

7th World Congress of Chemical Engineering
Glasgow, Scotland
July 10-14, 2005

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Argentina

How to achieve the maximum production, the maximum profits and/or the minimum costs?

Knowing:

- **total operation time (time horizon)**
- **process recipe**
- **quantity and capacity of units**
- **products' demand**

SOLUTION: Schedule optimization

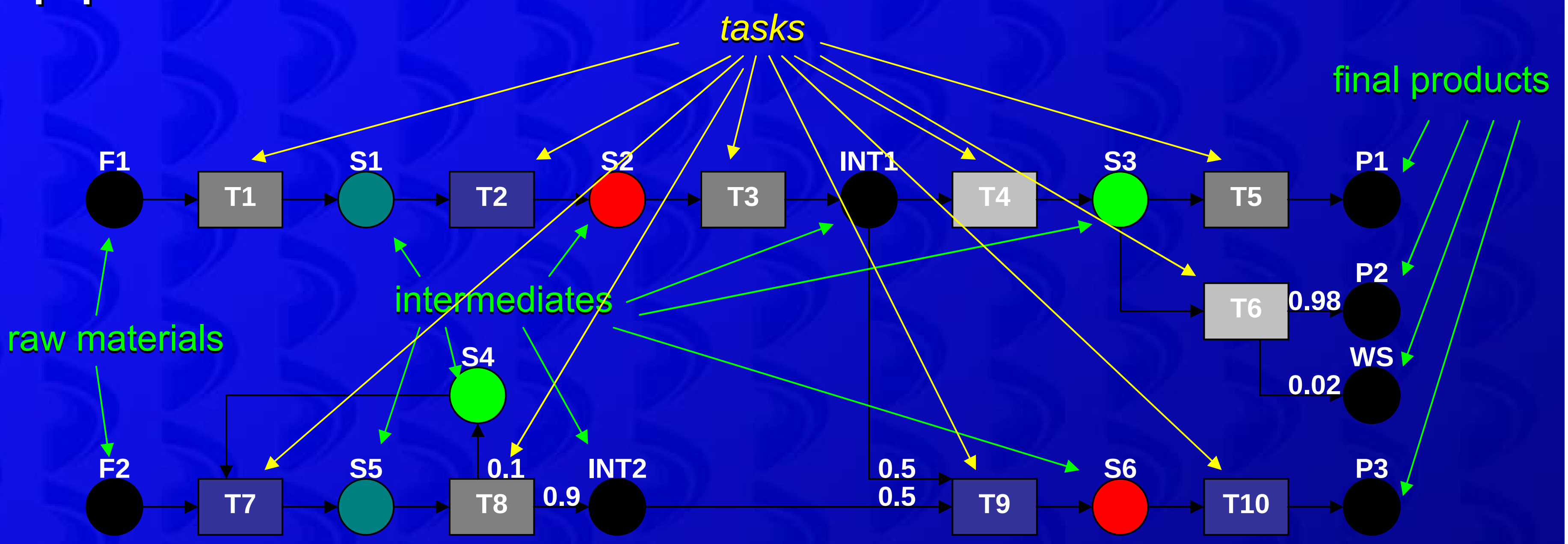
Determining:

- **the sequence and the timing of tasks taking place in each unit**
- **the batch size of tasks (i.e. the processing time and the required resources/utilities)**
- **the amount of final products sold and raw materials consumed**

SCHEDULE OPTIMIZATION – STATE TASK NETWORK

A framework for graphical representation and mathematical formulation of *recipes* (processes) for product manufacturing

Uses materials (states) and tasks as building blocks for the process description, with each task consuming and producing materials while using equipment



MODELLING FOR SCHEDULE OPTIMISATION – STN/RTN FORMULATIONS

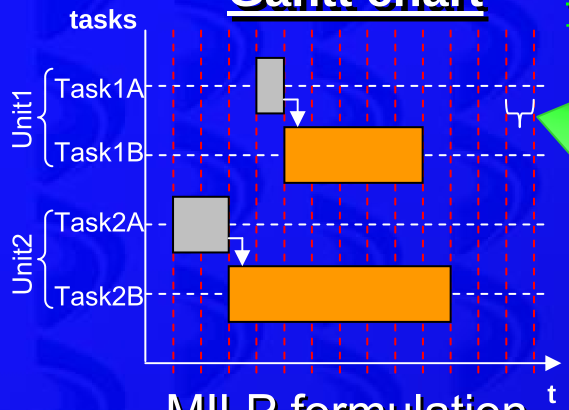
Discrete time representation (STN)

(Kondili et al., 1993)

Continuous time representation (RTN)

(Schilling & Pantelides, 1996)

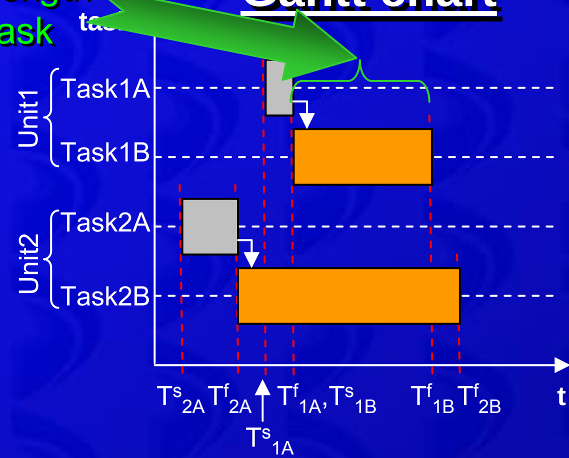
Gantt chart



Event: period of different length for each occurrence of a task

Periods of constant and equal length

Gantt chart



MILP formulation.

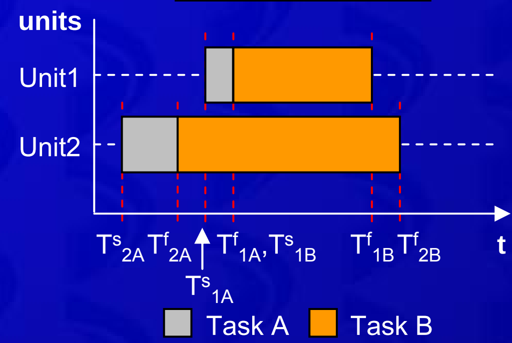
Too many periods needed to model in a realistic way

Produces smaller problems and models the time in a more realistic way

Decoupling task events and unit events

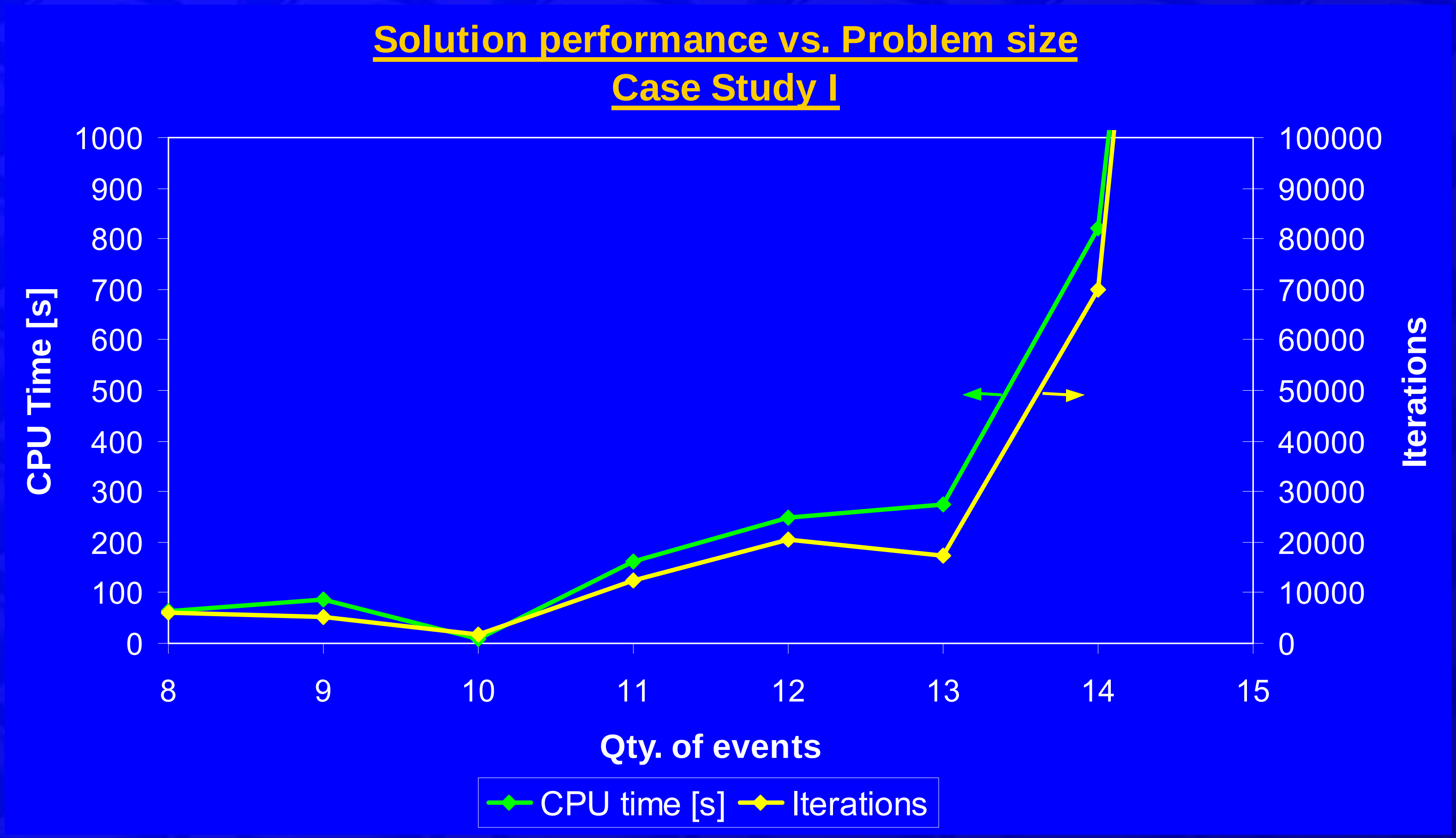
(Ierapetritou & Floudas, 1998)

Gantt chart



Gives smaller problems and better LP relaxations

SCHEDULE OPTIMISATION IS AN NP-HARD PROBLEM



STN/RTN formulations have, in general, a practical(*) size limit of 15-20 events

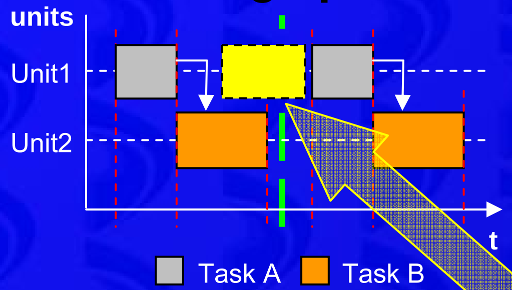
(*)Practical: solvable in less than 3600 seconds in a 1GHz/256MB system

IMPROVEMENTS FOR RTN FORMULATION – 1

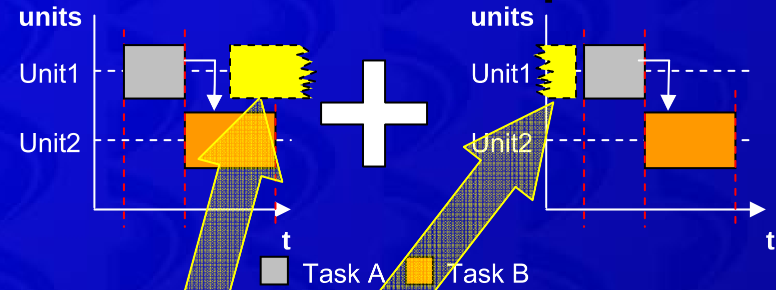
Decomposition approaches

(Basset, Pekny and Reklaitis, 1996 – Khmelnitsky, Kogan, and Maimon, 2000 – Gupta and Maranas, 1999 – Wu and Ierapetritou, 2003)

One large problem



Several smaller subproblems



How to model this?

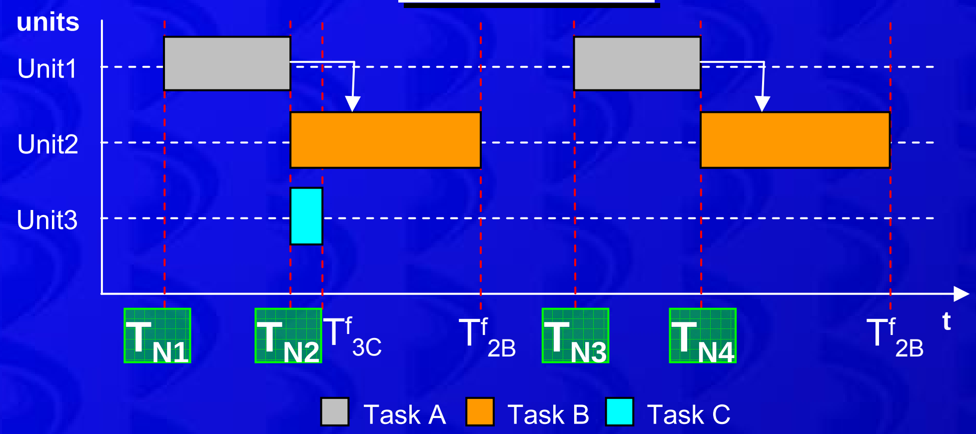
OR

How to give to the solver the possibility of choosing this solution?

IMPROVEMENTS FOR RTN FORMULATION – 2

Reducing problem size in other dimensions
(Maravelias & Grossmann , 2003)

Gantt chart



- Tasks' starting times can only take place at determined time points (T_N), thus reducing the number of time ordering equations.
- Storage is not modelled as a task, therefore reducing the number of binary variables.

PROCESS RECIPE MODELLING IN RTN

Two sets of constraints (equations) model the process recipe in RTN:

Material balances

Each task can only consume states that are being produced or were produced by its corresponding preceding task/s (and/or raw materials).

$$\sum_{i\in I_s} p_{si}^{p} \sum_{j\in J_i} B\left(i^{p}, j^{p}, n-1\right) - \sum_{i\in I_s} p_{si}^{c} \sum_{j\in J_i} B\left(i^{c}, j^{c}, n\right) = 0 \qquad \forall\, n\in N,\, s\in S$$

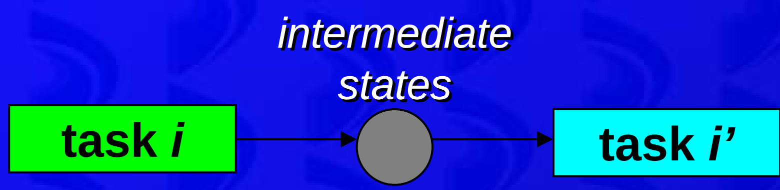
Time ordering

***B*s and *T*s are continuous variables**

If a task consumes states produced by other tasks, it has to start after those tasks have started (continuous) or after they have finished (batch)

$$T^{s}\left(i^{c}, j^{c}, n\right) \geq T^{f}\left(i^{p}, j^{p}, n-1\right) - H\left[2 - wv\left(i^{c}, n\right) - wv\left(i^{p}, n-1\right)\right]$$
$$\forall\ j^{c}, j^{p} \in J,\, i^{c} \in I_{j^{c}},\, i^{p} \in I_{j^{p}},\, n\in N$$

One-to-one pairs of tasks



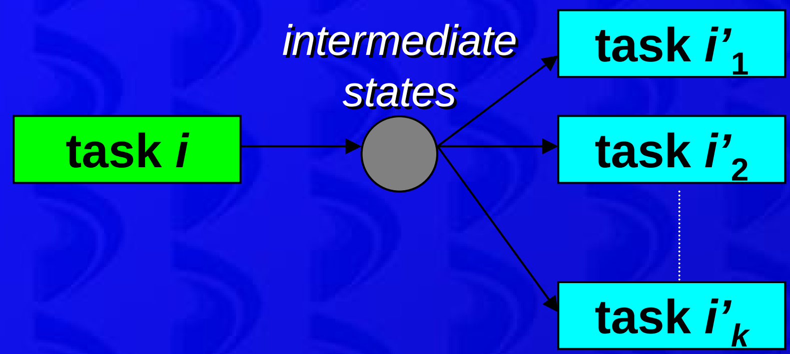
Both tasks continuous OR task i continuous/task i' batch

$$Y_{in} = Y_{i'n} \qquad \forall\, n \in N$$

Task i batch/task i' continuous

$$Y_{in} = Y_{i'n+1} \qquad \forall\, n \in N, n \neq N$$

One-to-many pairs of tasks



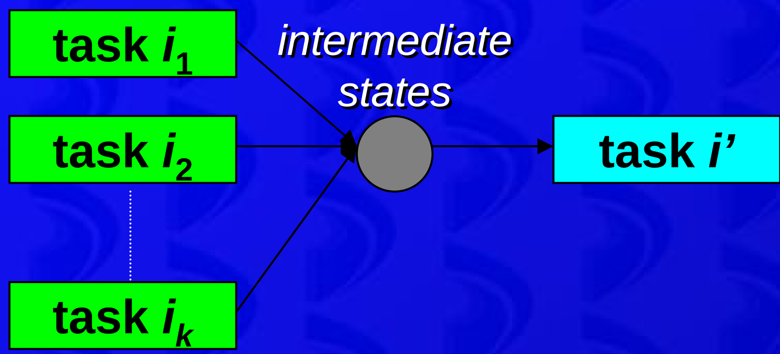
All tasks continuous OR task *i* continuous/tasks *i'* batch

$$\left.\begin{aligned} Y_{in} &\le Y_{i'_1 n} + Y_{i'_2 n} + \ldots + Y_{i'_K n} \\ Y_{in} &\ge Y_{i'_1 n} \\ Y_{in} &\ge Y_{i'_2 n} \\ &\vdots \\ Y_{in} &\ge Y_{i'_k n} \end{aligned}\right\} \quad \forall\ n \in N$$

Task *i* batch/tasks *i'* continuous

$$\left.\begin{aligned} Y_{in} &\le Y_{i'_1 n+1} + Y_{i'_2 n+1} + \ldots + Y_{i'_K n+1} \\ Y_{in} &\ge Y_{i'_1 n+1} \\ Y_{in} &\ge Y_{i'_2 n+1} \\ &\vdots \\ Y_{in} &\ge Y_{i'_k n+1} \end{aligned}\right\} \quad \begin{aligned} &\forall\ n \in N, \\ &n \ne N \end{aligned}$$

Many-to-one pairs of tasks



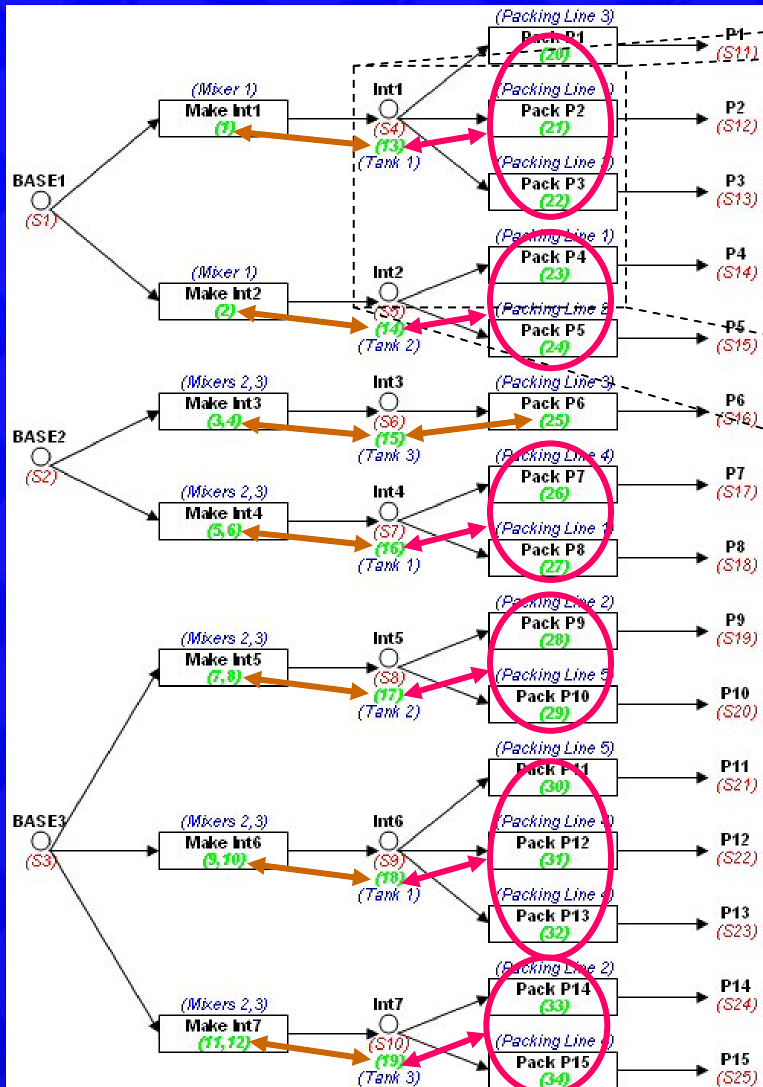
All tasks continuous OR tasks *i* continuous/task *i'* batch

$$\left.\begin{array}{c} Y_{i_1 n} \le Y_{i'n} \\ Y_{i_2 n} \le Y_{i'n} \\ \vdots \\ Y_{i_K n} \le Y_{i'n} \\ Y_{i_1 n} + Y_{i_2 n} + \ldots + Y_{i_K n} \ge Y_{i'n} \end{array}\right\} \quad \forall\, n \in N$$

Tasks *i* batch/task *i'* continuous

$$\left.\begin{array}{c} Y_{i_1 n} \le Y_{i'n+1} \\ Y_{i_2 n} \le Y_{i'n+1} \\ \vdots \\ Y_{i_K n} \le Y_{i'n+1} \\ Y_{i_1 n} + Y_{i_2 n} + \ldots + Y_{i_K n} \ge Y_{i'n+1} \end{array}\right\} \quad \begin{array}{c} \forall\, n \in N, \\ n \neq N \end{array}$$

CASE STUDY I – Multiproduct Plant (15 products/11 units/34 tasks)



Unit	Rate/Capacity [ton/hr]/[ton]	Clean-up time [hr]
Mixer 1	17.00	---
Mixer 2	12.24	---
Mixer 3	12.24	---
Tanks 1,2,3	60	---
Pack line 1	5.833	1
Pack line 2	2.708	4
Pack line 3	5.571	1
Pack line 4	3.333	2
Pack line 5	5.357	---

Product	Demand	Product	Demand
P1	110.0	P11	7.0
P2	107.0	P12	8.5
P3	5.5	P13	3.0
P4	10.0	P14	2.5
P5	4.5	P15	5.0
P6	7.0		
P7	3.0		
P8	27.0		
P9	3.5		
P10	5.0		

Modelled with:

- **Ierapetritou & Floudas formulation (1998)**
- **I & F form. with proposed constraints**
  - – One-to-one pairs – One-to-many pairs

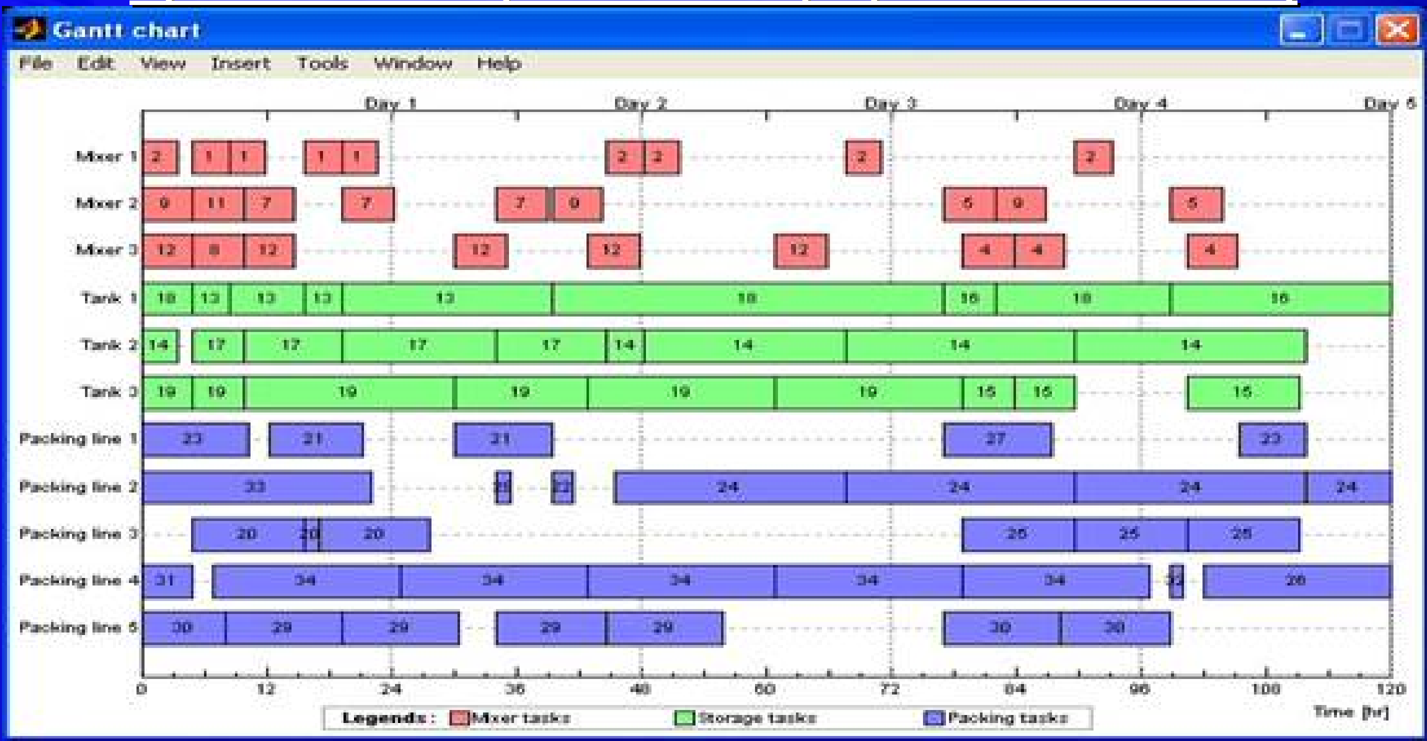
CASE STUDY I – RESULTS

	Ierapetritou and Floudas	With proposed modifications
Integer variables	405	405
Continuous variables	1485	1485
Constraints	3982	4198
Obj. function (LP Relaxation)	1620 Tons.	1620 Tons.
Obj. function (MILP Solution)	1560 Tons.	1620 Tons.
Integrality gap	3.85 %	0.00 %
CPU time	49.96 sec.	30.66 sec.

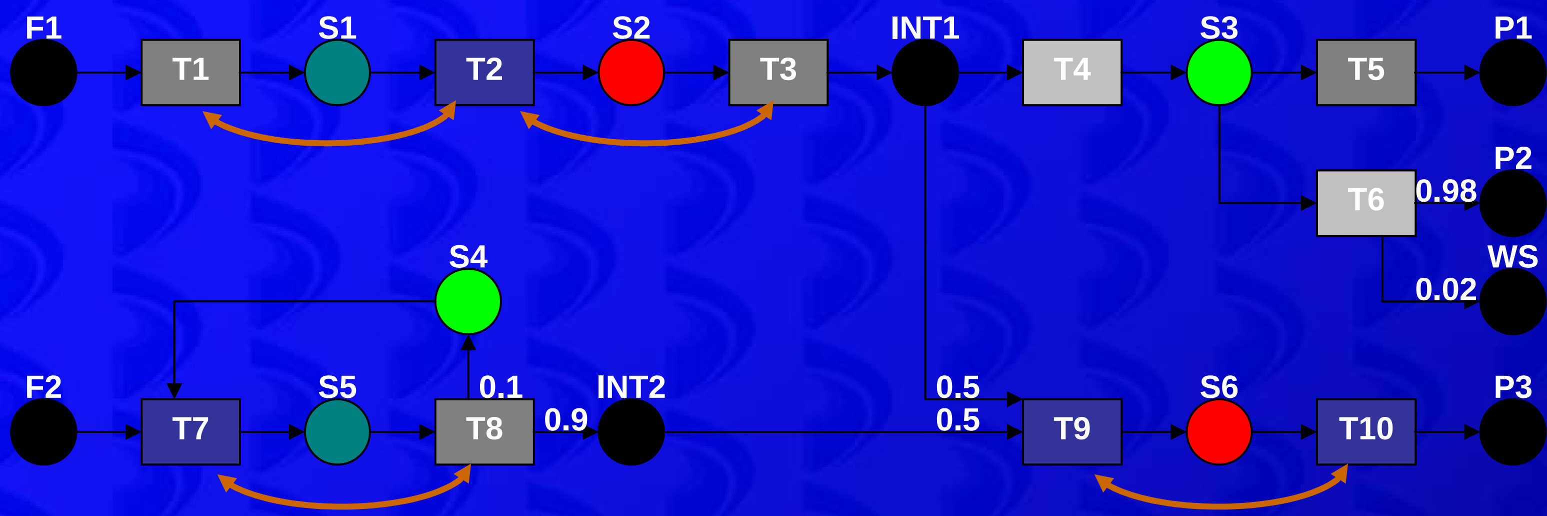
Stopping criterion: Integrality gap <10%

Hardware: AMD Duron 996Mhz – 240Mb RAM memory **Software:** GAMS 21.2/CPLEX 8.1

Optimal schedule (obtained with proposed modifications)



CASE STUDY II – Multiproduct Plant (3+1 products/6 units/10 tasks)



Task	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
Unit	U1	U2	U3	U1	U4	U4	U5	U6	U5	U6
B^{MAX}	5	8	6	5	8	8	3	4	3	4
Dur(α)	2	1	1	2	2	2	4	2	2	3
Utility	LPS	CW	LPS	HPS	LPS	HPS	CW	LPS	CW	CW
Γ	3	4	4	3	8	4	5	5	5	3
Δ	2	2	3	2	4	3	4	3	3	3

B^{MAX} in tons, α in hr, γ in kg/hr, δ in kg/hr*ton

Modelled with:

- **Maravelias & Grossmann formulation (2003)**
- **M & G form. with proposed constraints**
  - One-to-one pairs

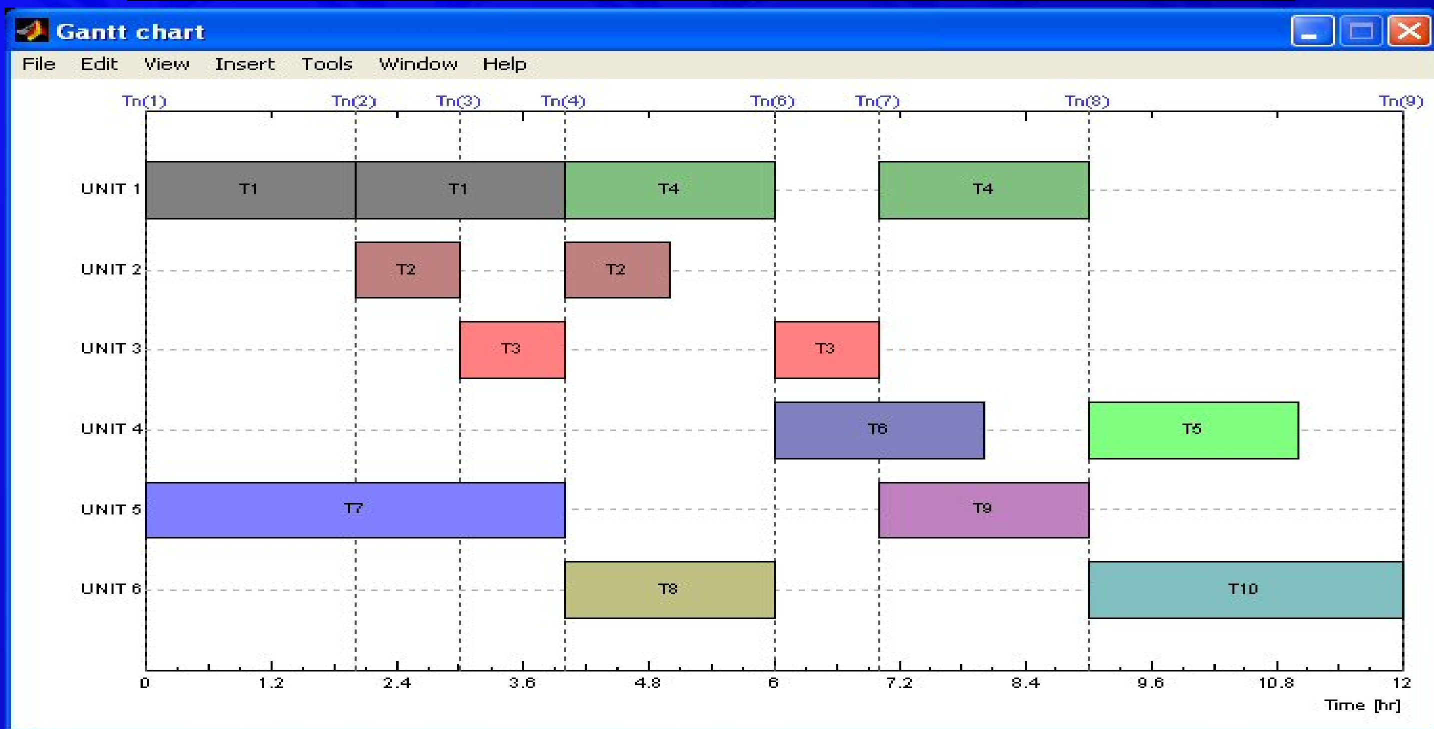
CASE STUDY II – RESULTS

	Maravelias and Grossmann	With proposed modifications
Integer variables	180	180
Continuous variables	1224	1224
Constraints	1655	1691
Obj. function (LP Relaxation)	12.34 Tons.	12.34 Tons.
Obj. function (MILP Solution)	11.319 Tons.	11.35 Tons.
Integrality gap	9.02 %	8.72 %
CPU time	56.64 sec.	26.36 sec.

Stopping criterion: Integrality gap <10%

Hardware: AMD Duron 996Mhz – 240Mb RAM memory **Software:** GAMS 21.2/CPLEX 8.1

Optimal schedule (obtained with proposed modifications)



CONCLUSIONS

- ✓ A new set of constraints for modeling the process recipe for scheduling problems is presented.
- ✓ They are an additional method, reinforcing the task relations expressed thru material balances and time ordering.
- ✓ They can be applied to several RTN representations.
- ✓ The proposed modifications allow finding better values of the objective function in less time than the original formulation where they are applied.
- ✓ The improved performance comes from the effective elimination of binary variables and faster integer cuts.

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