INGENIERIA INDUSTRIAL
UNIVERSIDAD DE CHILE

fcfm

Methodology to evaluate long-term mining plans with uncertainty in the price of copper

AMSI 2019, Perth

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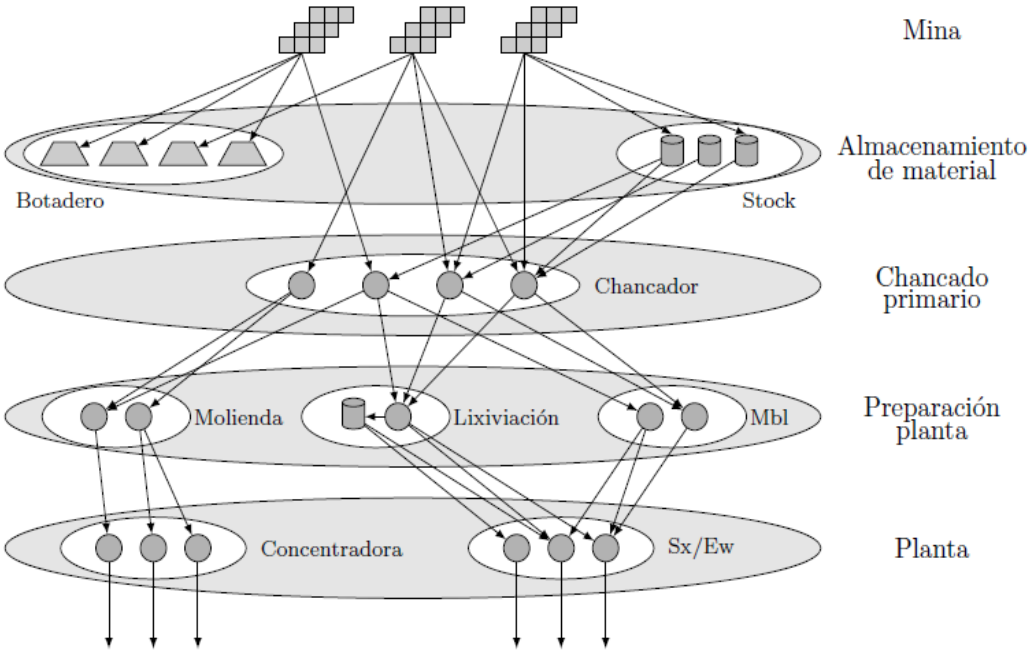
Contents

- Motivation
- Methodology for Flexible Robust Planning
- Progressive Hedging
- Application: Quetena Project (CODELCO)

Motivation

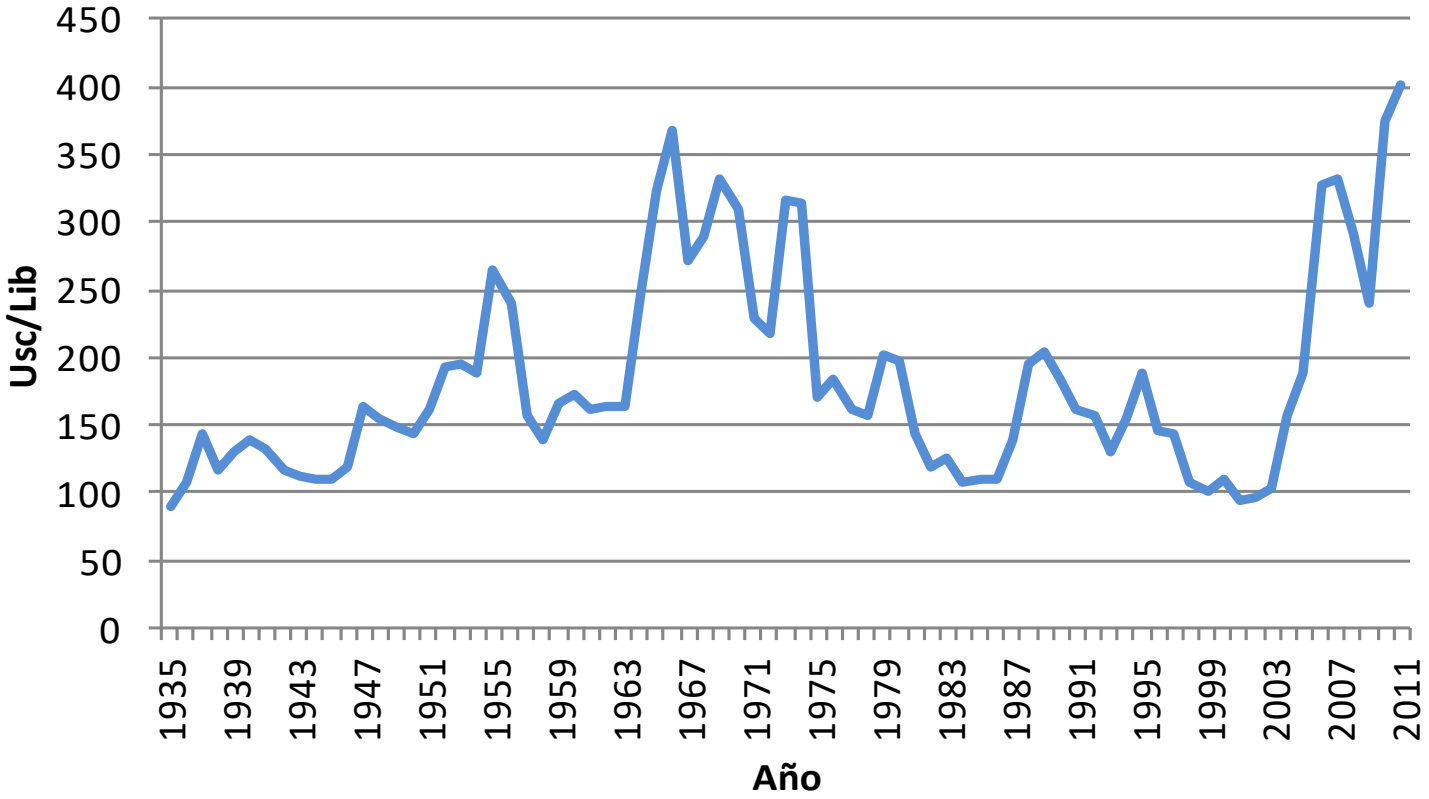
Motivation



- Sequence for pushback extraction
- Delivery of material through a capacitated network
- Objective: Maximize the VAN of the mining business

Motivation

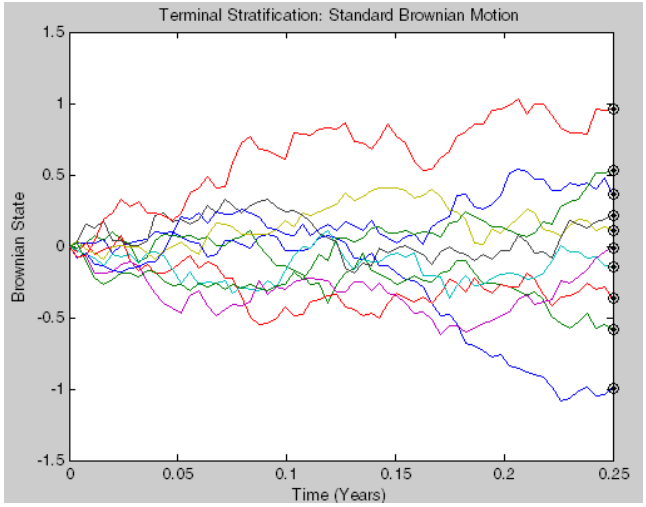
- Historical Price of Copper



Methodology for Flexible Robust Planning

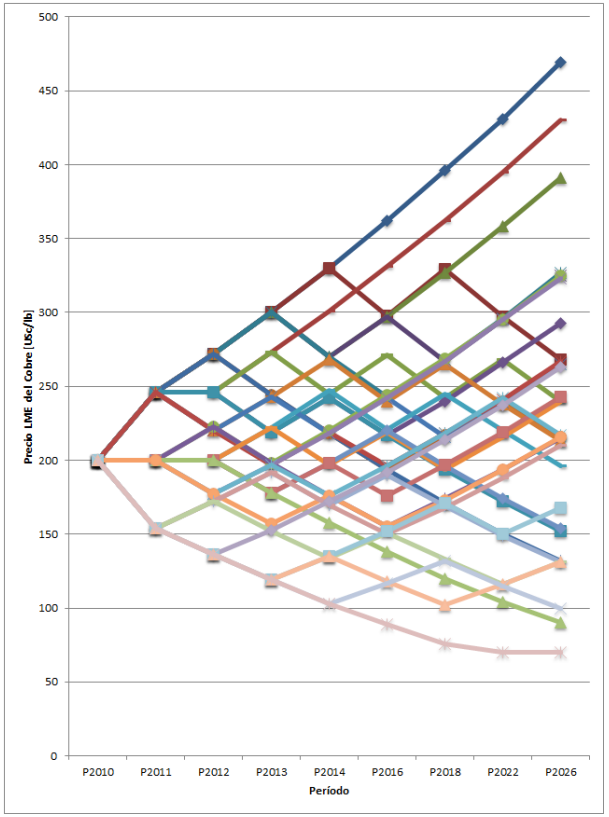
Methodology for Flexible Robust Planning

- Copper Price Scenarios:



Generation of scenarios

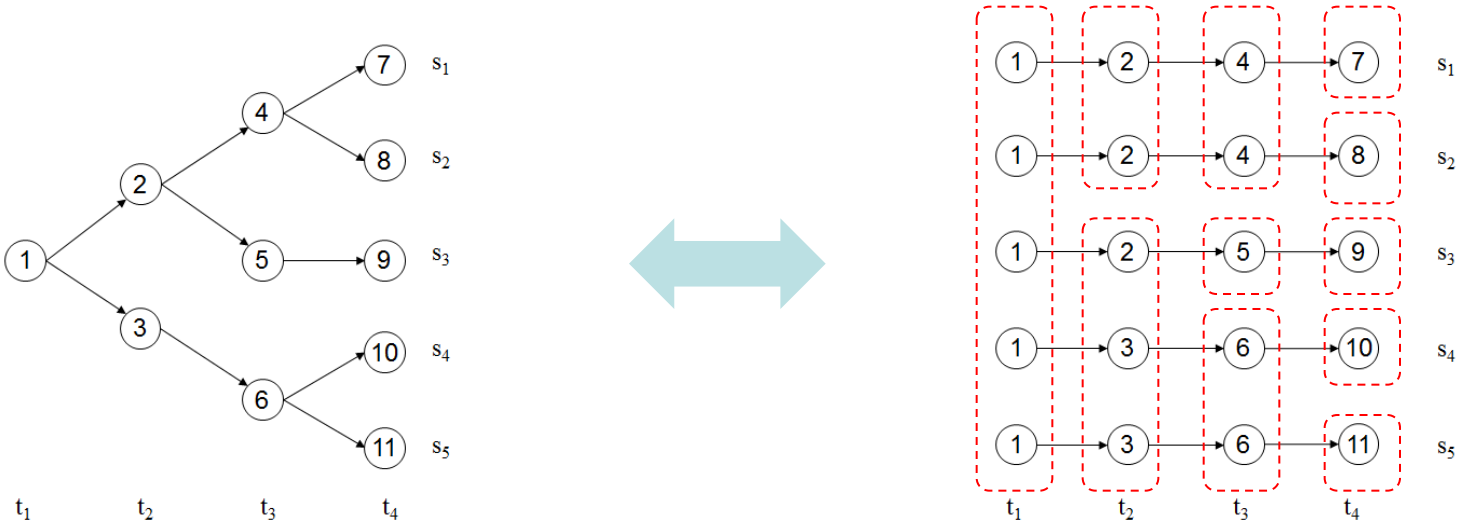
Mean Reversion Process or
Wiener Process



Scenarios tree

Methodology for Flexible Robust Planning

- Stochastic Programming:
  - A problem is defined which considers all the scenarios simultaneously
  - Non-anticipativity: "For every pair of scenarios, if they share the same price trajectory up to period t, then their solutions must be identical up to period t"



Methodology for Flexible Robust Planning

- Problem size:
  - The size makes the problem intractable computationally

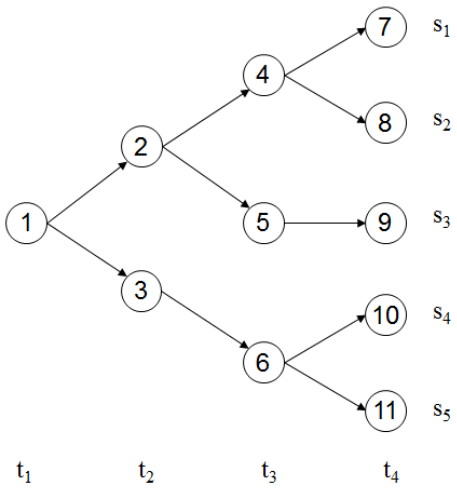
Escenarios	Restricciones	Variables	Variables Binarias
1	28,525	93,136	4,255
16	345,272	1,003,569	44,506
32	648,530	1,814,923	79,199

Example of the increasing problem size

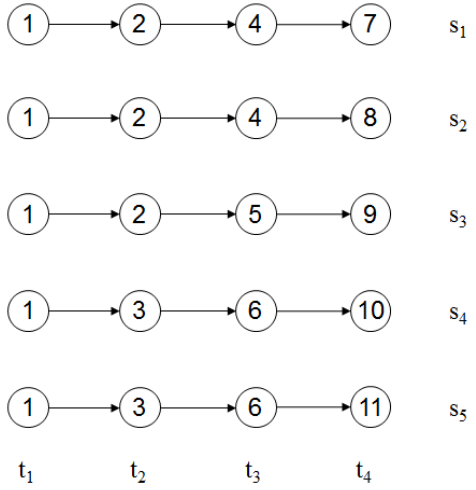
Progressive Hedging

Progressive Hedging

- Methodology created by R. Wets and R.T. Rockafellar.
- Lagrangian Relaxation is used and the problem is broken down by scenarios finding an optimum for each one.



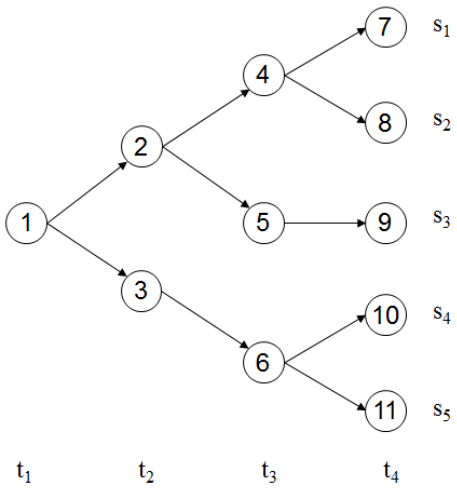
Tree for price scenarios



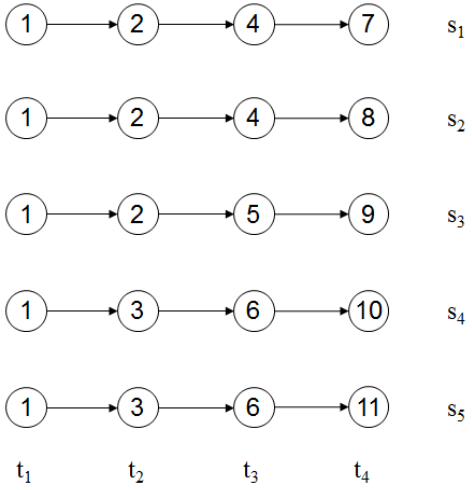
Decomposition by scenarios

Progressive Hedging

- The result satisfies all planning constraints and is optimal for each scenario, but the principle of non-anticipativity is not met.



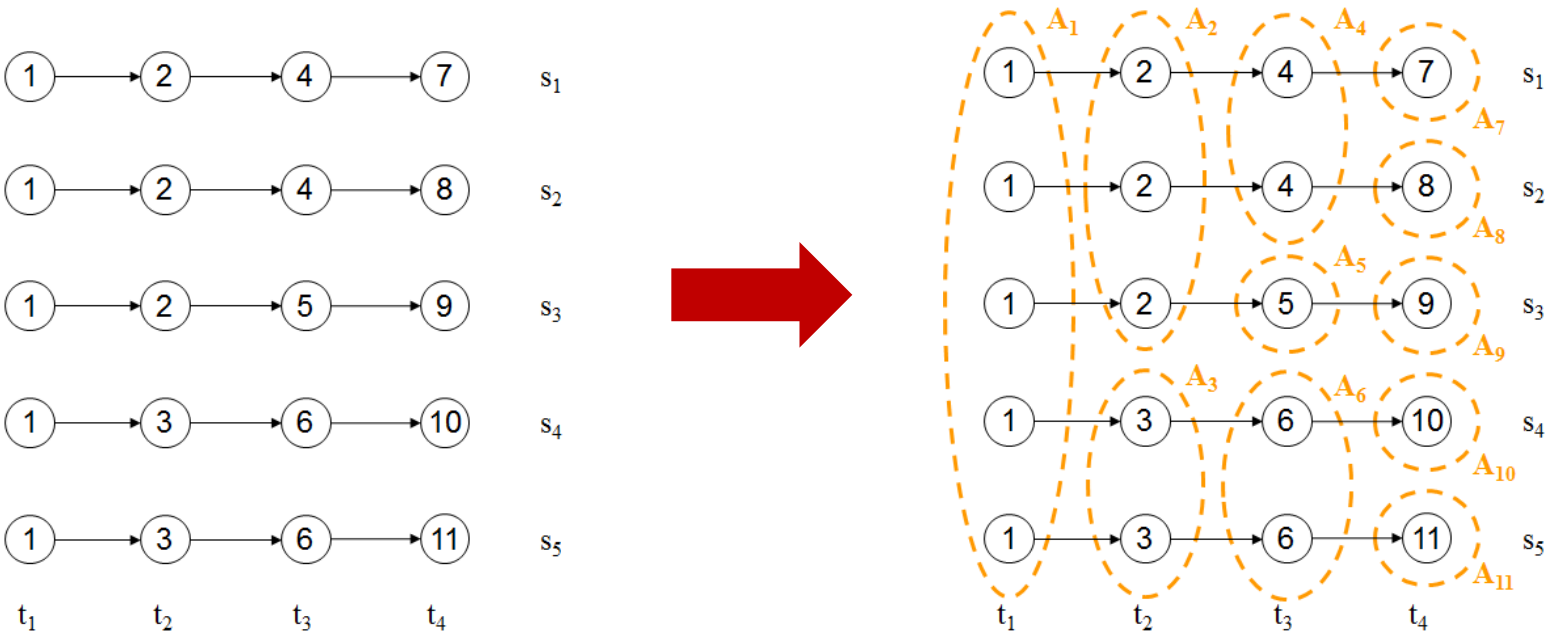
Tree for price scenarios



Decomposition by scenarios

Progressive Hedging

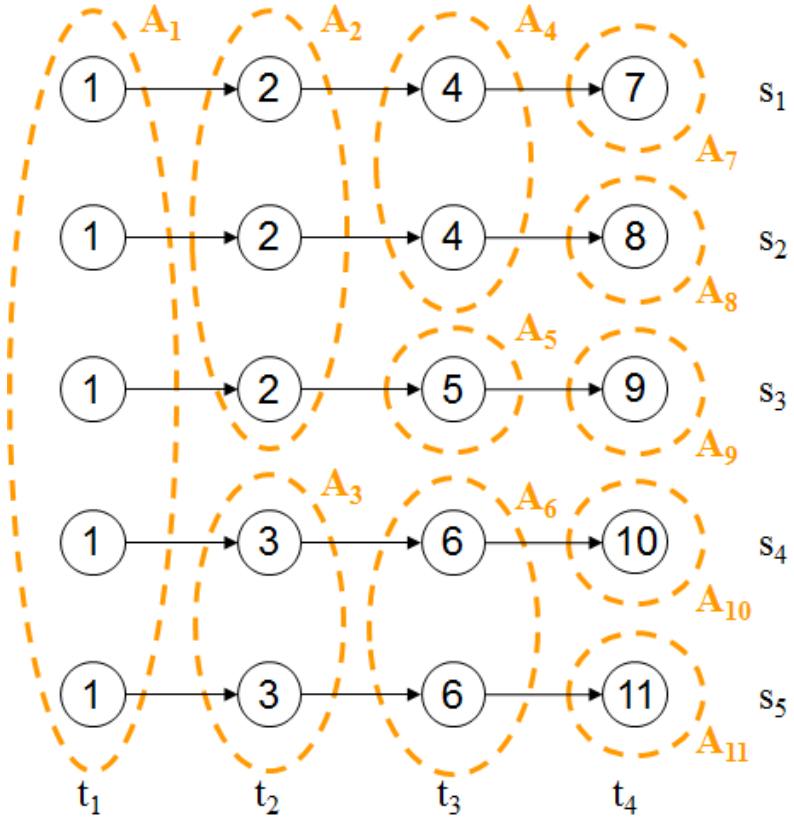
- It is penalized for not fulfilling the principle of non-anticipativity, for each period and scenario.



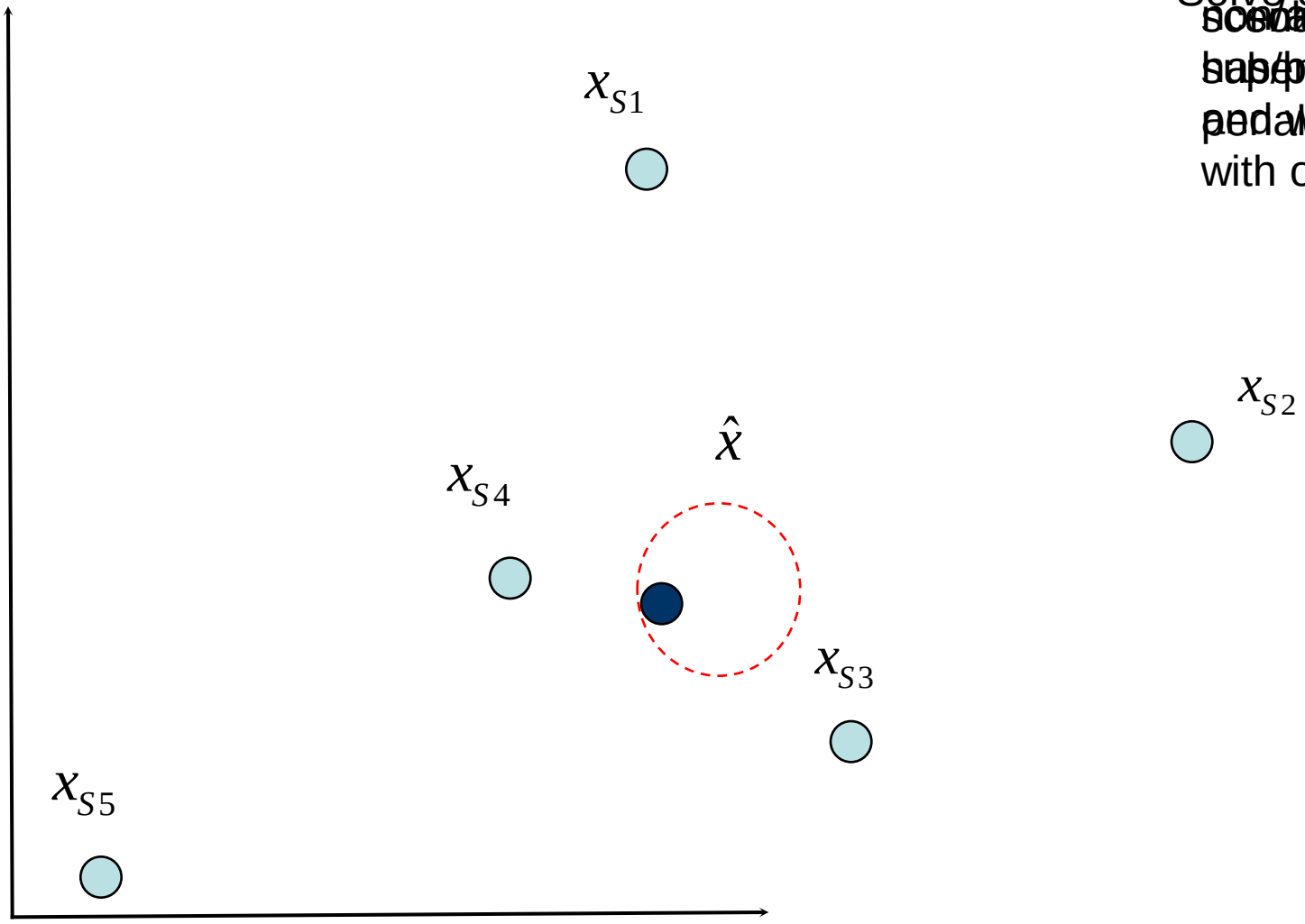
- Each of the scenarios is solved again, forcing them to fulfill non-anticipativity in each of the sets Ai.

Progressive Hedging

- With the new solutions it is penalized again until the solutions of the scenarios fulfill the principle of non-anticipativity.



Progressive Hedging



Solve each scenario

Progressive Hedging

- Resolution sequence

First Iteration

- The scenarios are solved separately

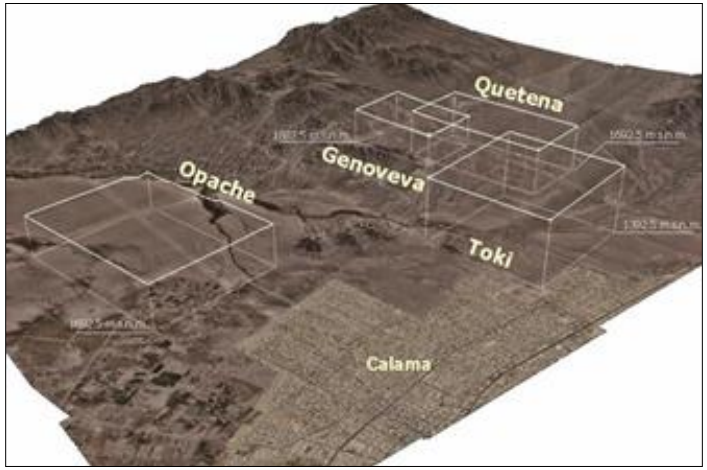
PH Iterations

- Scenarios are solved separately with penalties
- Variables are fixed at the end of each iteration
- A certain number of iterations are performed

Stochastic model

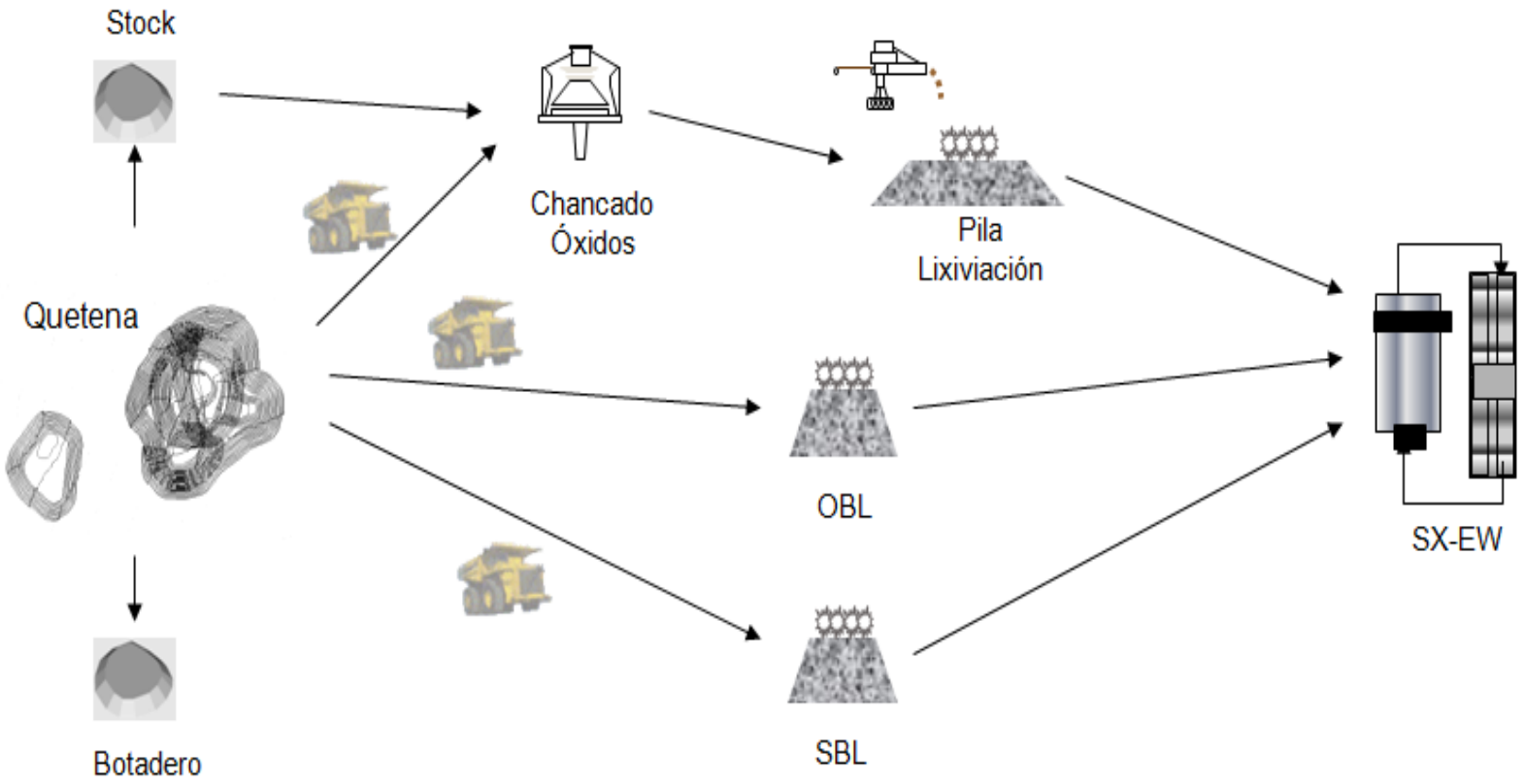
- **The fixed variables are transferred to the stochastic model**
- **A final solution is obtained**

Application: Quetena Project (CODELCO)



Application: Quetena Project (CODELCO)

- Description:



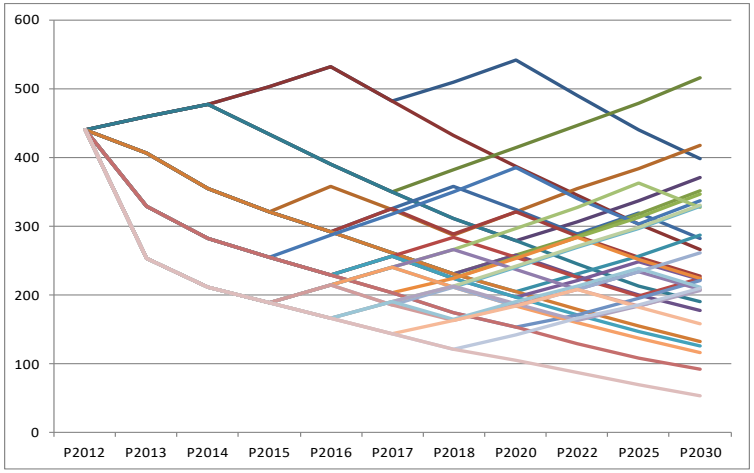
Application: Quetena Project (CODELCO)

- Description:

Fases	Yacimiento	N° de Bancos	Tonelaje Total (Kton)	Ley < 0.1 (Kton)	Oxidos			Sulfuros	
					Ley > 0.1 (Kton)	Ley > 0.12 (Kton)	Ley > 0.15 (Kton)	Ley > 0.1 (Kton)	Ley > 0.2 (Kton)
801	Quetena	17	103,224	80,039	23,056	22,941	22,309	129	129
802	Quetena	19	87,580	44,585	41,603	41,603	41,455	1,393	1,383
803	Quetena	21	137,744	65,319	69,472	68,545	64,880	2,953	2,949
804	Quetena	23	125,868	70,241	53,738	53,738	44,941	1,889	1,889
805	Quetena	21	143,384	78,192	62,335	62,335	48,627	2,857	2,762
806	Genoveva	14	118,977	51,547	66,827	62,042	50,821	603	409
807	Genoveva	18	71,982	25,519	43,621	42,261	32,635	2,842	863
808	Quetena	24	154,518	102,271	48,156	43,999	34,182	4,091	2,401
Total		157	943,277	517,711	408,809	397,464	339,851	16,757	12,784

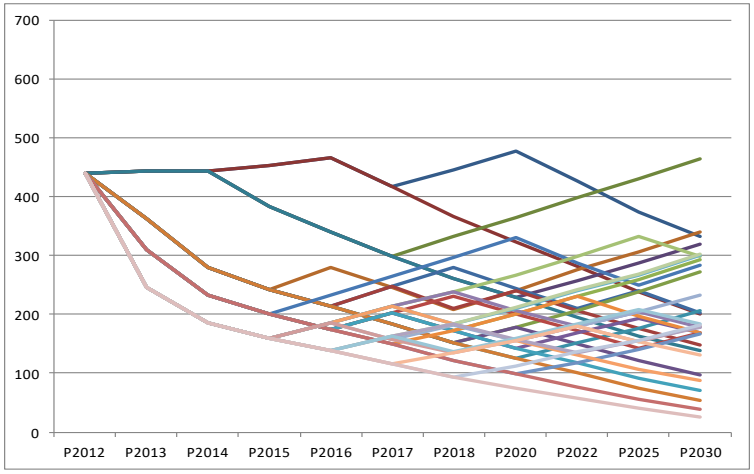
Application: Quetena Project (CODELCO)

- Instances (Mean Reversion):



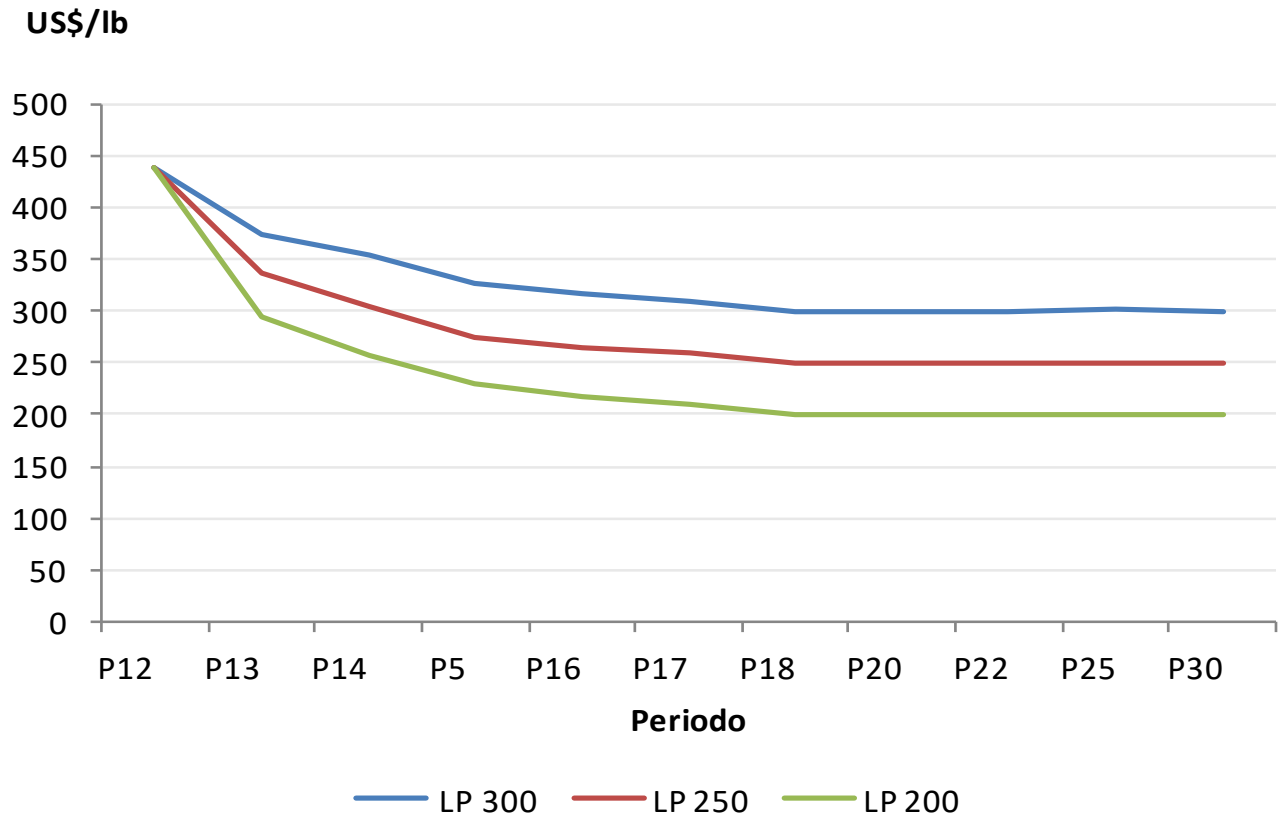
- Number of scenarios
  - 16 scenarios
  - 32 scenarios

- Long-term average price
  - 3.0 US$/lb
  - 2.5 US$/lb
  - 2.0 US$/lb



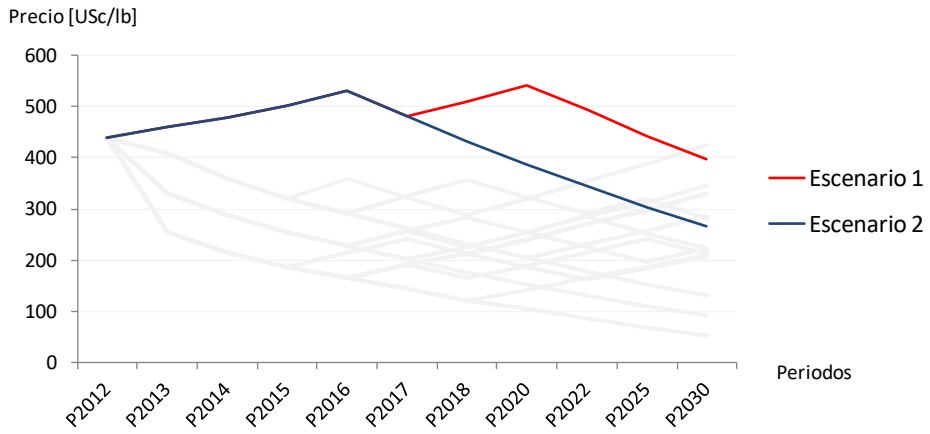
Application: Quetena Project (CODELCO)

- Series of average price:



Application: Quetena Project (CODELCO)

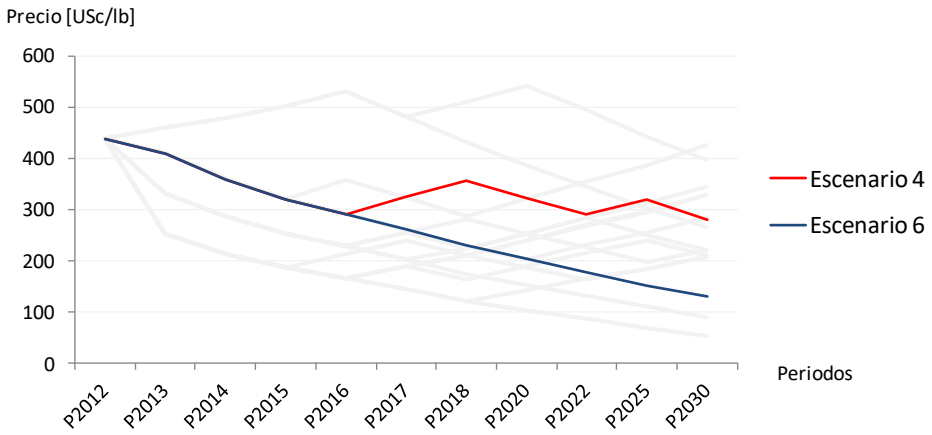
- Flexibility of the solutions (LT price: USD$ 2.5, 16 scenarios):



Escenario	Material	P2012	P2013	P2014	P2015	P2016	P2017	P2018	P2020	P2022	P2025	P2030
Escenario 1	Mineral				28	30	29	30	30	29	17	
	Stock			4				2	2	4		
	Baja Ley			6	59	92	135	78	82	30	15	
	Lastre		100	200	121	88	45	92	96	72	57	
	Total		100	210	210	210	210	203	210	136	91	
	Stock a Planta				2		1	0		1	3	
Escenario 2	Mineral				28	30	29	30	30	29		
	Stock			4								
	Baja Ley			6	59	92	135	49	122	33	29	
	Lastre		100	200	121	88	45	131	58	72	57	
	Total		100	210	210	210	210	210	210	134	85	
	Stock a Planta				2		1	0				

Application: Quetena Project (CODELCO)

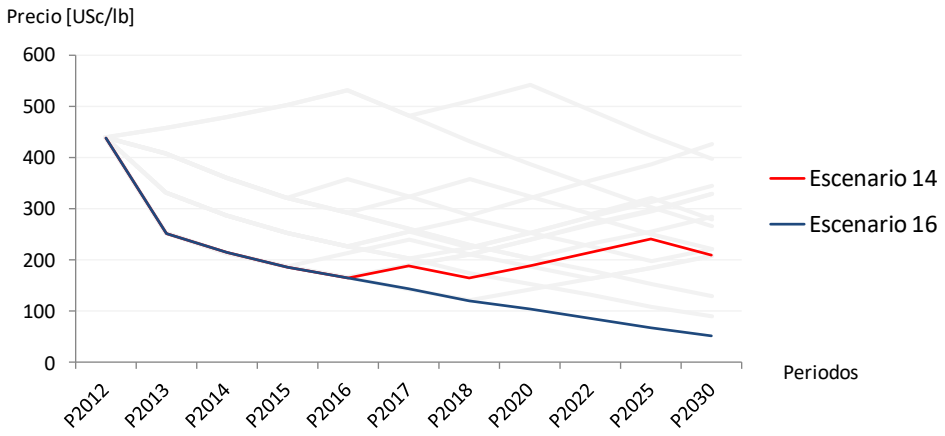
- Flexibility of the solutions (LT price: USD$ 2.5, 16 scenarios):



Escenario	Material	P2012	P2013	P2014	P2015	P2016	P2017	P2018	P2020	P2022	P2025	P2030
Escenario 4	Mineral				30	5	19	30	30	20	20	
	Stock			15	11							
	Baja Ley			41	75	27	44	135	82	28	22	
	Lastre		99	153	95	153	146	45	98	72	57	
	Total		99	210	210	210	210	210	210	120	98	
	Stock a Planta					25	1					
Escenario 6	Mineral				30	5	29	21				
	Stock			15	11							
	Baja Ley			41	75	27	145	57	93			
	Lastre		99	153	95	153	25	97	71			
	Total		99	210	210	210	200	176	164			
	Stock a Planta					25	1					

Application: Quetena Project (CODELCO)

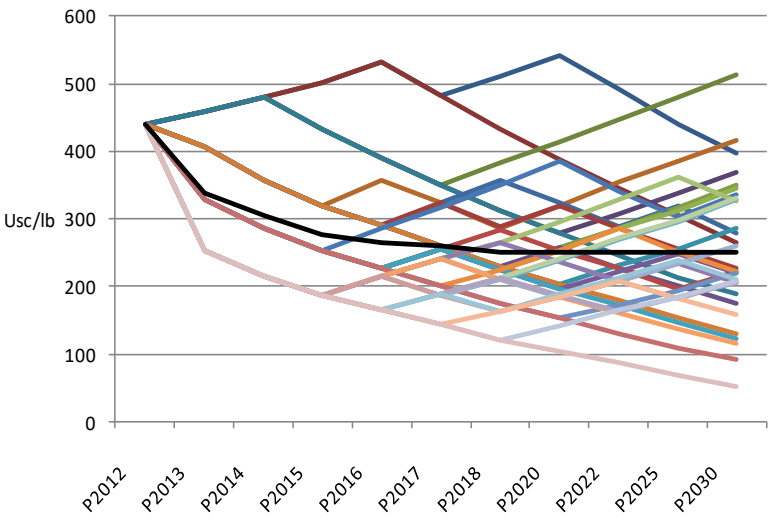
- Flexibility of the solutions (LT price: USD$ 2.5, 16 scenarios):



Escenario	Material	P2012	P2013	P2014	P2015	P2016	P2017	P2018	P2020	P2022	P2025	P2030
Escenario 14	Mineral				20	20	19	20	20	20	23	
	Stock				0	1						
	Baja Ley				18	4	6	4	4	47	81	
	Lastre			130	91	102	19	16	16	47	106	
	Total			130	129	126	45	40	40	113	210	
	Stock a Planta						1	0				
Escenario 16	Mineral				20	20	23					
	Stock				0	1						
	Baja Ley				18	4	97					
	Lastre			130	91	102	21					
	Total			130	129	126	141					
	Stock a Planta											

Application: Quetena Project (CODELCO)

- LT price: USD$ 2.5, 32 scenarios:



Deterministic

	VAN (MM USD$)
VAN Escenario Promedio	549
VAN Promedio Iter Zero	646

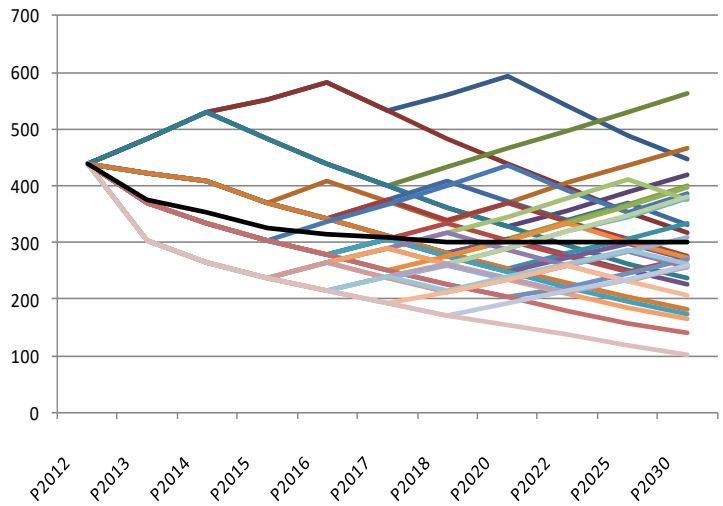
Stochastic

	VAN (MM USD$)
VAN Estocástico	619
Flexibilidad	71

Flexibility = 12,9%

Application: Quetena Project (CODELCO)

- LT price: USD$ 3.0, 32 scenarios:



Deterministic

	VAN (MM USD$)
VAN Escenario Promedio	915
VAN Promedio Iter Zero	971

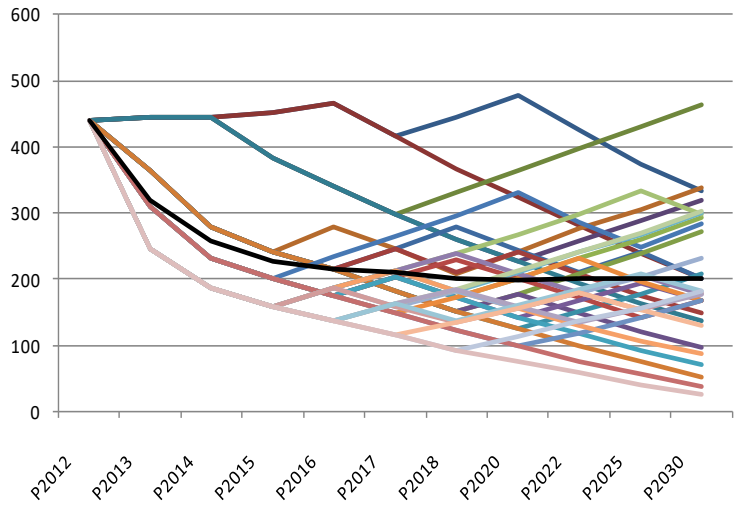
Stochastic

	VAN (MM USD$)
VAN Estocástico	951
Flexibilidad	36

Flexibility = 3,9%

Application: Quetena Project (CODELCO)

- LT price: USD$ 2.0, 32 scenarios:



Deterministic

	VAN (MM USD$)
VAN Escenario Promedio	238
VAN Promedio Iter Zero	367

Stochastic

	VAN (MM USD$)
VAN Estocástico	330
Flexibilidad	92

Flexibility = 38,8%

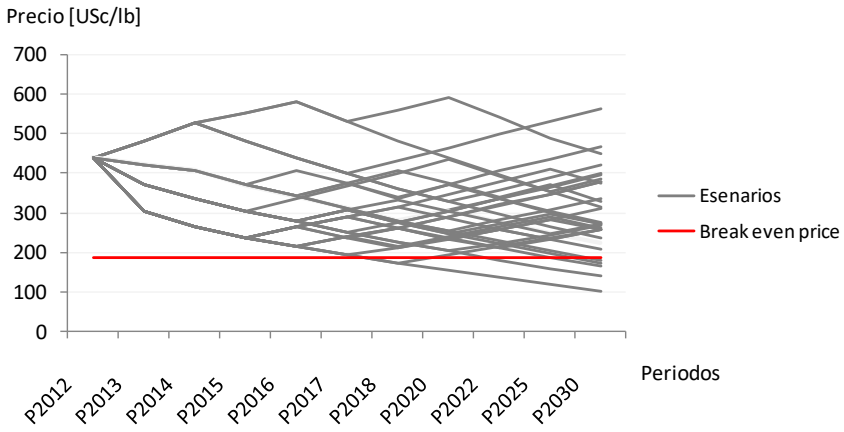
Application: Quetena Project (CODELCO)

- Summary:

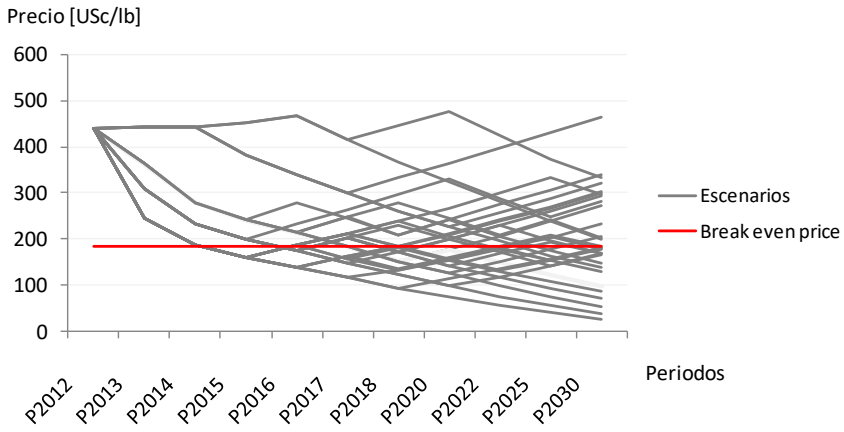
Precio LP [USc/lb]	# Escenarios	VAN Escenario Promedio	VAN Promedio Iter Zero	VAN Estocástico	Flexibilidad
300	16	911,663	977,599	948,161	4.0%
	32	914,828	971,303	950,640	3.9%
250	16	547,028	662,231	640,431	17.1%
	32	548,502	646,092	619,261	12.9%
200	16	244,471	380,586	359,967	47.2%
	32	238,059	366,950	330,311	38.8%

Application: Quetena Project (CODELCO)

- Sensitivity to long-term price



Tree of 32 scenarios
LT average price: USD$ 3.0



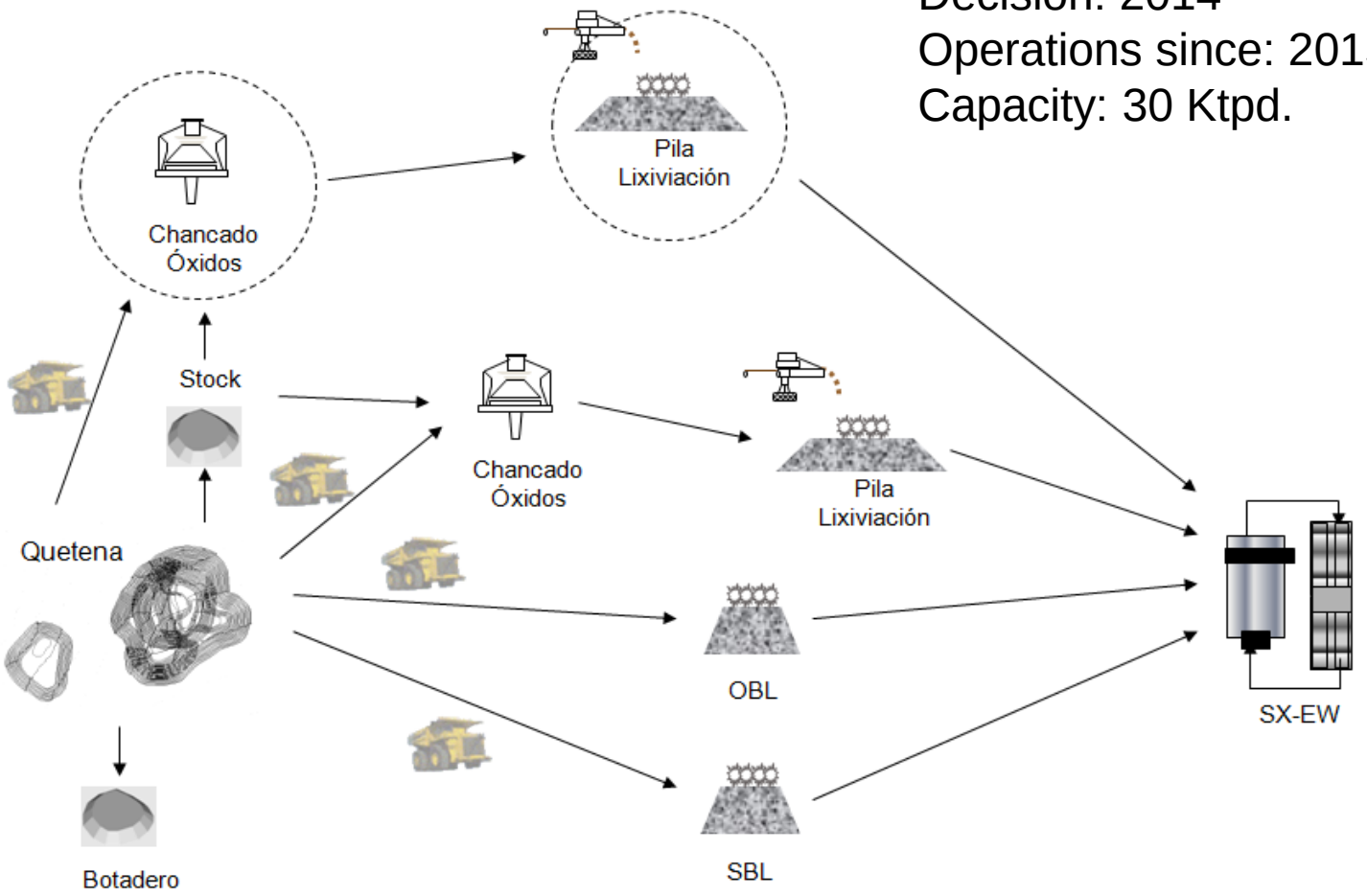
Tree of 32 scenarios
LT average price: USD$ 2.0

Application: Quetena Project Flexibility with investments

Quetena Project: Flexibility with investments

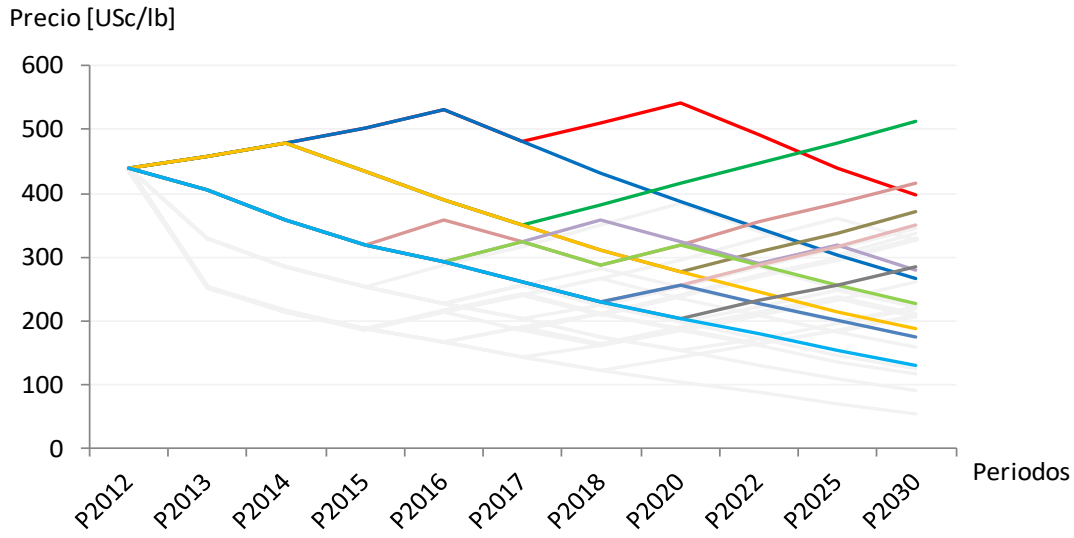
- Instance

Investment: MM US$ 283
Decision: 2014
Operations since: 2015
Capacity: 30 Ktpd.



Quetena Project: Flexibility with investments

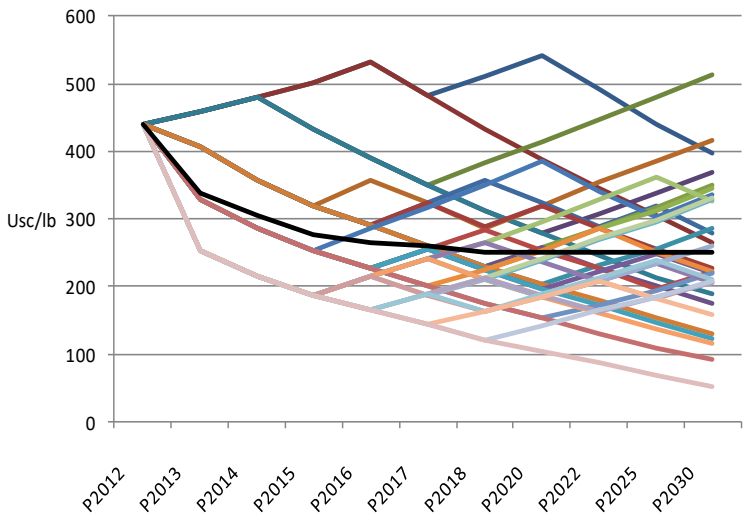
- LT price: USD$ 2.5
  - 32 scenarios, with investment option.



Scenarios in which the investment was made

Quetena Project: Flexibility with investments

- LT price: USD$ 2.5
  - 32 scenarios, with investment option.



Deterministic	VAN (MM USD$)
VAN Escenario Promedio	549
VAN Promedio Iter Zero	681

Stochastic	VAN (MM USD$)
VAN Estocástico	653
Flexibilidad	104

Flexibility = 18,9%

Quetena Project: Flexibility with investments

- Summary (results with investments):

LT price: USD$ 2.5

# Escenarios	Flex. Inversión	VAN Escenario Promedio	VAN Promedio Iter Zero	VAN Estocástico	Flexibilidad
16	No	547,028	662,231	640,431	17.1%
16	Si	546,860	704,960	675,114	23.5%
32	No	548,502	646,092	619,261	12.9%
32	Si	548,716	680,830	652,667	18.9%

Quetena Project: Performance

- Problem size:

Escenarios	Restricciones	Variables	Variables Binarias
1	28,525	93,136	4,255
16	345,272	1,003,569	44,506
32	648,530	1,814,923	79,199

Quetena Project: Performance

- Resolution times:

# Escenarios	Precio LP [USc/lb]	Iteraciones PH [min]	Cross Over [min]	Tiempo Total [min]	Variables Binarias	Variables Binarias Fijadas
16	300	35	19	54	44,506	18,386
	250	38	16	54	44,506	20,542
	200	45	10	55	44,506	23,638
32	300	63	27	90	79,199	29,962
	250	58	50	108	79,199	32,864
	200	78	21	99	79,199	39,282