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Mathematical methods for productivity and quality in the production of plastic films

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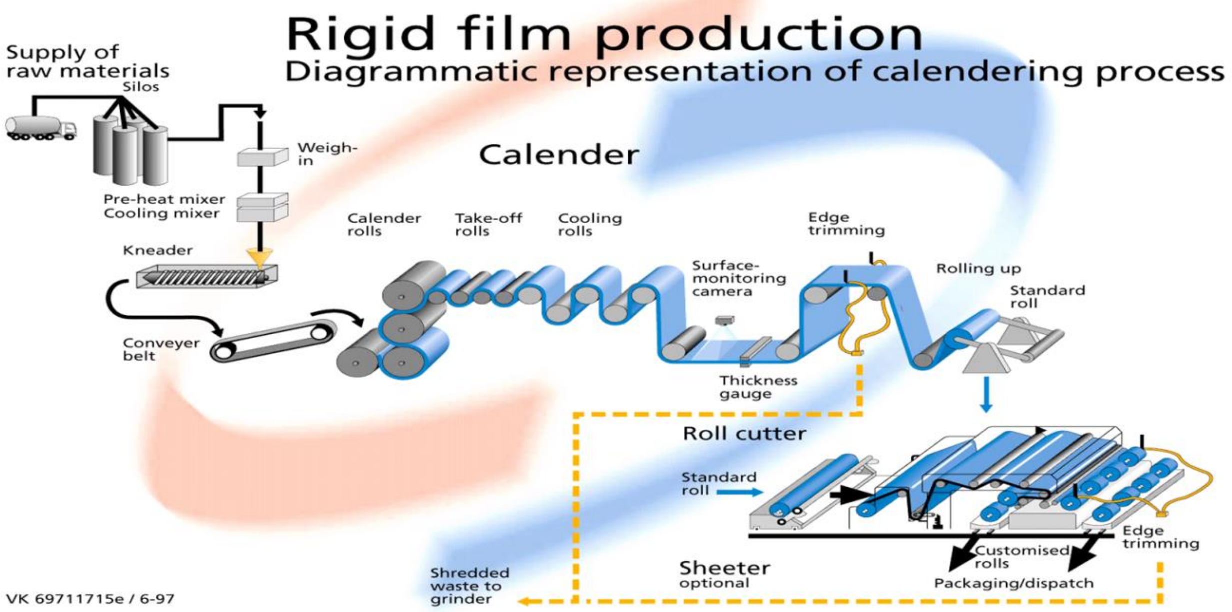
Film production with calendering



Properties/ quality of kp-films from rigid PVC

- Thickness tolerance MDO, TDO
- Shrink MDO, TDO
- Mistake-free (black points, specks, ...)
- Surface roughness, luster
- Barrier again water vapor and/or oxygen
- Thermoforming
- Printability
- Color consistency
- Mechanical and thermal properties

Kp-machinery

41 calender and calandrette in 9 sites with a capacity of rigid PVC of about 400 Tto/year

Technology

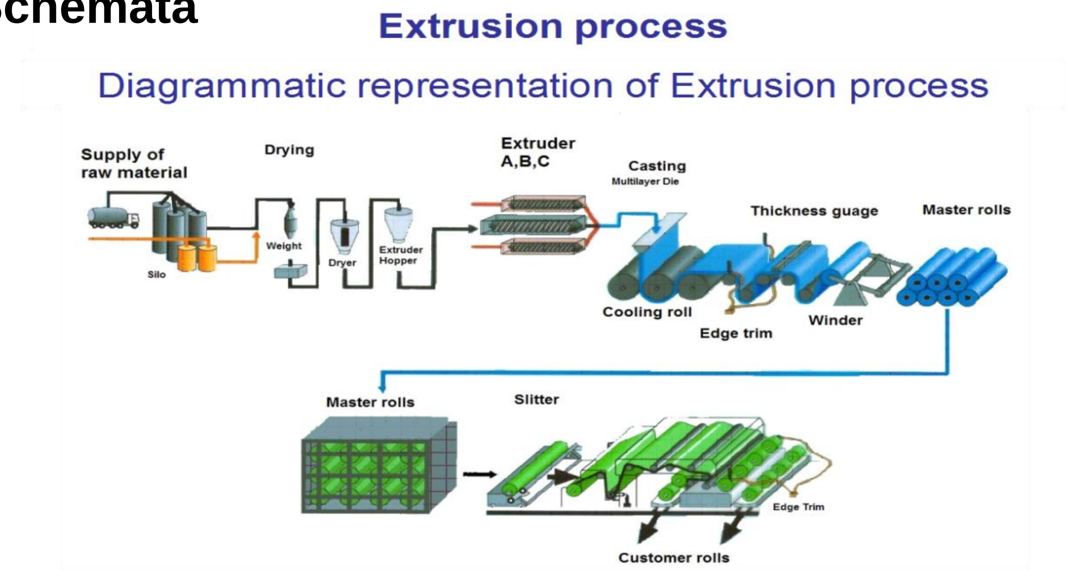
- Silo storage and Big-Bag
- Dosing
- Mixing (heat and cool)
- Gelation (Buss-kneader, extrusion)
- Important roll temperature, roll velocity
  roll diameter, surface, roughness
  roll parallelism
- Inline measurement
  thickness, surface defects, color, gloss

Specification

- Thickness from 25 to 1200 µm
- Width from 100 to 2500 mm
- Surface: gloss or different embossed
- Shrinkage from 0 to 60 % MDO
- Color : all Lab

Film production with cast extrusion

Schemata



Properties/ quality of kp-films from extrusion

- Multilayer:
  - Coextrusion, up to 7 layers; multiple polymer combinations
  - Lamination, thermal and aqueous; multiple polymer combinations
  - Side-by-side (XY) structures
- In line MDO or TDO for shrink applications
- Foaming
- PCR-content
- FDA, Reach compliance
- Colors, tints, color consistency, bi-color, light blocking, UV inhibitors
- Surface roughness, luster
- Corona treatment

Kp-machinery

- Global presence, with 35 extrusion lines in 12 sites (Americas, Europe, Asia).
- Global Capacity of over 250ktons/year

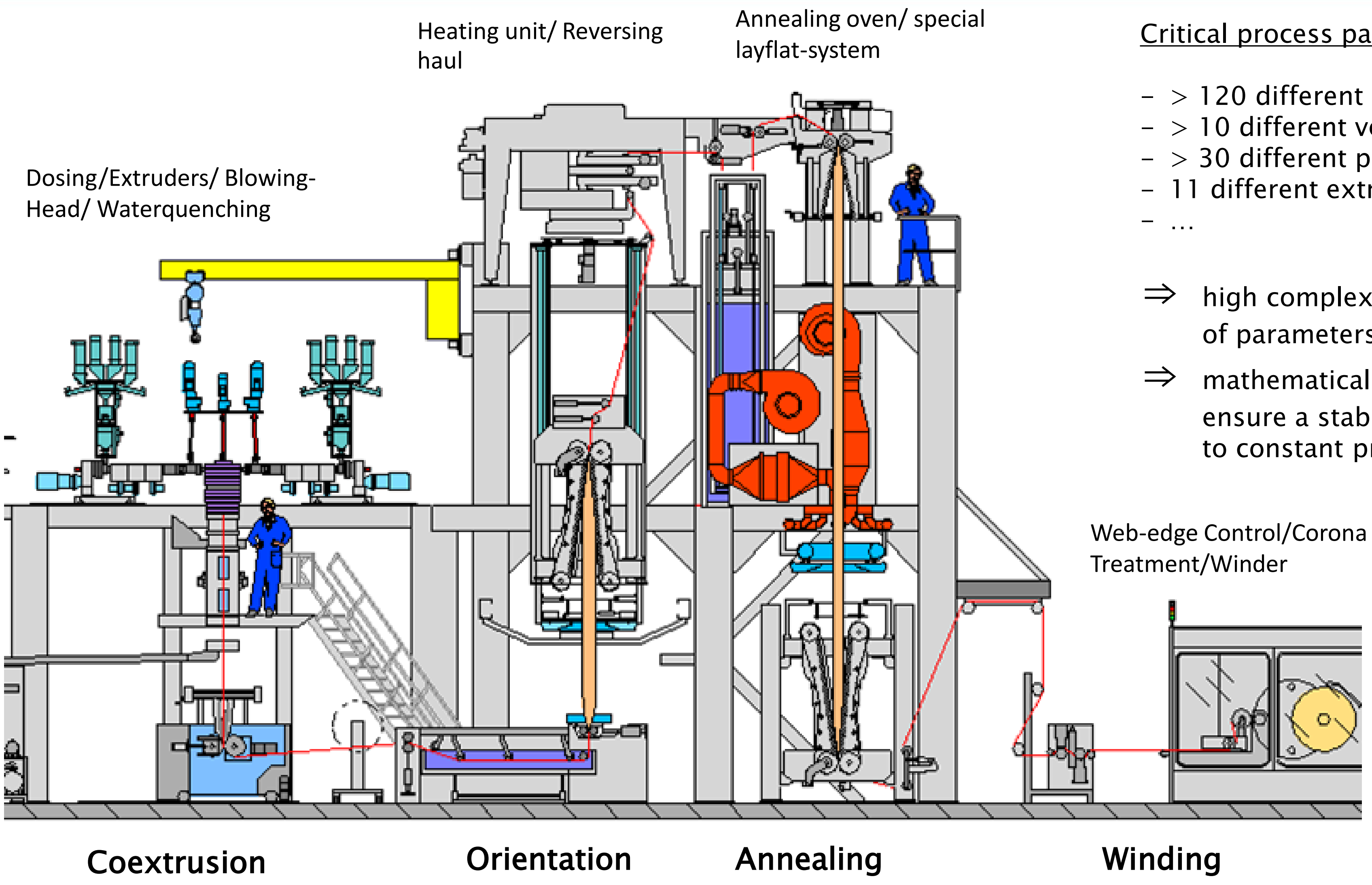
Technology

- Incoming raw materials, drying, blending
- Extrusion, decontamination, melt filtration, foam incorporation
- Layer combination, profile control
- Blown film, cast film, rollstack
- Lamination, Coating, Winding
- In-Line Measurement
  - Vision System (OCS)
  - iV
  - Color, gloss, haze
  - Gauge

Specification

- Thickness from 20 to 1650 µm
- Width up to 2200mm (6.2m for TDO)
- Recycle content up to 100%
- Shrinkage from 0 to 80%, MDO or TDO
- Color tolerance

Film production with blowing extrusion



Critical process parameters:

- > 120 different temperatures
- > 10 different velocities
- > 30 different pressure values
- 11 different extruder output
- …

⇒ high complexity of the interplay of parameters

⇒ mathematical methods to ensure a stable process leading to constant product quality

Material- and process values in film production

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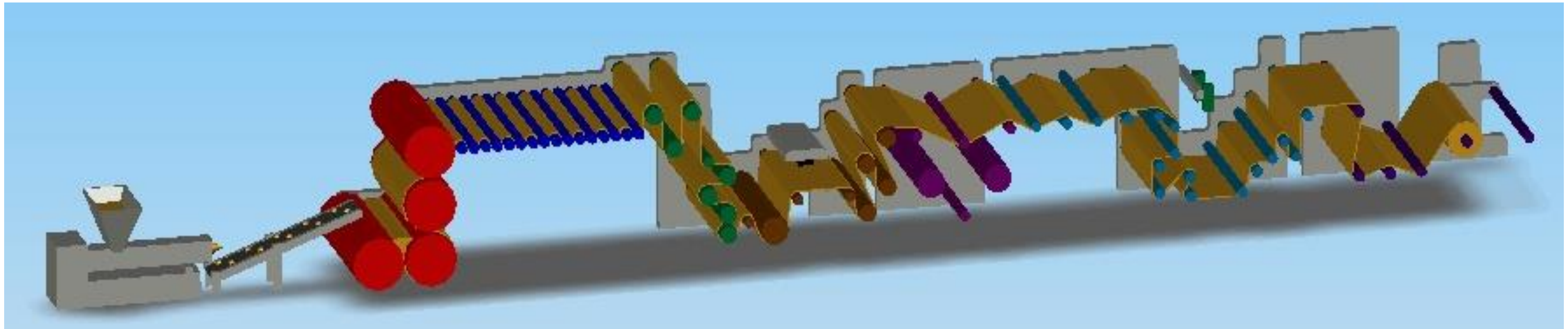
Material value
- Density ρ
- Viscosity η = f (T,Ẏ)
- Flow index n
- Specific heat capacity c_p
- Head conduction λ
- Heat transfer k
- Grain size distribution Δd
- Melting temperature T_S

Machine value
- Construction of calender or extrusion
- Construction of nozzle
- Roll diameter D
- Distance h
- Roughness Rz

Process value
- Velocity v
- Different velocity   Δv
- Temperature T
- Temperature field T(x,y)
- Output Q
- Pressure p

Quality value
- Thickness
- Glos
- Color Lab
- Mistake
- Shrinkage
- strength



By calendering :   about 100 values with 800 relationsship
example: higher temperature ➔ lower viscosity ➔ lower pressure ➔ higher output with lower thickness

Development objectives of Klöckner Pentaplast for calendering film

- High quality (law thickness distribution, no surface defects such as black spots, specks and holes, small color tolerances, optimal shrinkage)

- High poductivity (quick changeovers, high velocity, high degree of automation)
- New characteristics for customers and service

Quality of the final product will depend on (cooperation with Prof.Chistyakova)

1. optimal gelling in the extruder
2. Optimal dosing of liquid colors in the extruder
3. optimal thickness distribution by roll-bending and Acrossing
4. optimal cooling of the film for high transparency
5. Optimal shrinkage of polymeric films
6. Small number of films errors

Special characteristics of polymeric films

7. Anticounterfeiting
8. Thermoforming process
9. Ecological properties of different polymeric films
10. Plant development

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Basic equations for process optimization

Equation of the conservation of mass

$$\frac{\partial \varrho}{\partial t} + \frac{\partial}{\partial x}(\varrho v_x) + \frac{\partial}{\partial y}(\varrho v_y) + \frac{\partial}{\partial z}(\varrho v_z) = 0$$

Equation of motion

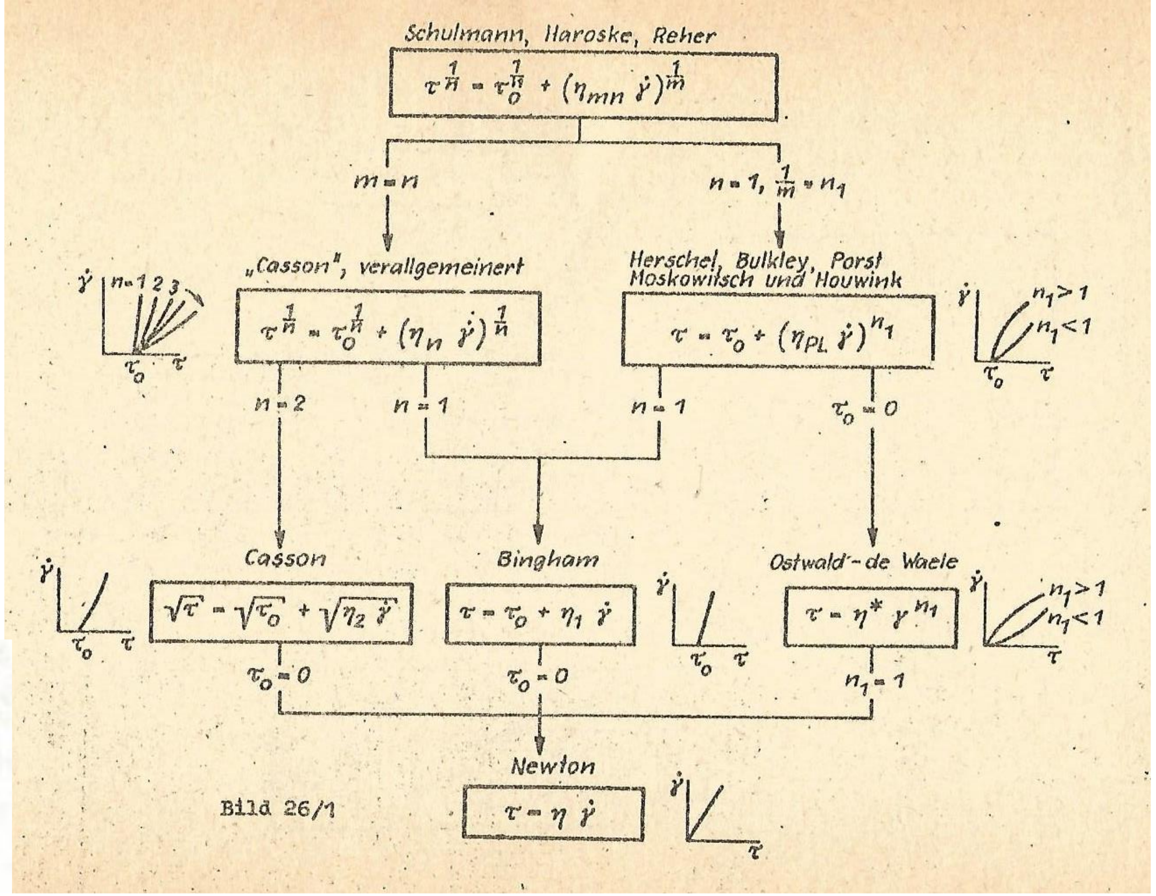
Die Bewegungsgleichung in kartesischen Koordinaten:

$$\frac{\partial P}{\partial x} = \frac{\partial p_{xx}}{\partial x} + \frac{\partial p_{yx}}{\partial y} + \frac{\partial p_{zx}}{\partial z} - \varrho\left(\frac{\partial v_x}{\partial t} + v_x \frac{\partial v_x}{\partial x} + v_y \frac{\partial v_x}{\partial y} + v_z \frac{\partial v_x}{\partial z}\right)$$

Heat balance

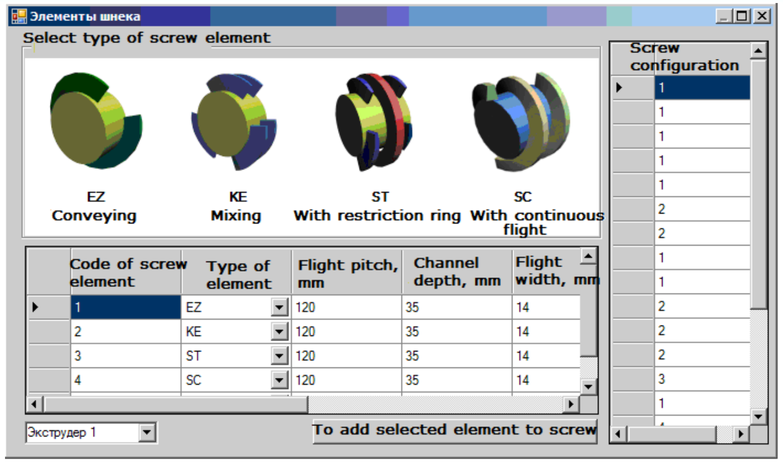
$$\varrho c_v \frac{dT}{dt} = -(\nabla \cdot q) - T\left(\frac{\partial P}{\partial T}\right)_\varrho (\nabla \cdot v) + (p : \nabla \cdot v)$$

c_v spezifische Wärme bei konstantem Volumen
q Vektor des Wärmestromes
$q = -k \nabla T$
k Wärmeleitfähigkeit der Flüssigkeit



rheological state function

1. optimal gelling in the extruder



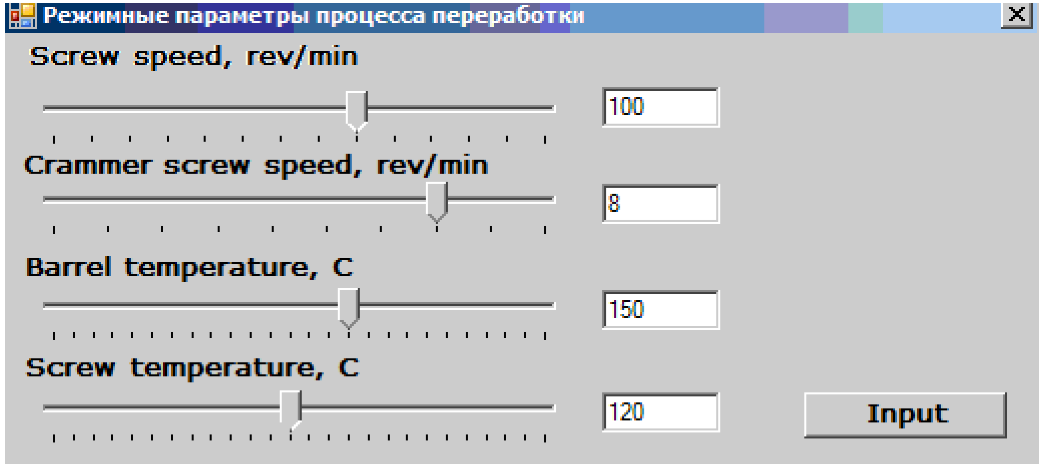
$$\int_0^{H^j} v_x^j\,dy = \dot{Q}_\delta^j + \dot{Q}_s^j,\quad W^j \cdot \int_0^{H^j} v_z^j\,dy = Q,$$

$$\partial P^j/\partial x = \partial \tau_{xy}^j/\partial y,\quad \partial P^j/\partial z = \partial \tau_{zy}^j/\partial y,$$

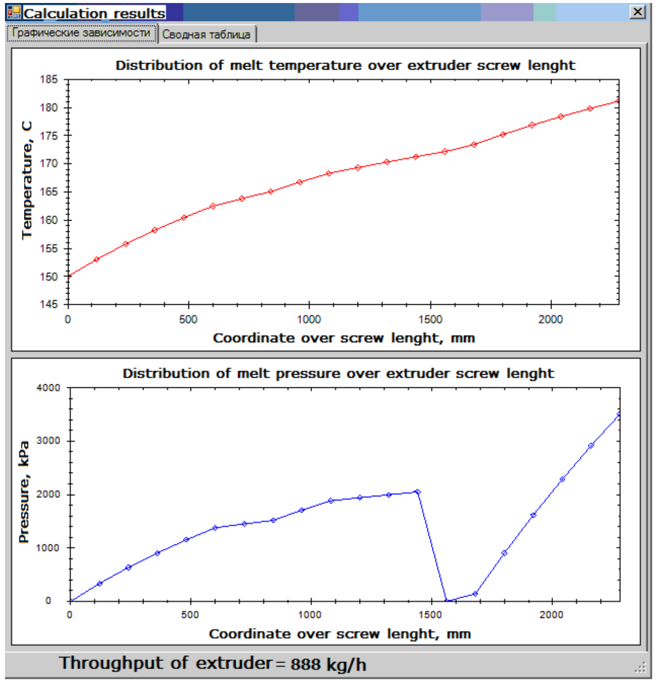
$$\tau_{xy}^j = \eta^j \cdot \left(dv_x^j/dy\right),\quad \tau_{zy}^j = \eta^j \cdot \left(dv_z^j/dy\right),$$

$$\mu^j = \mu_0 \cdot \exp\left[-b \cdot \left(T^j - T_0\right)\right],$$

$$\eta^j = \mu^j \cdot \left[\left(dv_x^j/dy\right)^2 + \left(dv_z^j/dy\right)^2\right]^{(n-1)/2},$$



$$\rho \cdot c_P \cdot Q \cdot dT^j/dz = -W^j \cdot \left[\alpha_b \cdot \left(T^j - T_b\right) + \alpha_{scr} \cdot \left(T^j - T_{scr}\right)\right] +$$
$$+W^j \cdot \left(U_x \cdot \tau_{xb}^j + U_z \cdot \tau_{zb}^j\right) - W^j \cdot \left(\dot{Q}_\delta^j + \dot{Q}_s^j\right) \cdot \partial P^j/\partial x - Q \cdot \partial P^j/\partial z,$$



Advantage:

- Control of the entire calender line over kneader
- faster changeover times by prediction

2. Optimal dosing of liquid colors in the extruder

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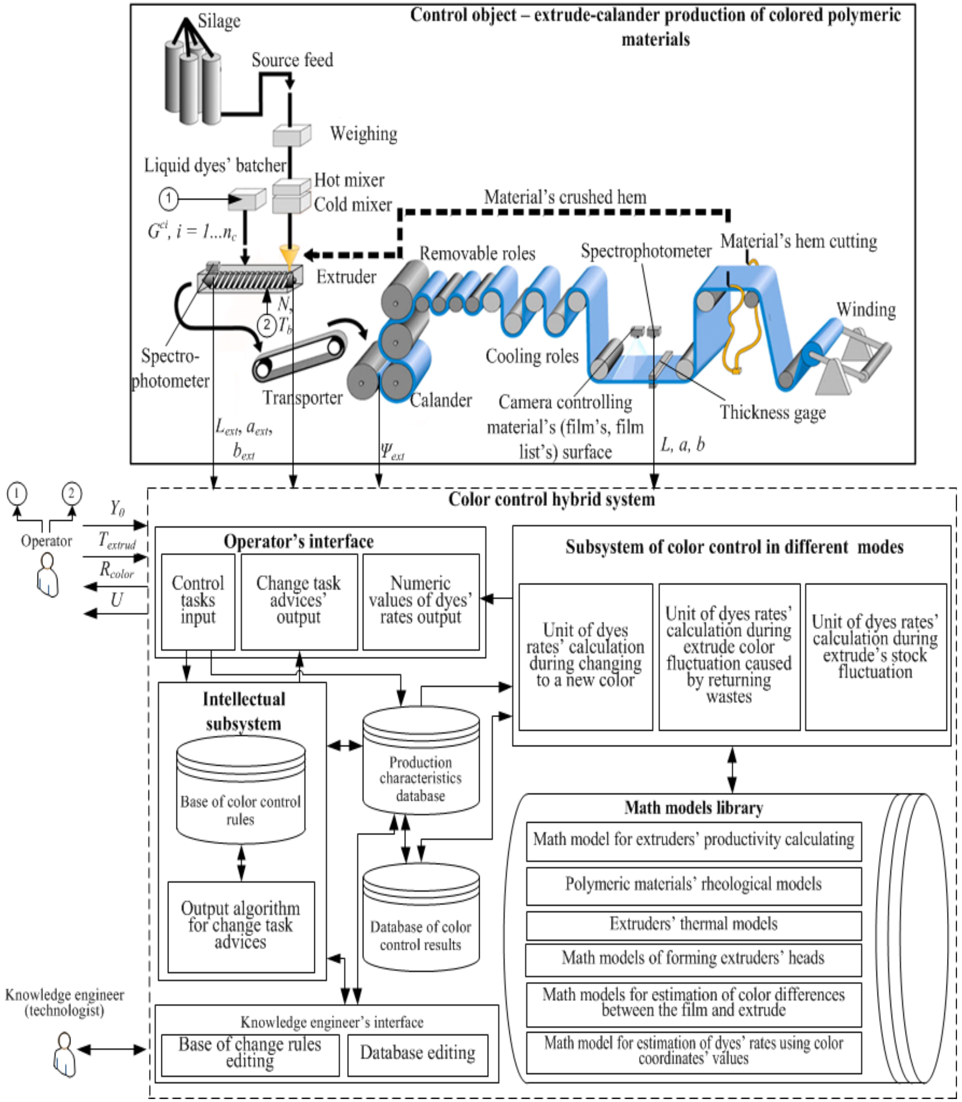
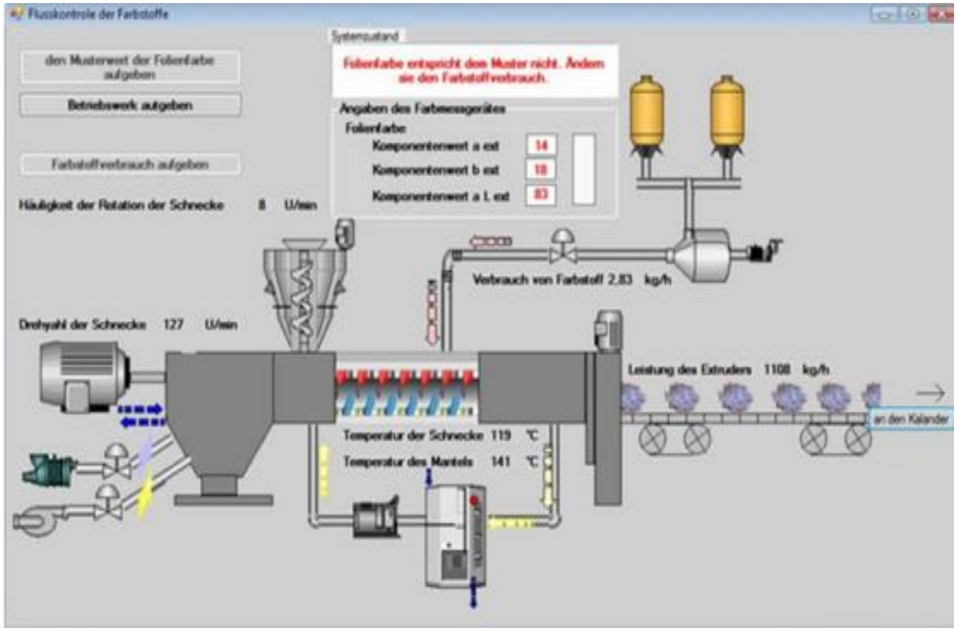
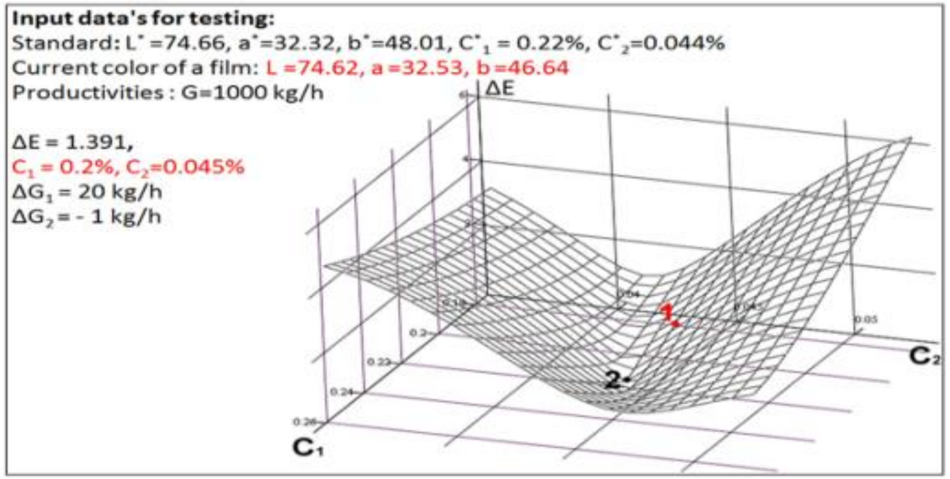


Advantage:

- Reduce color change time from 20 – 30 min to 3-4 min
- rapid correction possibility in color variations dE < 0,5





3. Optimal thickness distribution by roll-bending and acrossing

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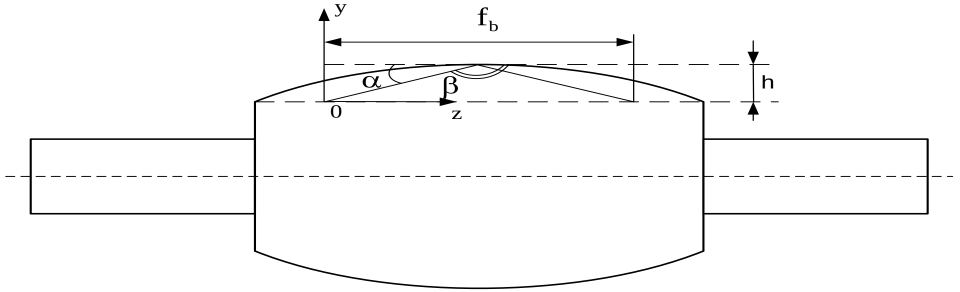
- mathematical model of the bombage



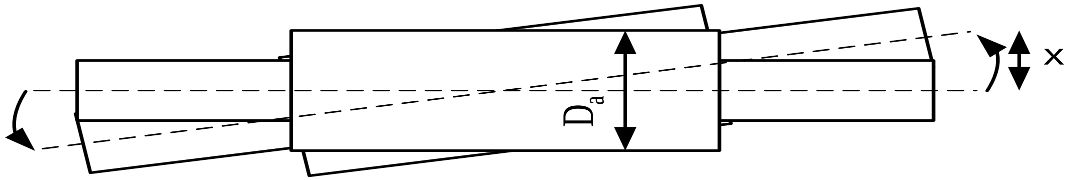
Thickness profil for film

$$S_h(z,h) = \frac{h}{1-\sin\alpha}\cdot\left\{\sin\left[\alpha + \frac{\beta-\alpha}{w}\cdot\left(z + \frac{w-f_b}{2}\right)\right] - \sin\alpha\right\}$$

Start and end of the bending

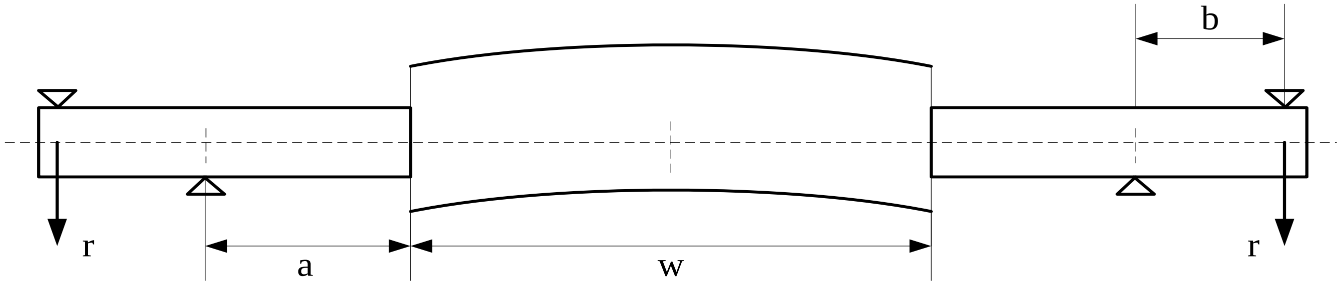
$$\alpha = \frac{\pi}{180}\cdot 20 + \frac{7}{18}\cdot\pi\cdot\frac{(w-f_b)}{w}, \quad \beta = \frac{\pi}{180}\cdot 160 - \frac{7}{18}\cdot\pi\cdot\frac{(w-f_b)}{w}$$

- mathematical model of accrossing



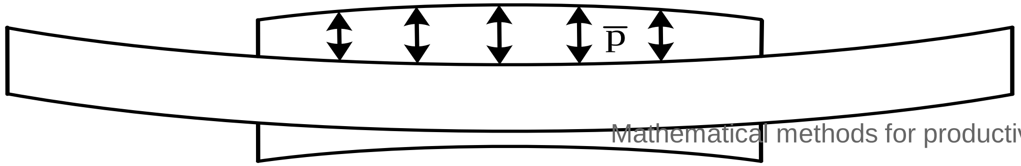
$$S_x(z,x) = \left(\sqrt{\left(x\cdot\frac{f_b}{w}\right)^2 + D_a^2} - D_a\right)\cdot\left(1 - \frac{2\cdot z}{f_b}\right)^2$$

- mathematical model of roll bending



$$S_r(z,r) = \frac{r\cdot b}{2\cdot E\cdot I_в}\cdot\left[z_3{}^2 - w\cdot z_3 - a\cdot\left(w + \frac{I_в}{I_ш}\cdot a\right)\right]$$

- **mathematical modell of roll deflection**



$$S_p(z) = d_2\cdot z^4 + d_1\cdot z + d_0, \quad d_k = f_k[S(z), p], \; k = 0,1,2$$

3. Optimal thickness distribution by roll-bending and acrossing

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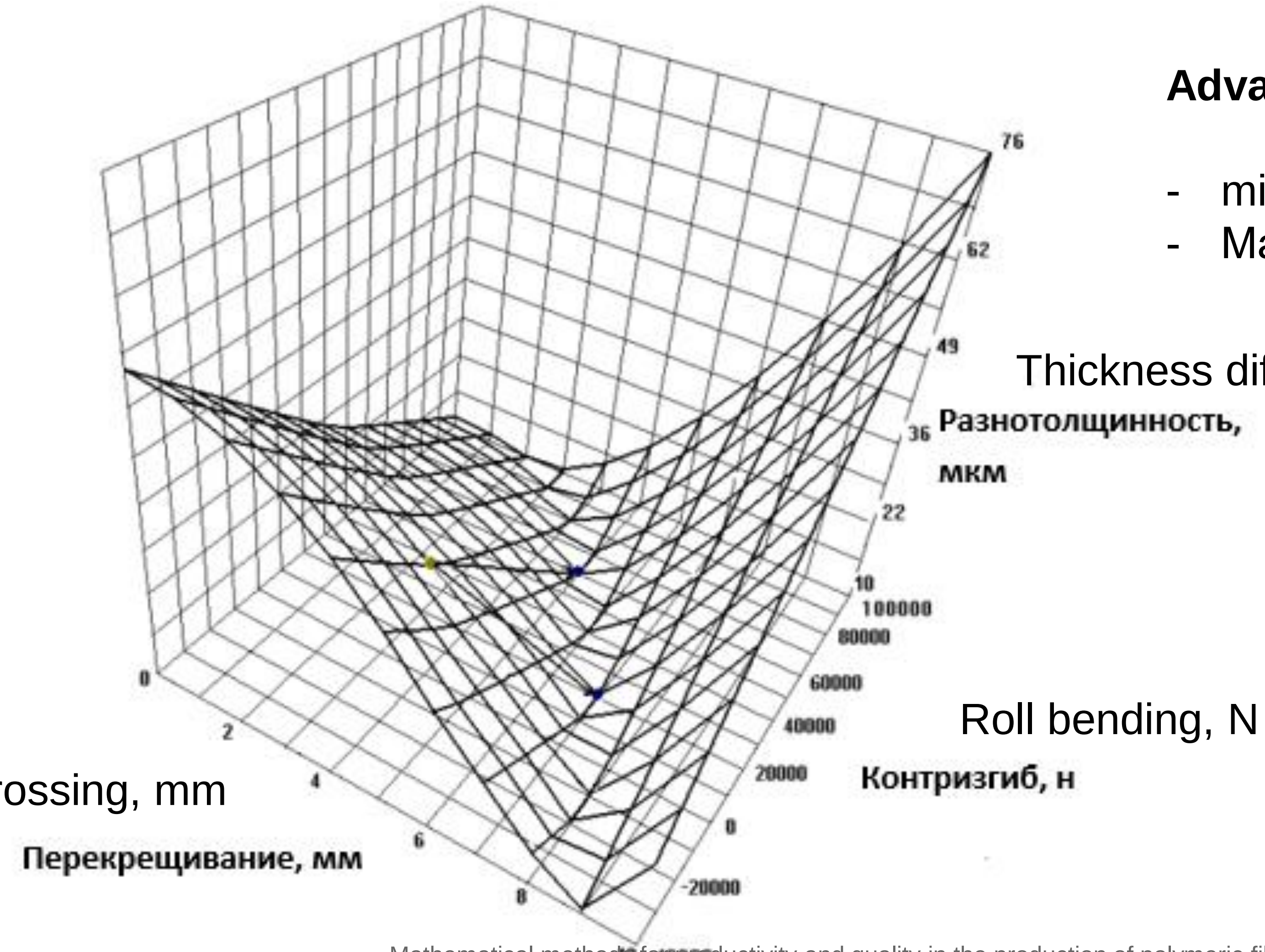
Depending on the film thickness difference of roll bending and accrosing to minimize the difference



Thickness difference, µm

Roll bending, N

Accrossing, mm

Advantage:

- minimum thickness variations
- Material savings in m² - sale

4. optimal cooling of the film for high transparency

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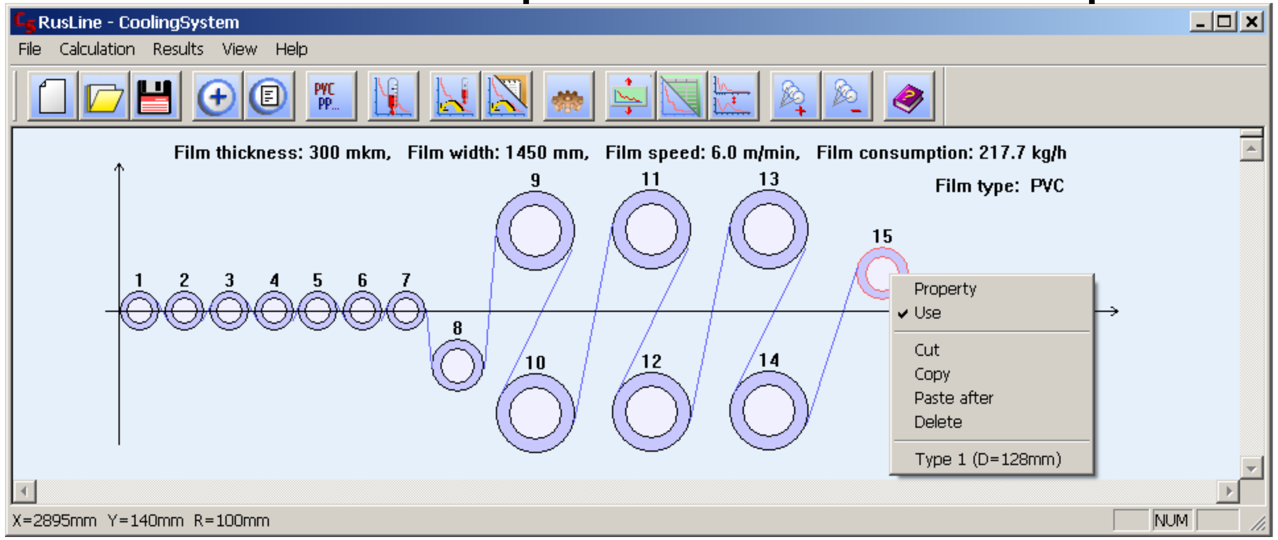
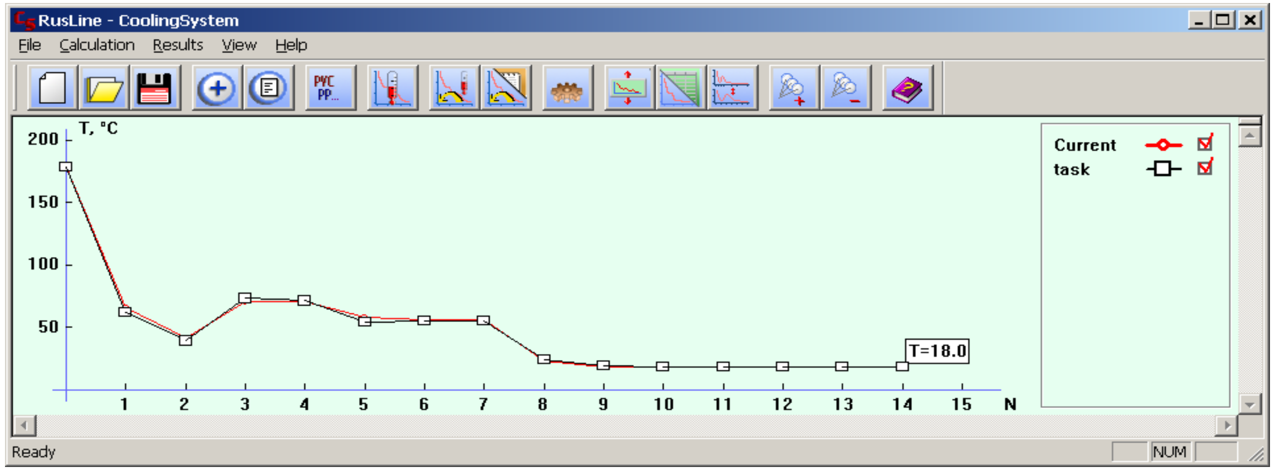
Prediction of the optimum uniform temperature cooling for a high film transparent





Temperature control is critical for transparency, the film shrinkage and the gloss of the film surface - crucial quality criteria.

The model allows the prediction of the optimum rolling temperatures.

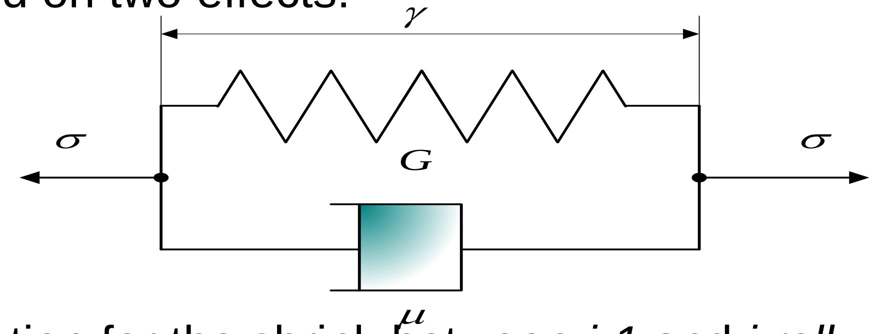
Advantage:

- Reduce of change time
- Reduce complaint for false shrink, gloss or transparency

5. Optimal shrinkage of polymeric films

Modell Muni-Rivlin

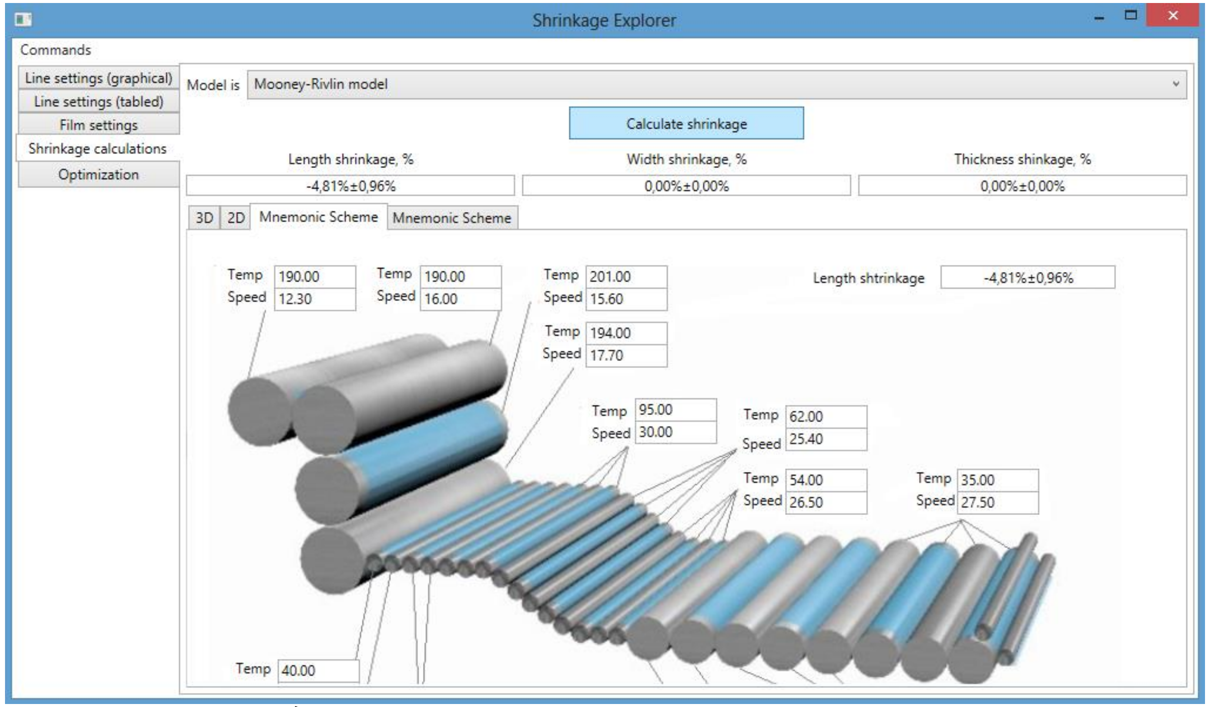
- based on two effects:



- Equation for the shrink between *i-1* and *i roll*:

$$C\cdot S_l^{\,6} + A\cdot S_l^{\,4} + \left(B - C - 2^{n+1}\left(\frac{U_{i-1}\cdot n}{L(1-n)}\right)^{n}\cdot\left[1-\frac{U_{i-1}}{Ui}\right]^{1-n}\cdot\frac{H_{i-1}W_{i-1}}{HW}\,\mu_0 e^{-b(T_{i+1}-T_i)}\right)\cdot S_l^{\,3} - A\cdot S_l^{\,2} - B = 0$$

- Total shrinkage is calculated from the sum of the orientations between the rollers of a calender line



Advantage:

- Reducing changeover time
- Reduce of Complaint for false shrink

6. small number of films errors

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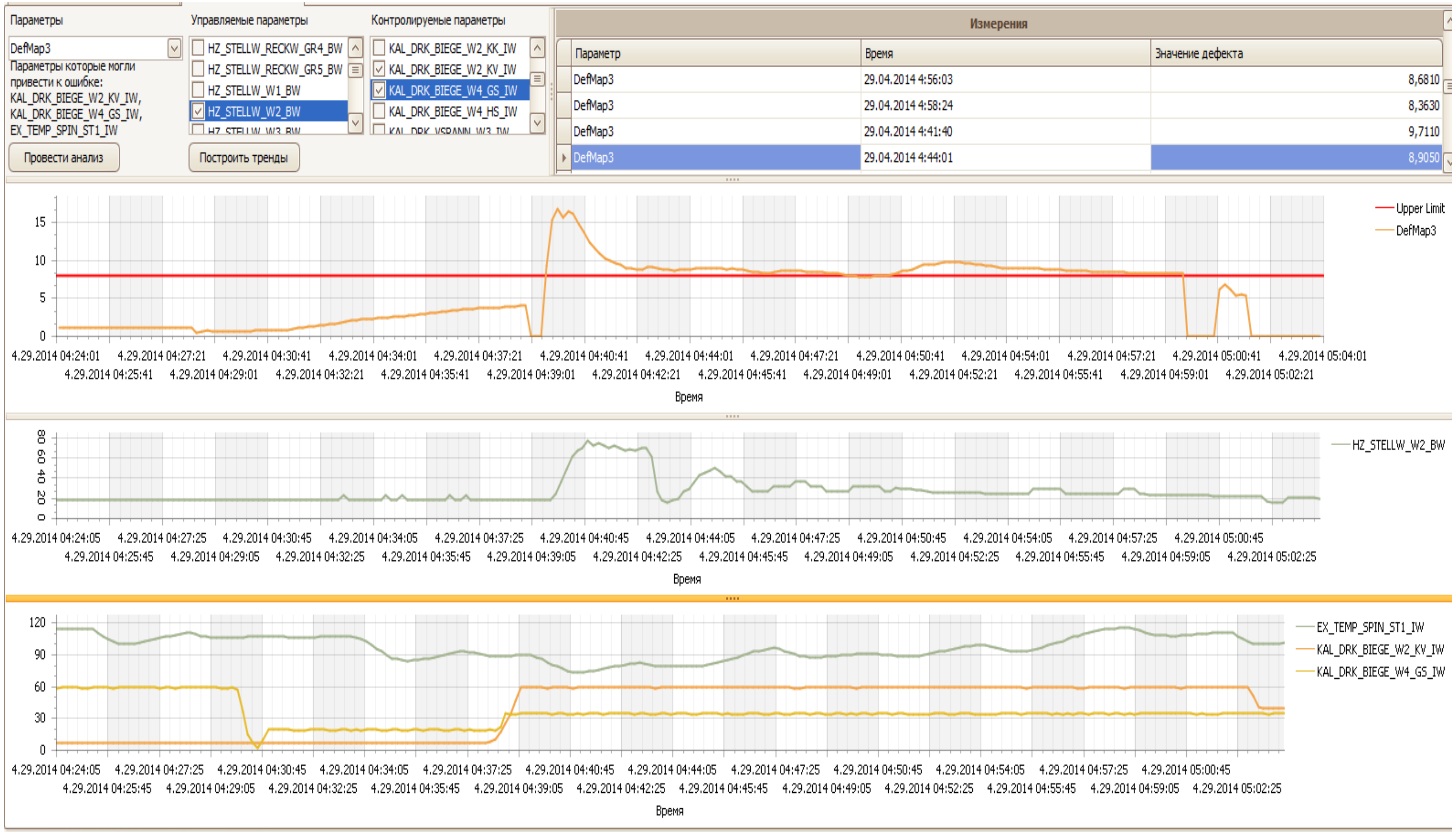
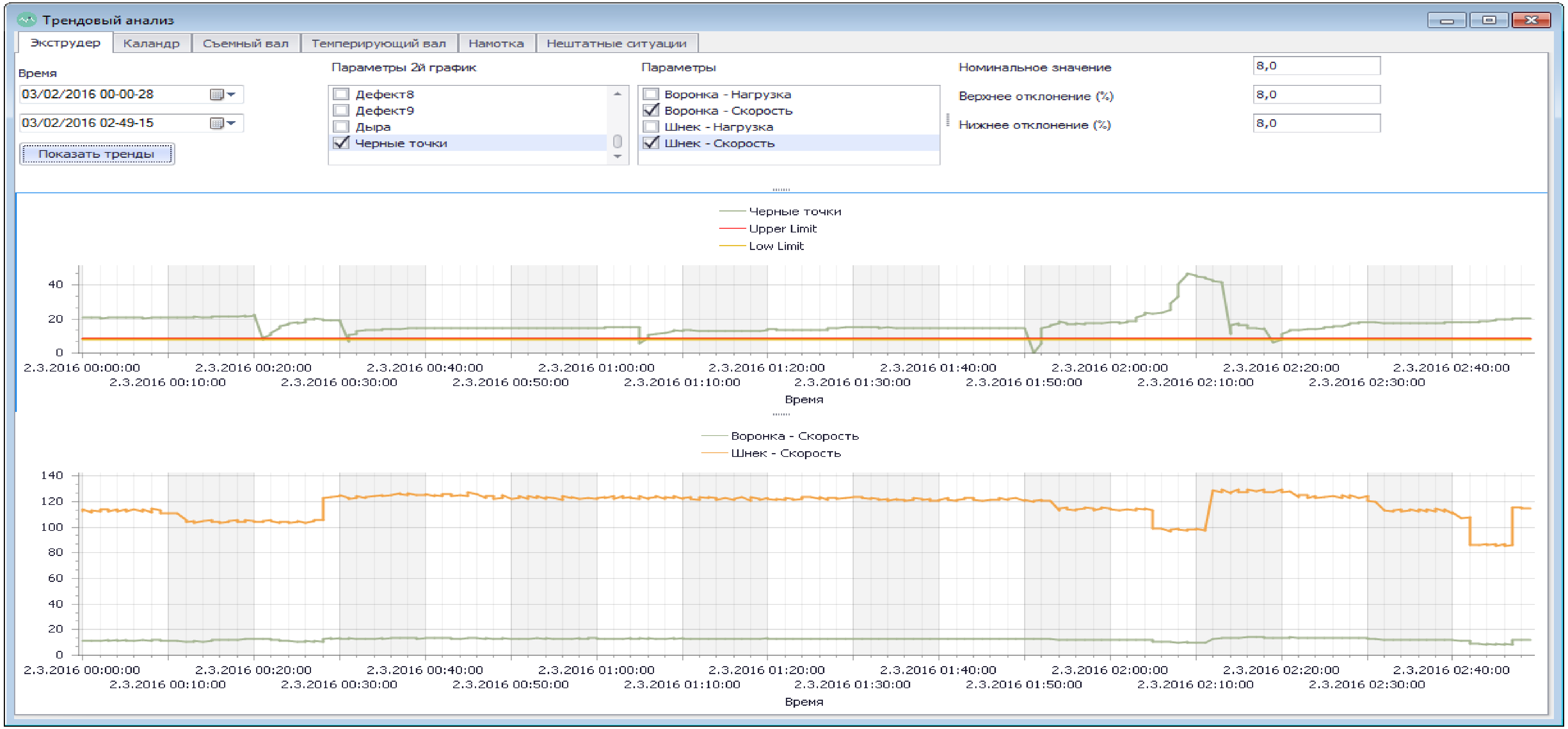


Data Mining and processing of quality data, process data and material data for the purpose of determining the causes of film failure!

Advantage:

- SPC
- Reduce of claim
- More good production

6. small number of films errors



7. Anticounterfeiting

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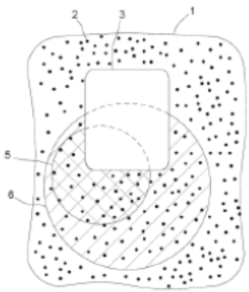
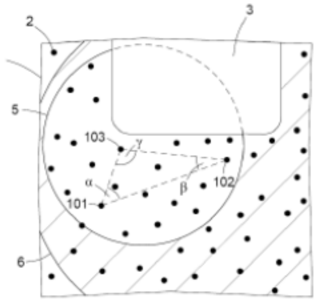


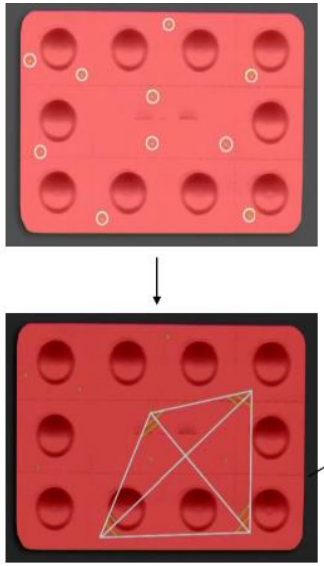


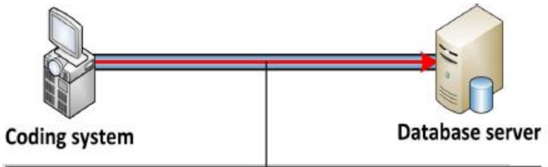
kp produces films with IR and UV pigments 0.001% (costs less than 0.01 C / m²)

- User receives an image with 3.4 or 5 points
- The software determines the angle of 1.4 or 10 triangles
- The check is to compare the angle of the existing triangles

This version is completely anti-counterfeit, since it is based on a random distribution of points!

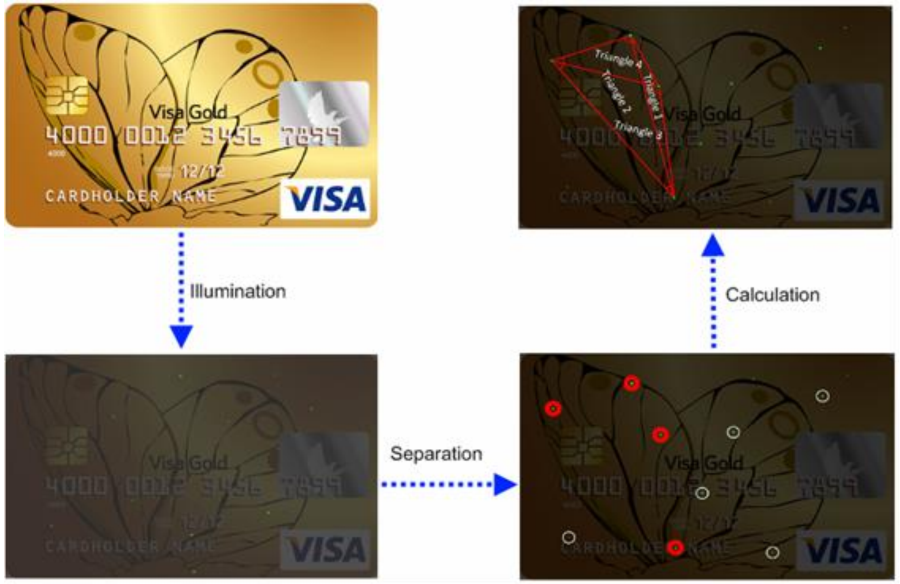
kp-Patent: DE 10 2008 032 781 A1
WO 2010/003585 A1
vom 14.01.2010



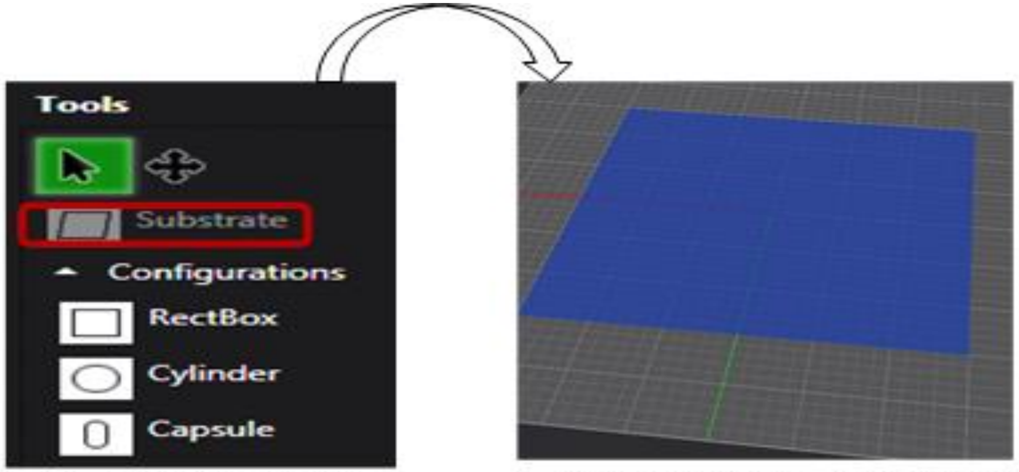


Identification data												
Card num	4000 0012 3456 7899											
Triangle 1			Triangle 2			Triangle 3			Triangle 4			
α_1	β_1	γ_1	α_2	β_2	γ_2	α_3	β_3	γ_3	α_4	β_4	γ_4	
7	13	160	26	68	94	32	48	100	33	35	112	
Valid thru	12.2012											
Type	Verpackung/ Kreditkarte											

Different points in a pharma blister

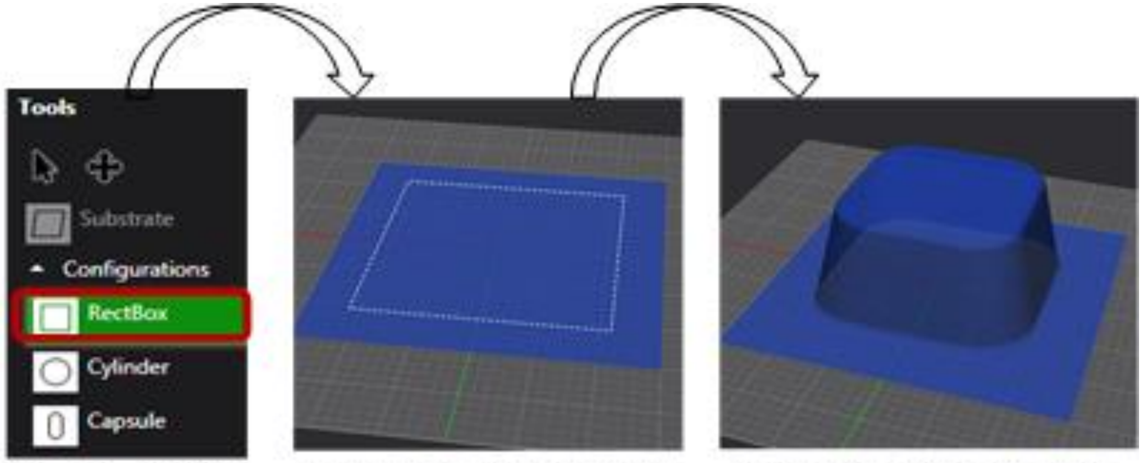


8. Thermoforming process



1. In toolbar choose tool «Substrate».

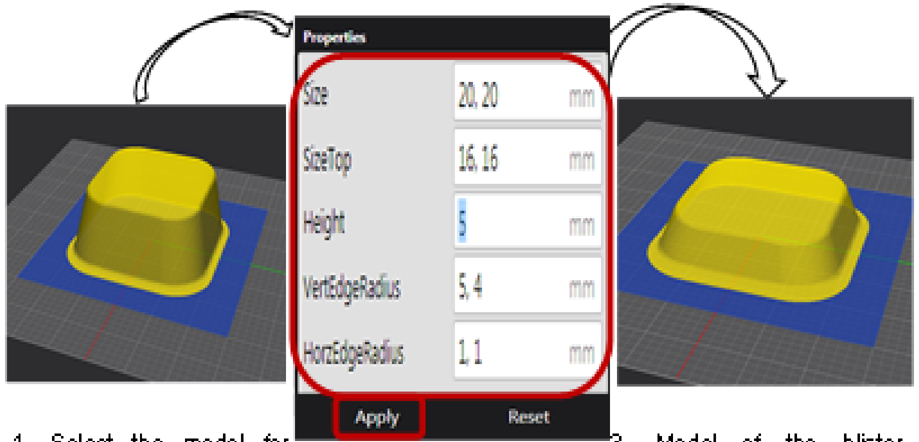
2. Substrate can be created with mouse click in work area.



3. In toolbar choose type of the geometry configuration.

4. In the work area choose blister placement using mouse.

5. Create 3D model of the blister by clicking mouse left button in the work area.



1. Select the model for editing using the right click.

2. In property panel enter required values of geometric parameters and click "Apply"

3. Model of the blister changes according to entered values of geometric parameters.

Advantage:

Optimize wall thickness distribution

- Even for high barrier
- high strength

9. Ecological properties of different polymeric films

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Oekobil 4 is a kp internal software which was developed by TU St.Petersburg to show the ecological comparison of different packaging material

Goal of Oekobil 4 is comparing the ecological characteristics of:

- PS
- PET
- PVC
- PP
- HDPE
- LDPE
- PVdC
- PLA
- $CaCO_3$

- tin plate
- glass
- aluminum
- paper
- carton

Energy consumption (MJ/kg)

Air quantity (m³/kg)

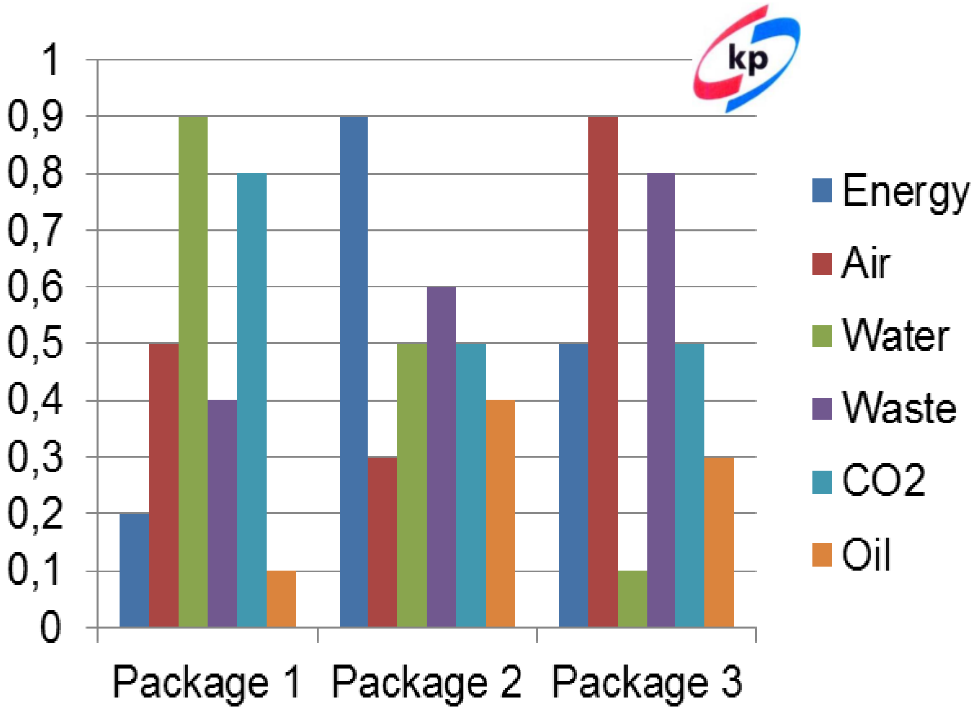
Water quantity (dm³/kg)

Solid waste (cm³/kg)

CO2 emissions (mg/kg)

Oil consumption (g/kg)

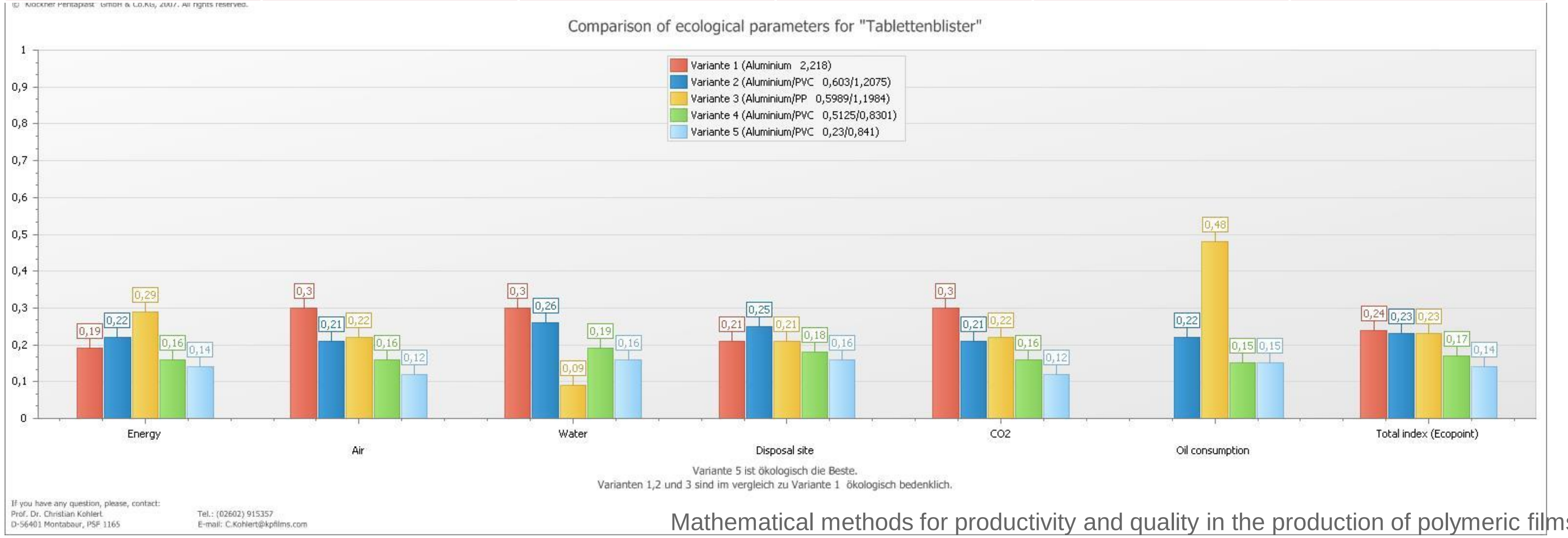
Water consumption (l/kg)

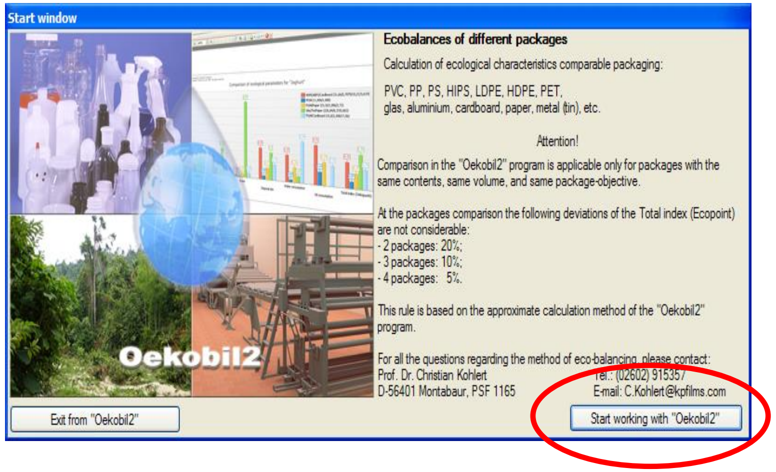


Eco Index Packaging 1 = (Energy cons. / total energy cons.) * 30% + (Air cons. / total air cons.) * 20% … + (oil cons. / total oil cons.) * 5 % + ……..

9. Ecological properties of different polymeric films

Packaging	Aluminum	PVC, aluminum	PP, aluminum	PVC, aluminum	PVC, paper, aluminum
Capacity (pieces)	10	10	10	10	10
Bottom film (gramms)	Aluminum 1,3262	PVC 1,2075	PP 1,1984	PVC 0,8301	PVC 0,841
Top film (gramms)	Aluminum 0,8922	Aluminum 0,603	Aluminum 0,5989	Aluminum 0,5125	Paper, aluminum 0,23





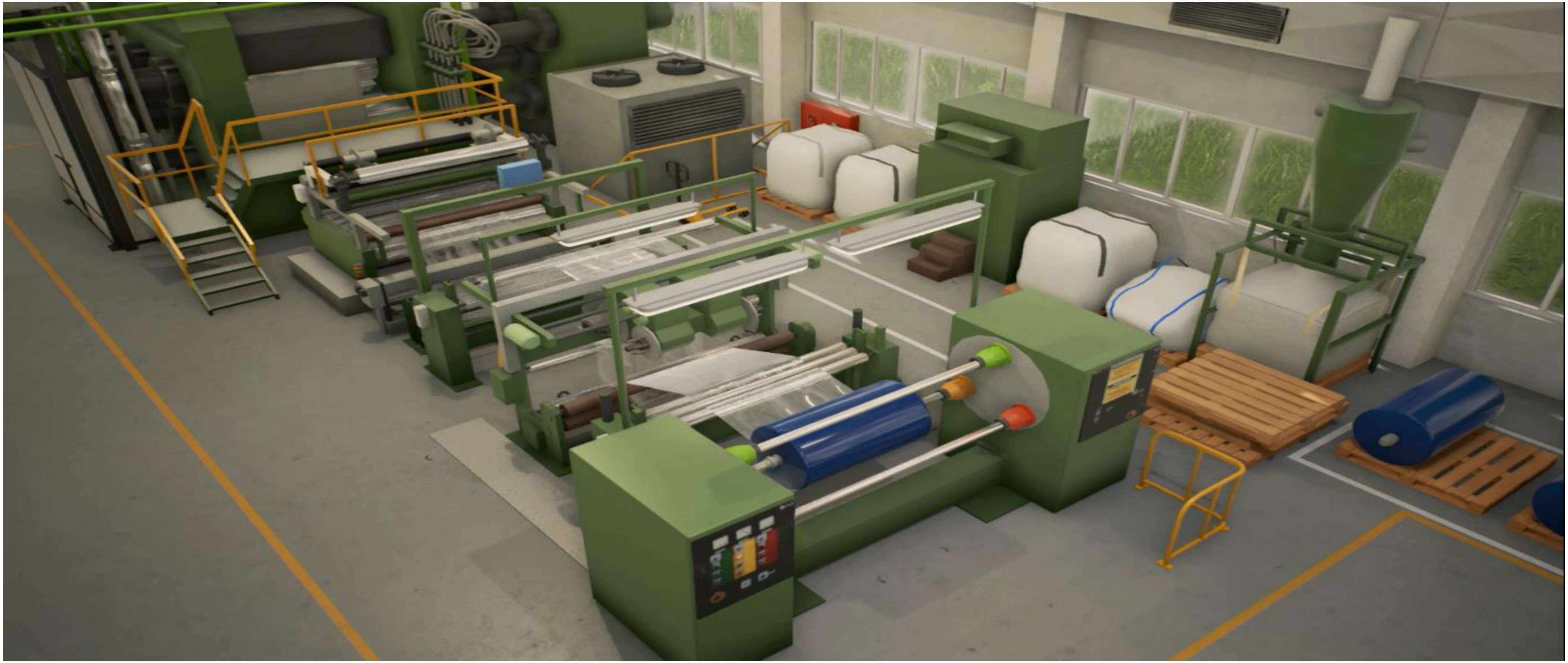
Advantage:

- Review environmental impact of different packaging options
- Decision support for customer

10. Plant development

Advantage:

- Optimization of machine installation in existing premises
- Optimization of process sequences
- Marketing



Future Film Center St.Petersburg

Name: Center Polymeric Engineering

machine	4-L pilot calender with PE lamination
	Laboratory mill with adhesion measurement
	Laboratory hot mixers
	2 srew laboratory extruder
	Laboratory Co-kneader BUSS
	Laboratory stretching traversal system TDO
	Laboratory stretching longitudinal system MDO
	Laboratory coating machine for nanosol
	Felt nozzle coating line
	Rotation coating line Weko
	Corona equipment
	IR and hot air drying
	IR-drying
	UV-drying
	Laboratory thermoforming machine

measurement	Oven Mathis for stability measurement
	Spectrophotometer for Lab-measurement
	Surface tension meter Krüss
	Surface friction measurement device
	surface defect camera
	Shirnkage measurement
	Shirnkage force measurement
	Hand rakel coater
	diving coater
	film thickness distribution
	format measeurement
	color adhäsion measurment

Type of cooperation	Contract research
	Pattern production
	Innovation processing
	Market analyse
	Literature and patent research
	further education

Possible F / E topics	development of formulation for rigit/soft films
	Technologocal optimzaion
	- compoundation
	- calendering
	- extrusion
	- lamination
	- coating
	- thermoforming
	Quality measurement with assessment
	- thickness of film
	- film defect
	- surface tension
	- color constantly
	- shrinkage and shrinkage force
	Coating with nanosol for
	- electrical surface conductiv
	- antimicobiel
	- Improvement / deterioration Printability
	- increase scratch resistance
	market analyse for polymeric products
	Joint innovations - example
	- anticounterfeiting
	- flexible solar cells
	- elctrcrom film
	- enegry efficience
	- coating of nanosol
	- using of liquid colors

Danke !

Спасибо !

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