Planning and scheduling of PPG glass production, model and implementation.

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Project description

Objectives:

1. Development of a Mixed Integer Linear Programming (MILP) model for the **planning and scheduling of the glass production**

   - **Capture the essence** of the process that **is not considered** in the Master Production Schedule
     - Management of waste glass (cullet)

2. Implement a user-friendly software tool to interface with the GAMS model.

   - **Current status: software tool and model is being tested by the supply chain group.**

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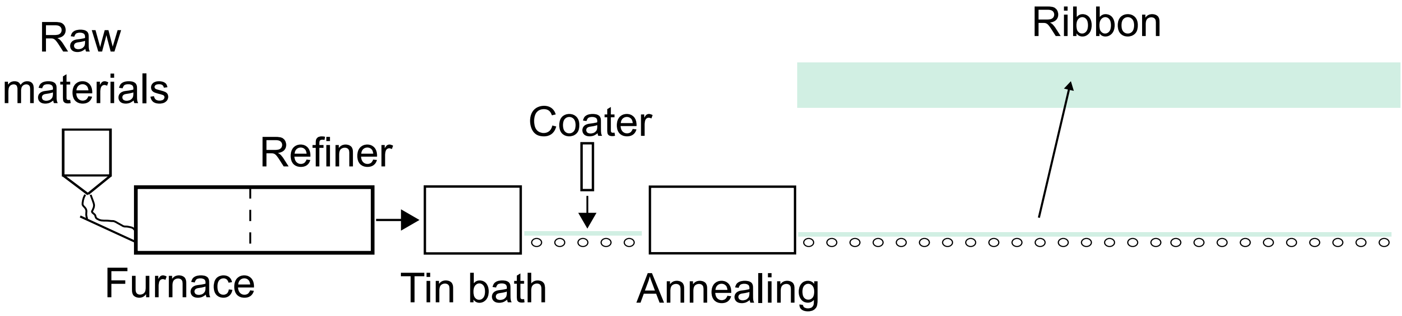
3. Increase the number of attributes of the products, add thickness as an attribute. Currently products are defined by color (substrate and coating).

4. Evaluate the scheduling robustness under uncertainty in some parameters.

Process and products

Continuous process:



Products defined by color

	Substrate	Coated
Solexia		
Caribia		
Azuria		
Solarbronze		
Solargray		
Graylite		

Process and products

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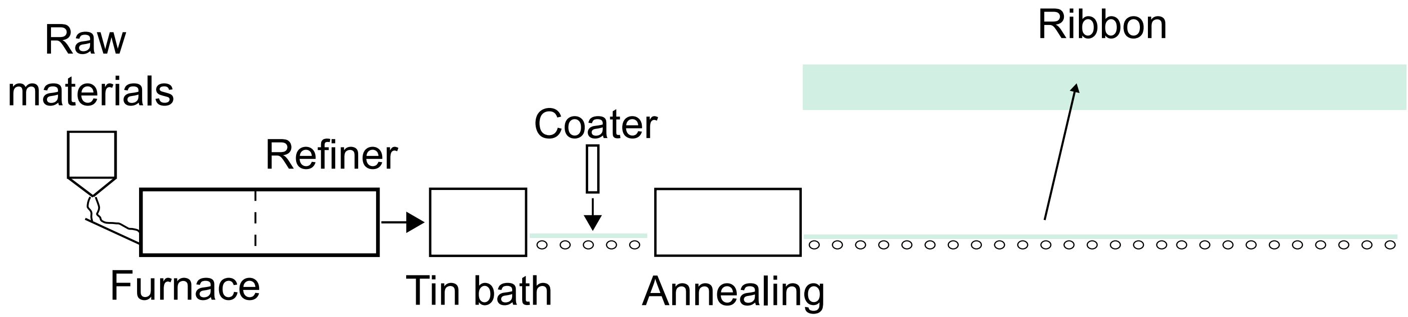

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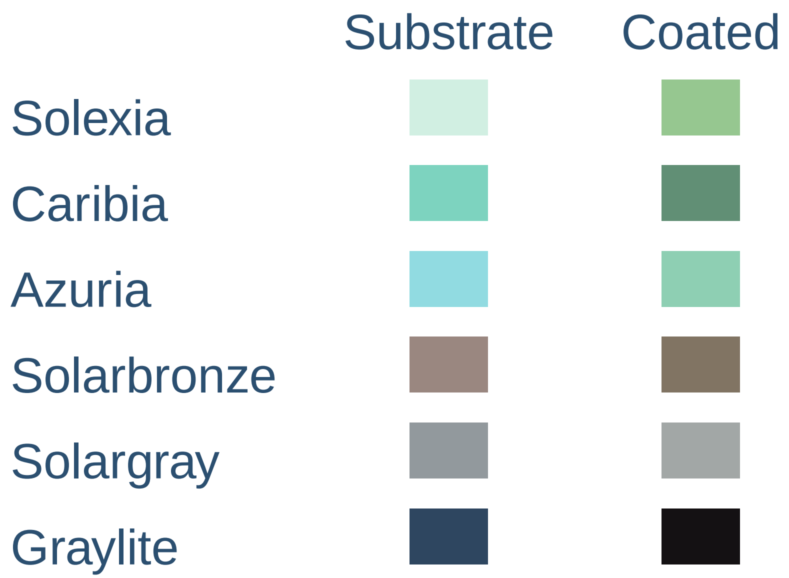

Features

- Raw materials define color of the substrate
- Sequence dependent changeovers between substrates
- No transition times between substrate and coated products

Process and products

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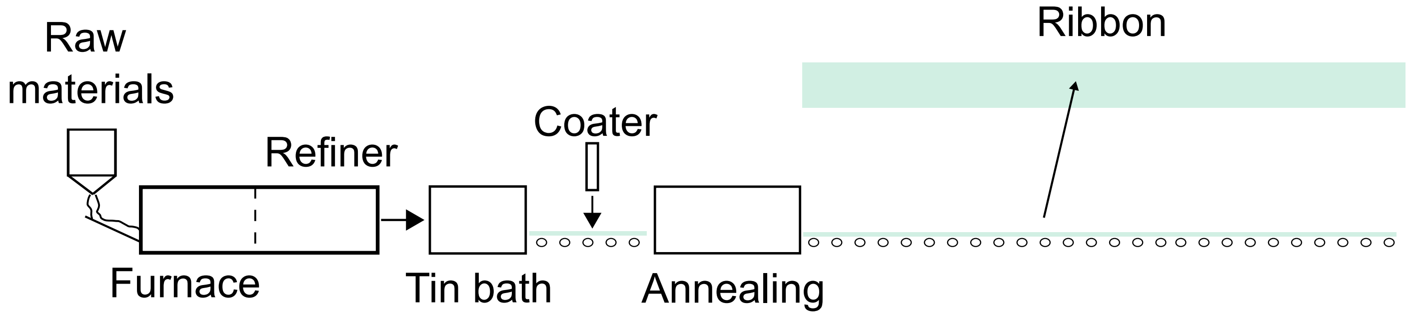

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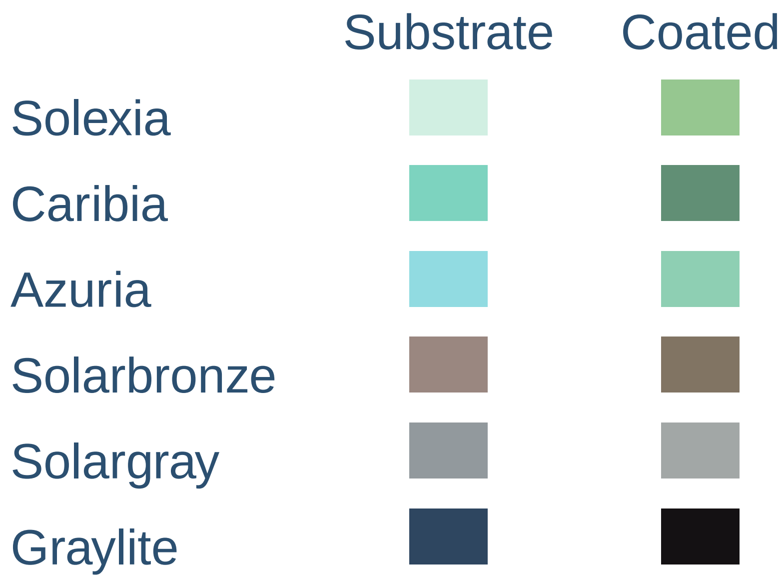

Features

- Raw materials define color of the substrate
- Sequence dependent changeovers between substrates
- No transition times between substrate and coated products
- Long transition times (order of days)
- High transition costs
- Continuous operation during changeover
- Minimum run length (days)

Cullet management

Cullet: waste glass

Good cullet: generated during the production run

Dilution cullet: produced during changeover from one substrate to other substrate

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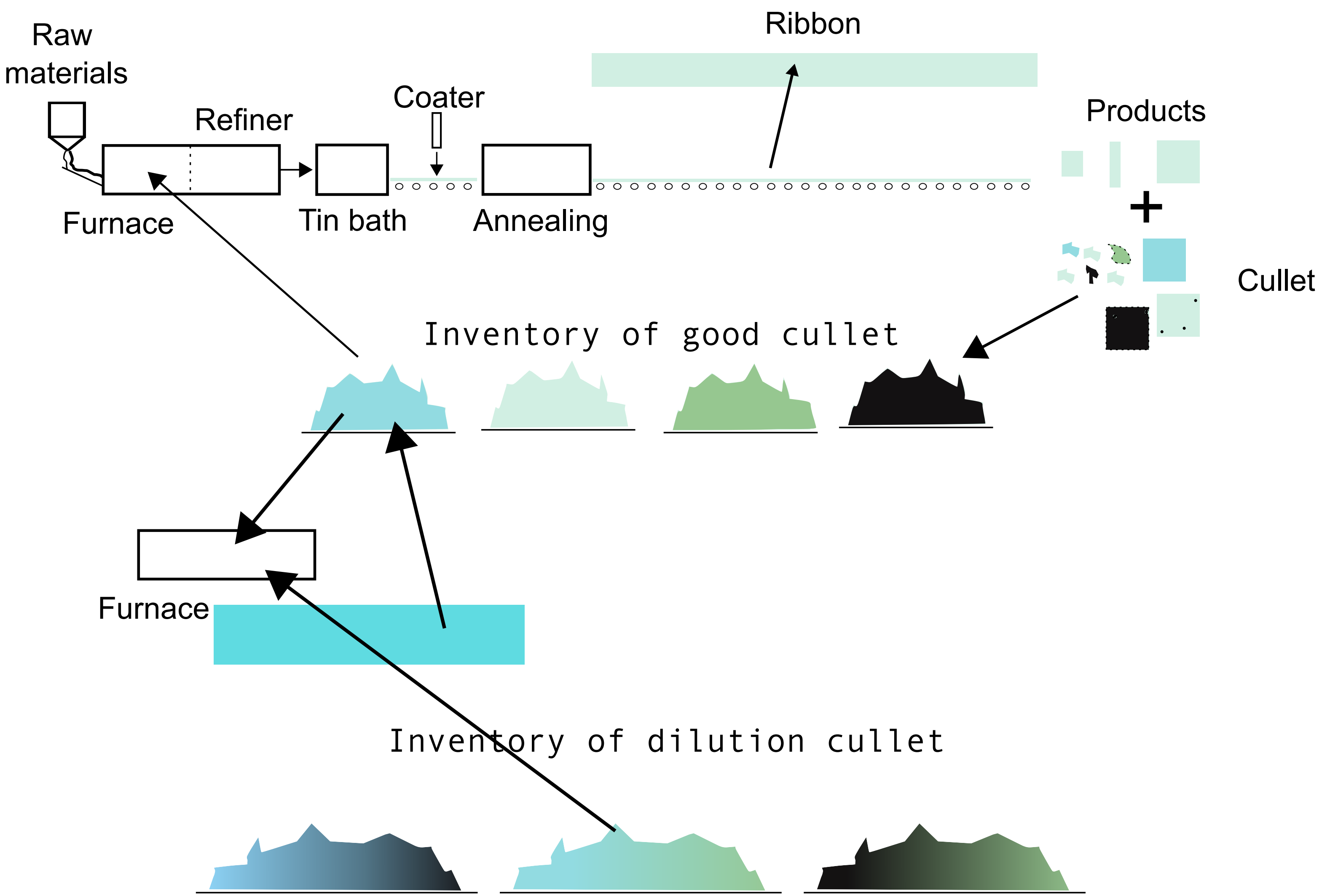

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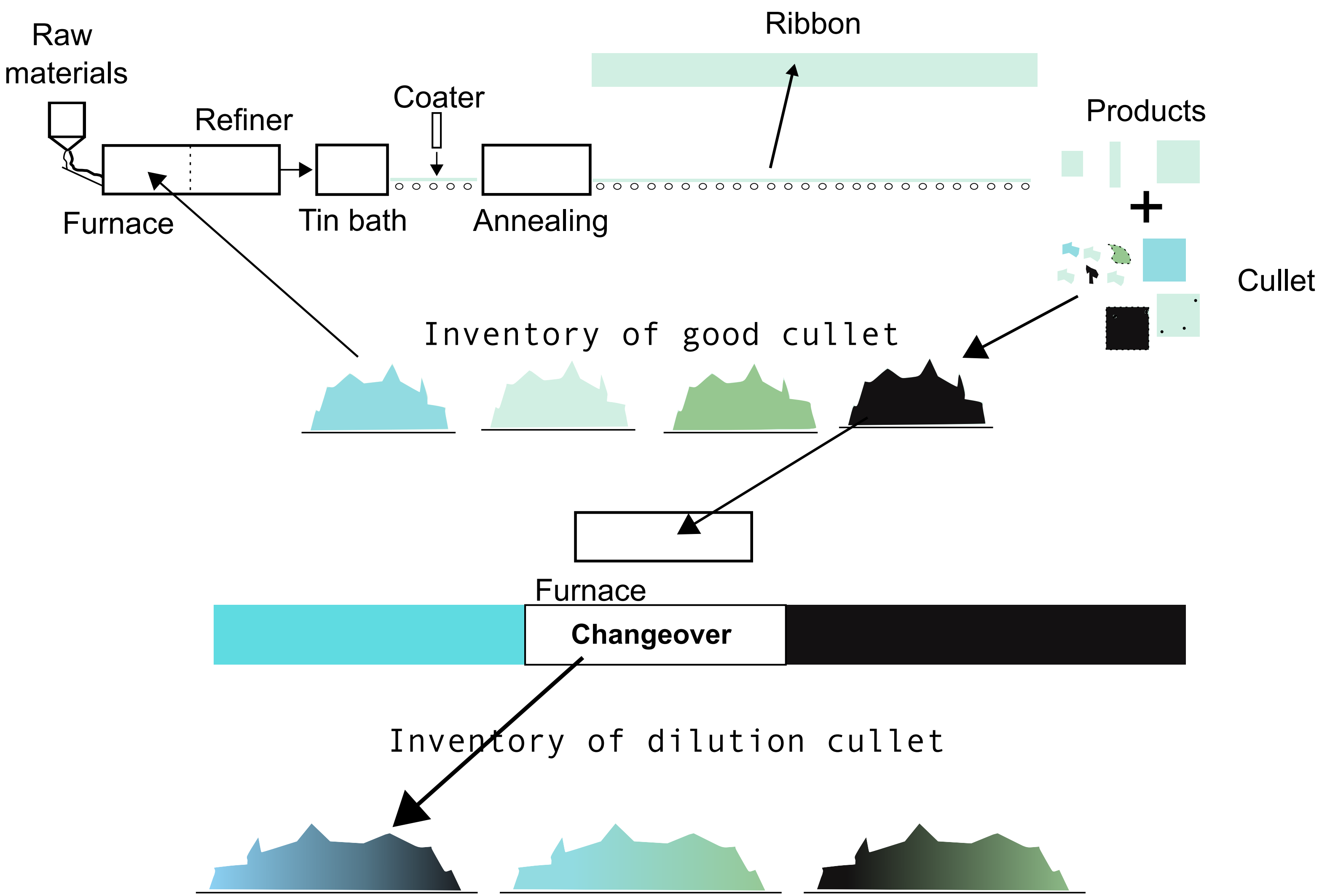

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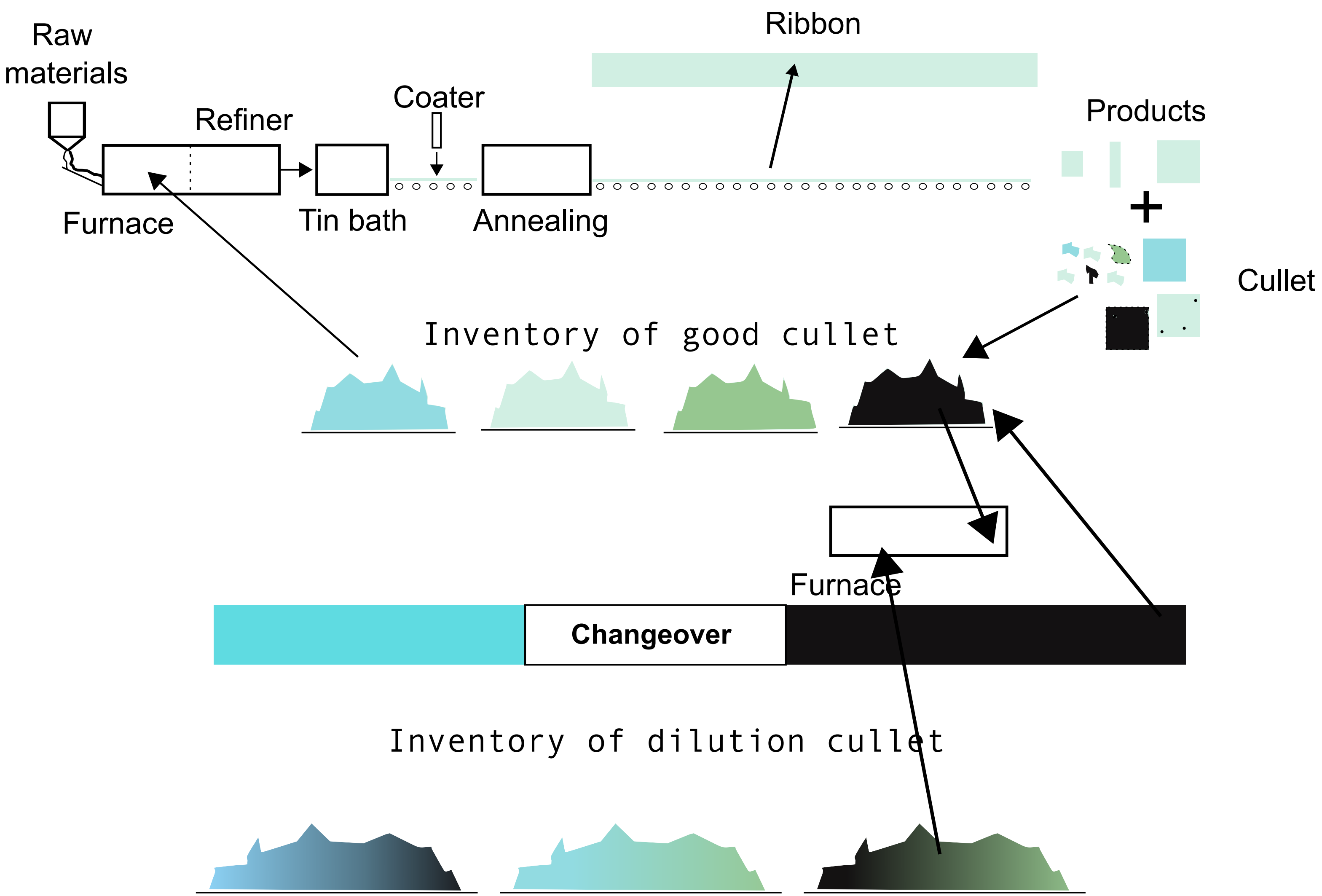

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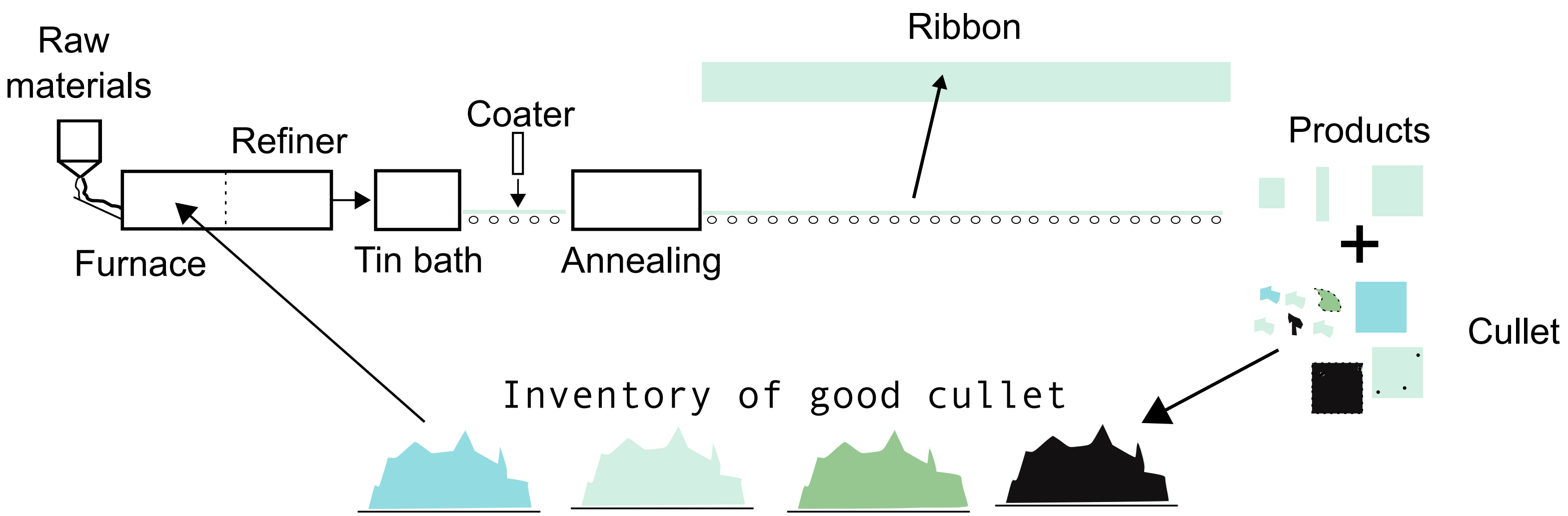


- The schedule determines the amount of cullet generated.
- The cullet in stock must meet the schedule requirements.

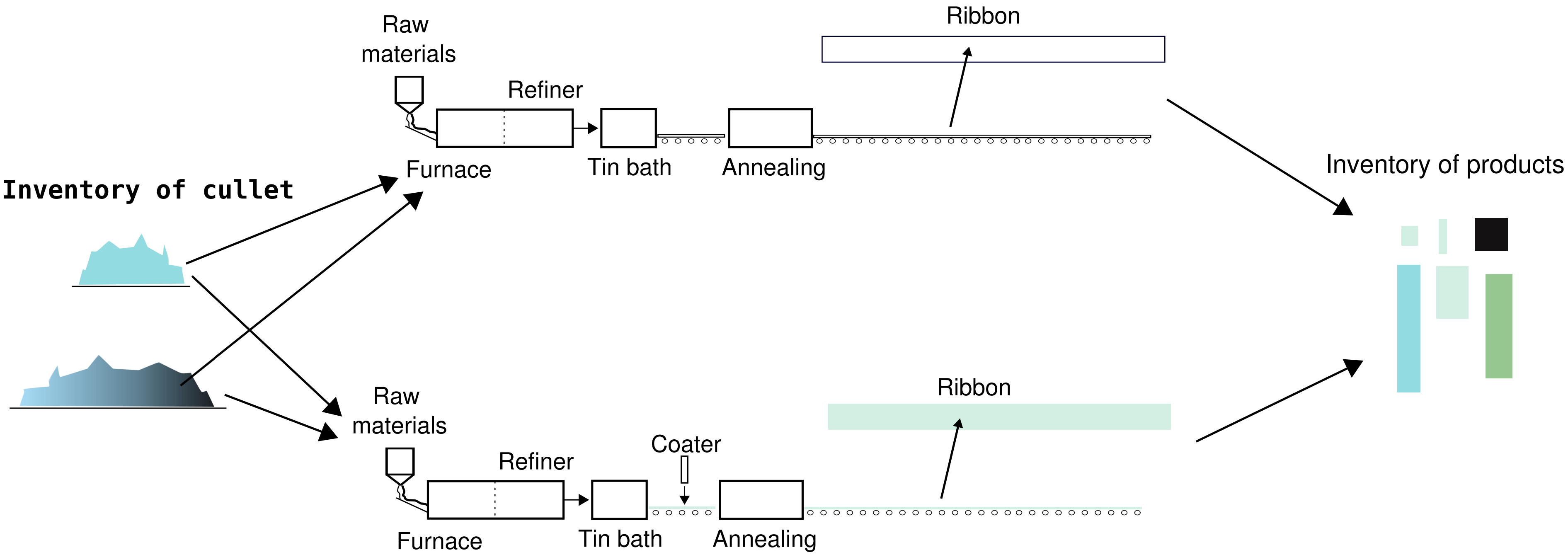
Cullet management

Cullet: waste glass

Good cullet: generated during the production run

Dilution cullet: produced during changeover from one substrate to other substrate

The tinted glass production can be distributed by two lines, which are integrated by a common set of products, cullet production, consumption and storage, and by the glass products storage.



MILP planning and scheduling models

Models implemented:

- **Scheduling model:** slot based continuous time model (Erdirik-Dogan and Grossmann, 2008)
  - detailed timing of the schedule
- **Planning model:** traveling salesman sequence based (Erdirik-Dogan and Grossmann, 2008)

Integrated using **rolling horizon algorithms** to cope with the complexity of the problem. (Lima and Grossmann, 2011)

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Size and performance of the models, for two different case studies

Application of both models **without using a rolling horizon algorithm**

Time horizon = 2 months, time periods = 1 month, 22 products without cullet

Scheduling model

Iteration	Equations	Variables	0-1 Variables	CPU (s)	RGap (%)	Obj
1	4,207	3,253	1,219	98.0	0.0	1,938.05

Bi-level decomposition, first the planning model and then the scheduling model

Iteration	Equations	Variables	0-1 Variables	CPU (s)	RGap (%)	Obj
1	1,625	1,467	601	**0.4**	**0.0**	1,938.48
1	2,046	2,082	169	**0.2**	**0.0**	1,938.05

Obj - value of objective function, profit.

MILP planning and scheduling models

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Size and performance of the models, for two different case studies

Application of both models **using** a rolling horizon algorithm

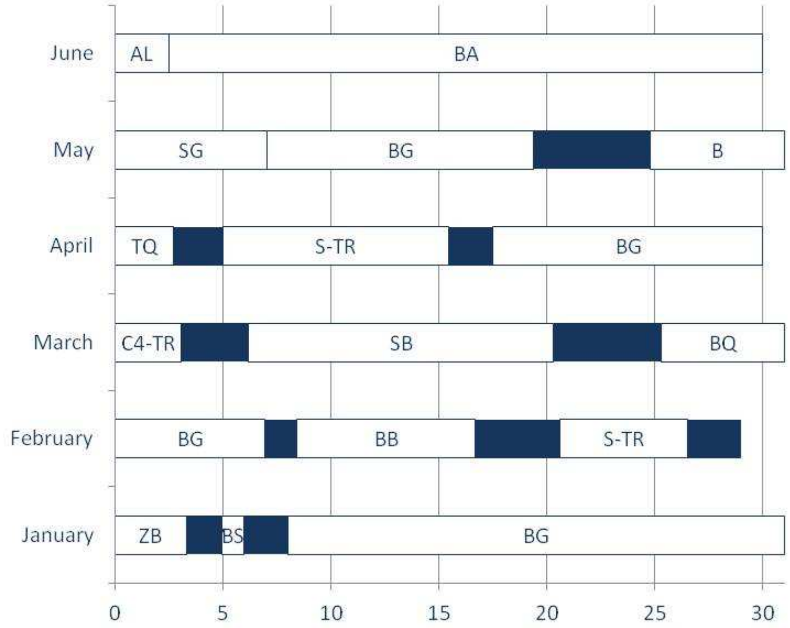
Time horizon = **15 months**, time periods = 1 month, 22 products **with cullet**

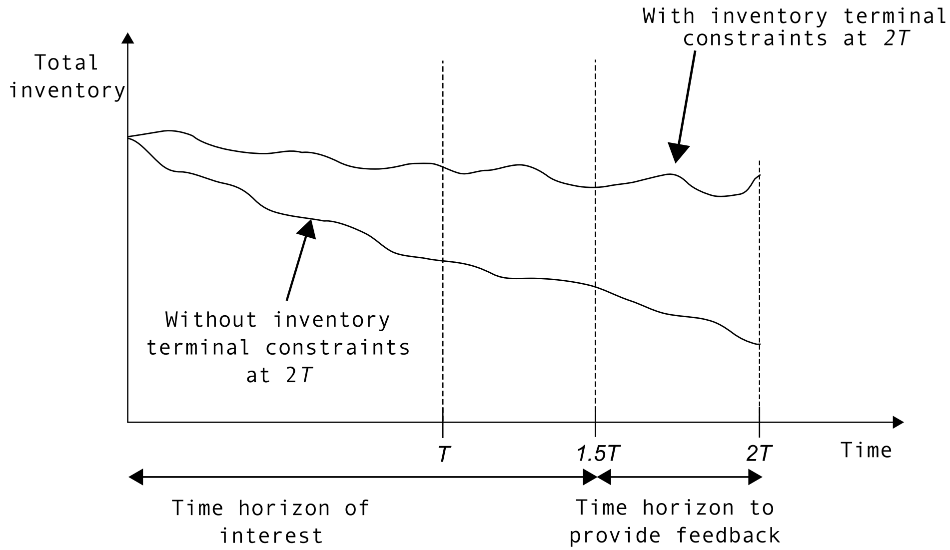
Iter.	Equations	Variables	0-1 Variables	Slots	CPU (s)	RGap (%)	Obj
1	10,072	12,516	3,350	-	3,600	14.1	6,936
2	13,977	19,500	2,384	9	100	0.0	-2,970
3	20,155	26,402	4,473	9	3,600	5.0	534
4	21,823	31,205	2,576	17	200	0.0	-6,136
5	28,213	38,177	4,673	17	3,600	1.7	-2,127
6	28,461	41,052	2,629	23	100	0.0	-5,290
7	34,914	48,042	4,821	23	3,600	5.4	-1,424
8	36,546	52,836	2,893	31	3,600	0.6	-4,794
9	43,062	59,844	5,032	31	3,600	6.2	-1,162
10	43,416	62,750	3,004	37	3,600	0.7	-4,291

Obj - value of objective function, profit, but including penalties for violation of some constraints.

Model improvement to meet process characteristics

First Gantt chart presented at the plant





Features of the process not captured:

1. Minimum run lengths (to keep process stability)
2. Relation between production time of substrate and substrate + coating (specific setup time)
3. Control of the inventory at the end of the time horizon

Initial model limitations:

1. Transition times across time periods
   (a) model only allowed transitions at the end of the time period
2. Cullet storage, consumption and production

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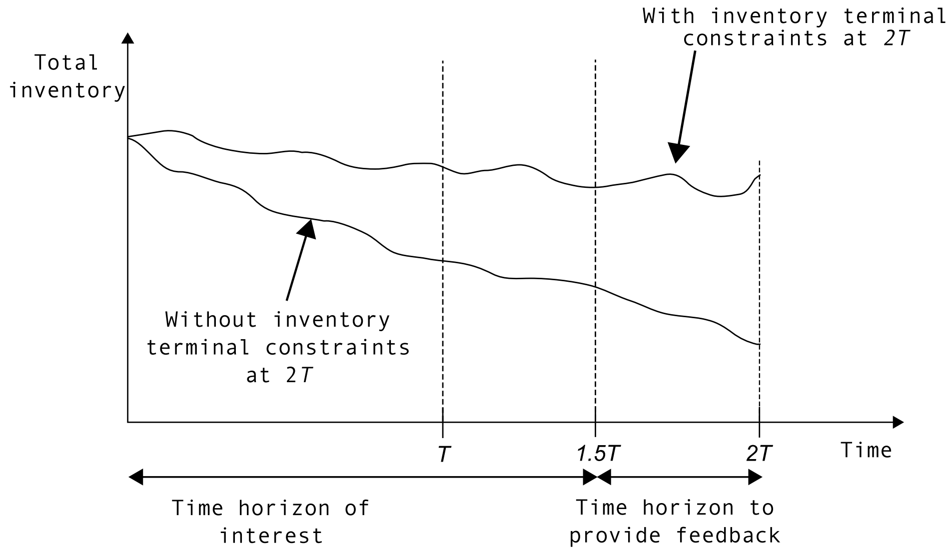

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Features added to the model

Definition of a family of pseudo-products, and the products are the members of the family

- 0-1 variables are defined over the pseudo-products
- Each pseudo-products aggregate the production time of all members of the family (products)

$$\tilde{\theta}_{i,t} = \sum_{p \in FAM_i} \tilde{\theta 2}_{p,t} + \delta_p YP_{p,t} \qquad \forall i \in I, t \in T$$

- Inventory levels are calculated for each product

$$INV_{p,t} - BCKL_{p,t} = INV_{p,t-1} - BCKL_{p,t-1} + r_p \tilde{\theta 2}_{p,t} - S_{p,t} \qquad \forall p \in P, t \in T$$

- Production time of the substrate must be equal to the production time of the substrate + coating

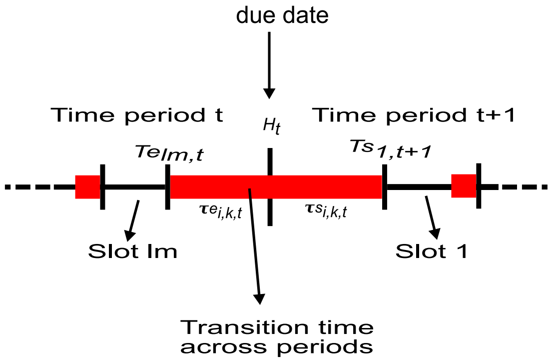
Changeovers across time periods (Lima and Grossmann, 2011)

$$\tau_{i,k} TRT_{i,k,t} = \tau e_{i,k,t} + \tau s_{i,k,t+1} \quad \forall i,k \in I, t \in T$$

$$Te_{l,t} + \sum_{i \in I} \sum_{k \neq i \in I} \tau e_{i,k,t} = HT_t \quad \forall l \in LL, t \in TS$$

$$Ts_{l,t} = \sum_{i \in I} \sum_{k \in I} \tau s_{i,k,t} + HT_{t-1} \quad \forall l \in LF, t \in T$$

$$\sum_{i \in I} \sum_{k \in I} \tau s_{i,k,t} \; + \; \sum_{i \in I} \sum_{l \in L} \theta_{i,l,t} \; + \; \sum_{i \in I} \sum_{k \in I} \sum_{l \in L} \tau_{i,k} Z_{i,k,l,t} \; +$$
$$+ \sum_{i \in I} \sum_{k \in I} \tau e_{i,k,t} = H_t \, \forall t \in T$$



Features added to the model (cont.)

Minimum run length across time periods are enforced using:

$$\tilde{\theta}_{i,t} \quad + \quad \sum_{t' \in B_{i,t}} TPB_{i,t'} \quad + \quad \sum_{t' \in A_{i,t}} TPA_{i,t'} \quad \geq \quad MRL_i\, YOP_{i,t} \, \forall i \in IM,$$

Production time t + Production time $t-1$ + Production time $t+1$

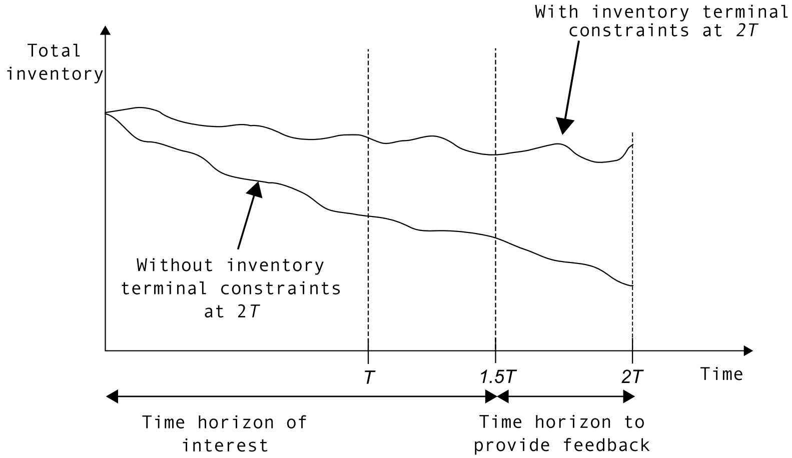
the processing time of $t-1$, $\tilde{\theta}_{i,t-1}$, and t,$\tilde{\theta}_{i,t}$, are only used if there is a transition between the same product across the time period ($TRT_{i,i,t} = 1$) :

$$\begin{bmatrix} TRT_{i,i,t} \\ TPB_{i,t} = \tilde{\theta}_{i,t} \end{bmatrix} \vee \begin{bmatrix} \neg TRT_{i,i,t} \\ TPB_{i,t} = 0 \end{bmatrix} \qquad \forall i \in IM, t \in T$$

$$\begin{bmatrix} TRT_{i,i,t-1} \\ TPA_{i,t} = \tilde{\theta}_{i,t} \end{bmatrix} \vee \begin{bmatrix} \neg TRT_{i,i,t-1} \\ TPA_{i,t} = 0 \end{bmatrix} \qquad \forall i \in IM, t \in T$$

Inventory at the end of the time horizon

Approach implemented: a minimum inventory above the safety stock for each product, which is enforced *N* time periods after the time horizon of interest.



Alternative approaches:

1. Re-schedule periodically and postpone the depletion of the inventory

2. Add the value of the final inventory in the objective function

   - the final inventory value is a piecewise linear function of the final inventory (Martin et al. 1993)

Days of sales	Value
1-60	90%
61-120	70%

Remark: If in the optimal solution exists backlog, the product with the lower price among the products that may have backlog will be selected.

Cullet model

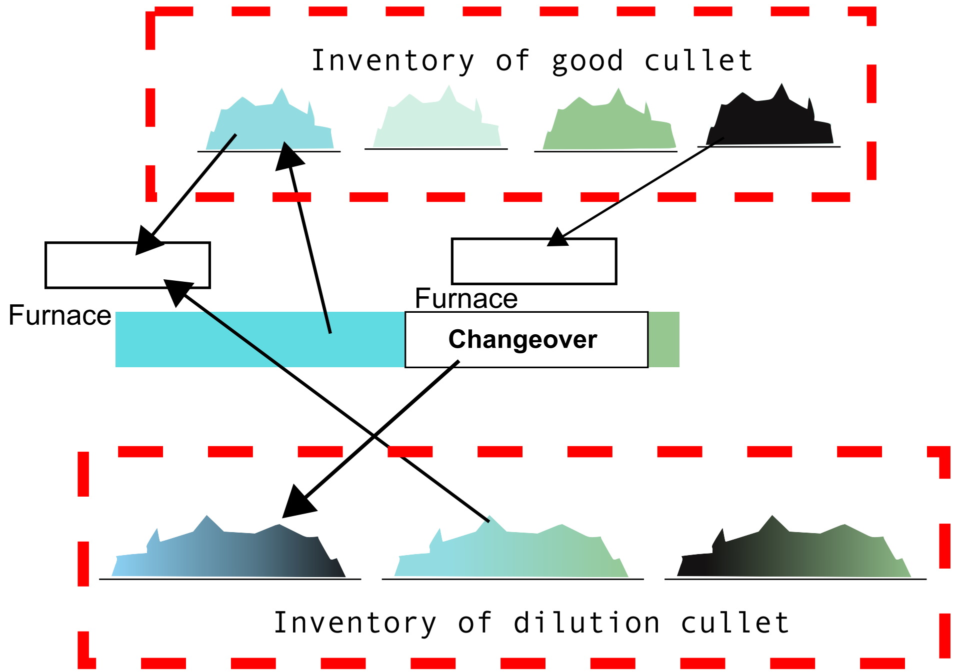
- Mass balance to the process (good and dilution cullet)
  - The consumption of cullet is a nonlinear function of the production length
  - δ-form **piecewise linear formulation (PLF)** to approximate the cullet consumption
  - The cullet consumption profile has 2 operating options for the total, good, and dilution cullet, ($tc1$,$dc1$,$gc1$) or ($tc2$,$dc2$,$gc2$)

$$
\begin{bmatrix}
Z1_{i,l,t} \\
tc1_{i,l,m,t} = b_{i,0,t} ZNS_{i,l,m,t} + \left(\dfrac{b_{i,1,t} - b_{i,0,t}}{a_{i,1,t} - a_{i,0,t}}\right) \delta^1_{i,l,m,t} + \left(\dfrac{b_{i,2,t} - b_{i,1,t}}{a_{i,2,t} - a_{i,1,t}}\right) \delta^2_{i,l,m,t} \\
dc1_{i,l,m,t} \leq db_{i,0,t} ZNS_{i,l,m,t} + \left(\dfrac{db_{i,1,t} - db_{i,0,t}}{a_{i,1,t} - a_{i,0,t}}\right) \delta^1_{i,l,m,t} + \left(\dfrac{db_{i,2,t} - db_{i,1,t}}{a_{i,2,t} - a_{i,1,t}}\right) \delta^2_{i,l,m,t}
\end{bmatrix} \vee
$$

$$
\begin{bmatrix}
\neg Z1_{i,l,t} \\
tc2_{i,l,m,t} = b'_{i,0,t} ZNS_{i,l,m,t} + \left(\dfrac{b'_{i,1,t} - b'_{i,0,t}}{a'_{i,1,t} - a'_{i,0,t}}\right) \delta^1_{i,l,m,t} + \left(\dfrac{b'_{i,2,t} - b'_{i,1,t}}{a'_{i,2,t} - a'_{i,1,t}}\right) \delta^2_{i,l,m,t} \\
dc2_{i,l,m,t} \leq db'_{i,0,t} ZNS_{i,l,m,t} + \left(\dfrac{db'_{i,1,t} - db'_{i,0,t}}{a'_{i,1,t} - a'_{i,0,t}}\right) \delta^1_{i,l,m,t} + \left(\dfrac{db'_{i,2,t} - db'_{i,1,t}}{a'_{i,2,t} - a'_{i,1,t}}\right) \delta^2_{i,l,m,t}
\end{bmatrix}
$$

Cullet model (cont.)

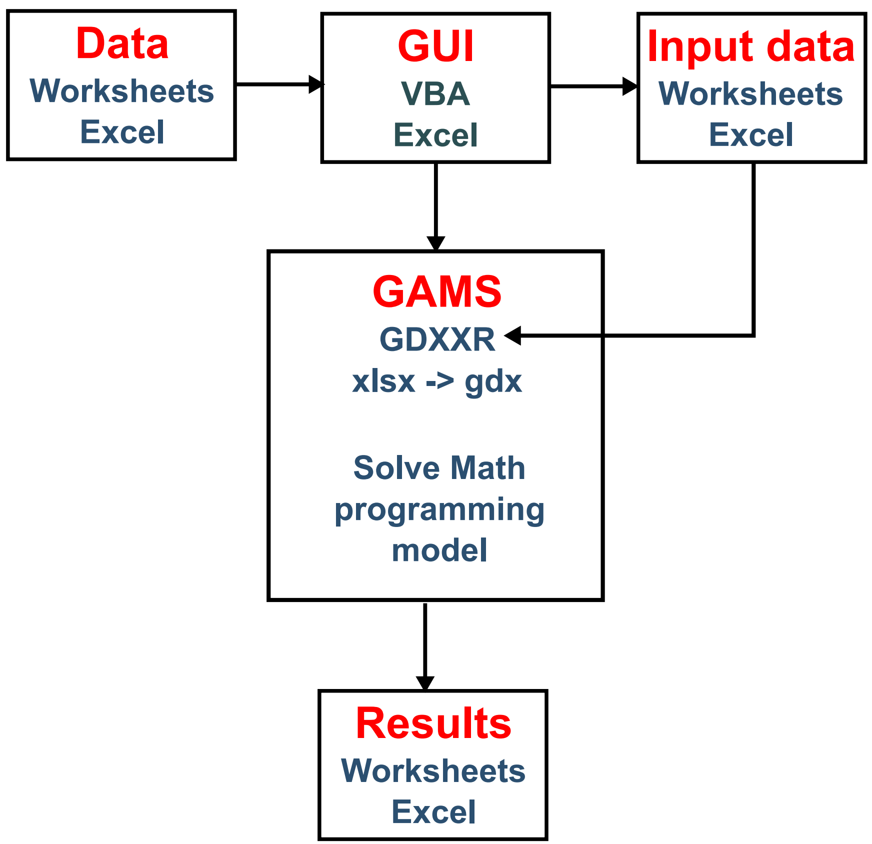
- Mass balance to the inventory (good, and dilution cullet) on a slot basis in the scheduling model and time period basis in the planning model
- Cullet inventory constraints
- Option to sell cullet with a penalty
- Synchronization of cullet storage, consumption and production
  - based on no simultaneous production or consumption of one type of cullet cullet in the same time period.



Implementation of the model

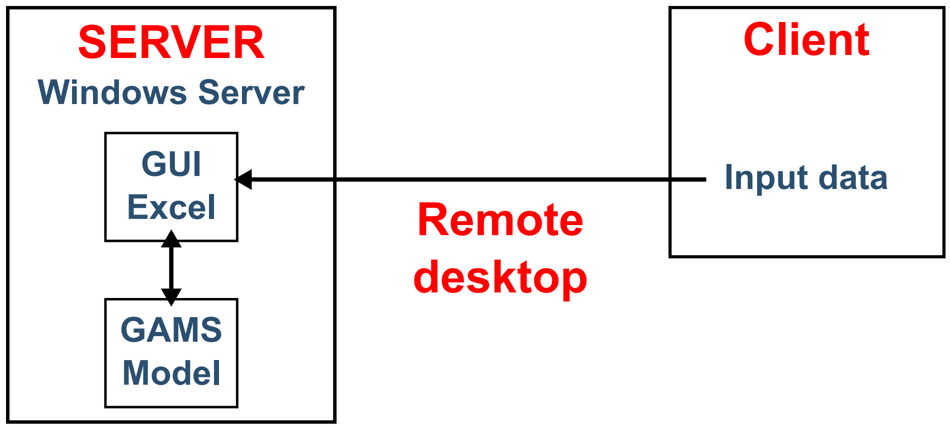
Software structure

- **Main components:** Model, GAMS, Excel
- Graphical User Interface (GUI) developed in VBA for Excel
- Manipulation of input data and output results structure developed in VBA for Excel
- The transfer of data from Excel to GAMS is made using gdx files



Platform

The software is installed in a Server running Windows Server, and the access is made using remote desktop.

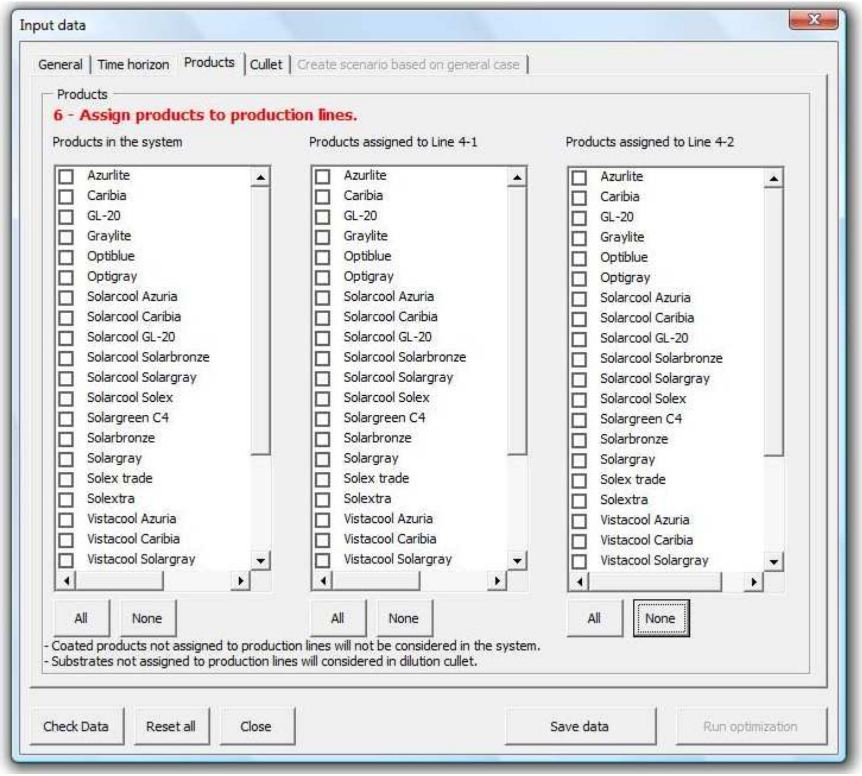


Advantages

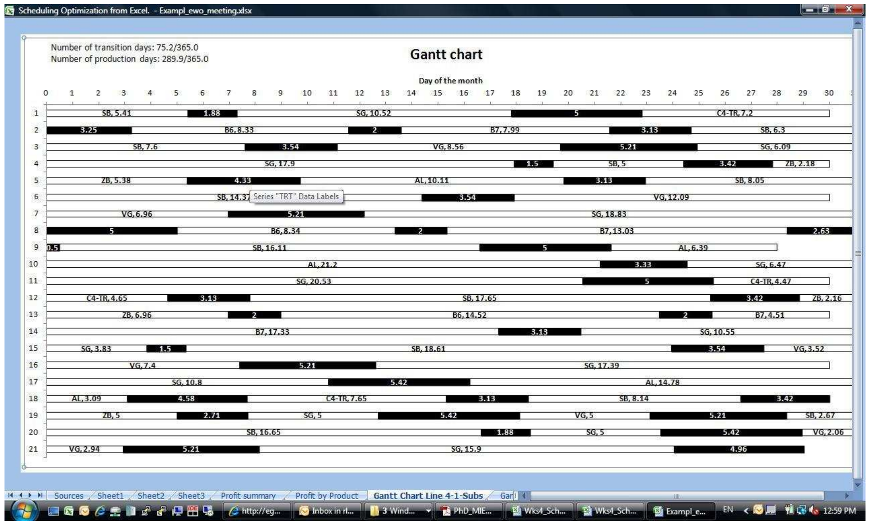
1. The software is only installed in **one machine**.
2. Easy to maintain, update, and **enhance the software**.
3. Log off the system and leave the **optimization running in the server**.

Parts of the front-end of the model

GUI to define parameters of the problem



Gantt chart and inventory results



Results:

- Summary economic results
- Profit contribution by product, detailed results by product
- Gantt charts for both lines, and production description by text (sort by date and products)
- Inventory profiles for all products

Screenshots of cullet results

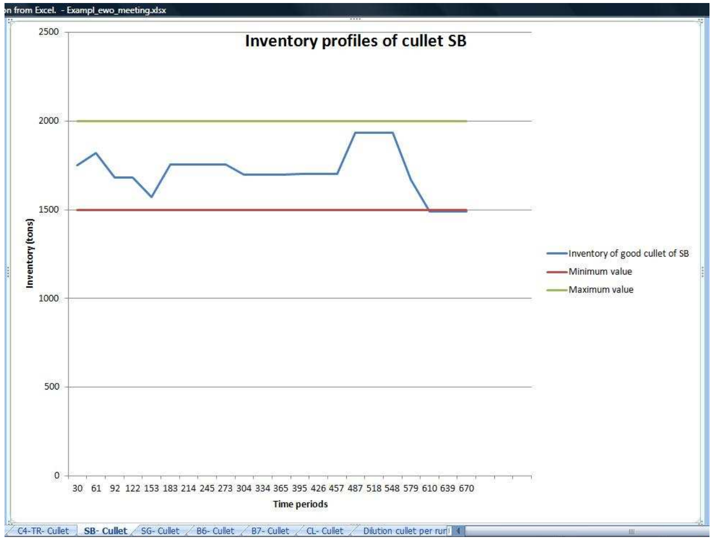
Consumption of dilution cullet bu run

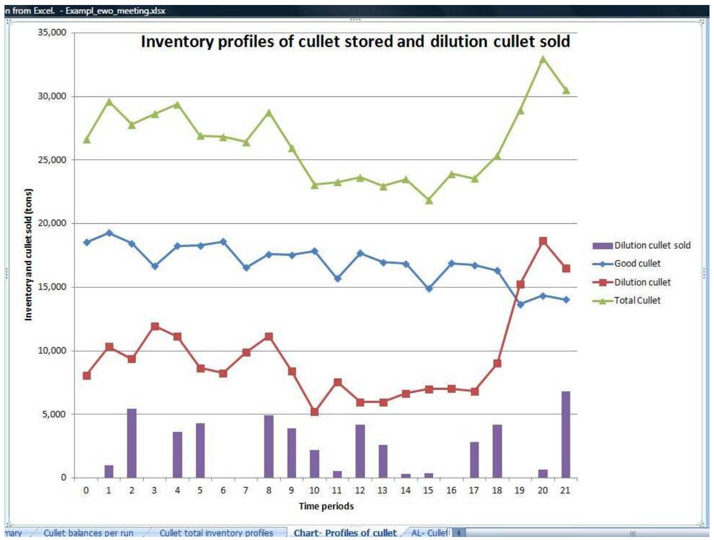
Scheduling Optimization from Excel. - Exampl_ewo_meeting.xlsx

Type and amount of dilution cullet used in each production run (tons)

Dilution cullet		Product run	Time period	Dilution cullet used (tons)
SG	AL	SB	1	294
SB	VG	SG	1	571
C4-TR	CL	C4-TR	1	83
SB	SG	SB	2	772
SG	C4-TR	SB	2	204
VG	SB	VG	3	345
VG	SG	VG	3	1
SB	VG	SG	3	2,702
SB	SG	SB	4	272
C4-TR	CL	AL	5	53
SG	C4-TR	SB	5	1,436
SG	SB	SB	5	995
VG	SG	VG	6	2,575
SB	VG	SG	7	1,820
SG	C4-TR	SB	9	1,355
CL	C4-TR	AL	9	431
VG	SG	SG	10	2,521
SB	VG	SG	10	694
C4-TR	CL	C4-TR	11	105
SG	C4-TR	SB	12	1,617

Cullet charts





Cullet results

- Cullet summary (consumption, generation, accumulation)
- Cullet balances per run
- Inventory profiles for cullet (by color and totals)
- Quality and quantity of dilution cullet used per run

Concluding remarks

- A MILP model for the optimal planning and scheduling of two production lines has been developed.
- The model involves specific features adapted for the lass production.
- The integration of cullet management and glass production planning and scheduling is a new approach.
- The model is implemented in a software tool using Excel as front-end.
- The software started to be used by the supply chain group in parallel with the current approach.

Future model extensions

1. Include the **thickness** as an additional attribute.
    - It will increase the size of the model in terms of continuous variables, and equations.
    - There is no changeover or setup between products with same color with different thicknesses
2. Assessment of the **impact of the variability** of the main parameters in the robustness of the production schedule and economic impact.
    - Incorporate the uncertainty of some parameters in the decision making process.

Scientists study what is.

***Engineers** create what never was.*

Von Kármán

I figure it how to run it.

And I got results back!

JS

References

Martin, C.H., Dent, D.C., Eckhart, J.C. (1993). Integrated production, distribution, and inventory planning at Libbey-Owens. Interfaces, 23(3), 68-78.

Erdirik-Dogan, M.,Grossmann,I.E.(2008).Simultaneous planning and scheduling of single-stage multi-product continuous plants with parallel lines. Computers & Chemical Engineering, 32(11), 2664-2683.

Lima, R.M., Grossmann, I.E., Jiao, Y., Long-term scheduling of a single-unit multi-product continuous process to manufacture high performance glass . Computers& Chemical Engineering, 35, 554-574.