Sustainable design of reverse osmosis membrane processes in ingredient production

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Membrane Technology Forum 2024
St. Paul, MN – June 2024

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The Food & Beverage industry faces multiple challenges …

External

INFLATION

SUPPLY CHAIN DISRUPTION

SUSTAINABILITY

CONSUMER DEMANDS

Internal

SPEED OF INNOVATION

WORKER SHORTAGES

DATA TRANSPARENCY

GLOBAL STANDARDIZATION

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The F&B industry is evolving again to meet these challenges

1784

Industry 1.0

Mechanization
& Steam power

1870

Industry 2.0

Mass production
& Electrification

1969

Industry 3.0

Automation &
electronics

TODAY

Industry 4.0

IoT

Process automation & optimisation is one of the biggest focus areas for innovation by food manufacturers, **73% of manufacturers** are investing in process automation & optimisation

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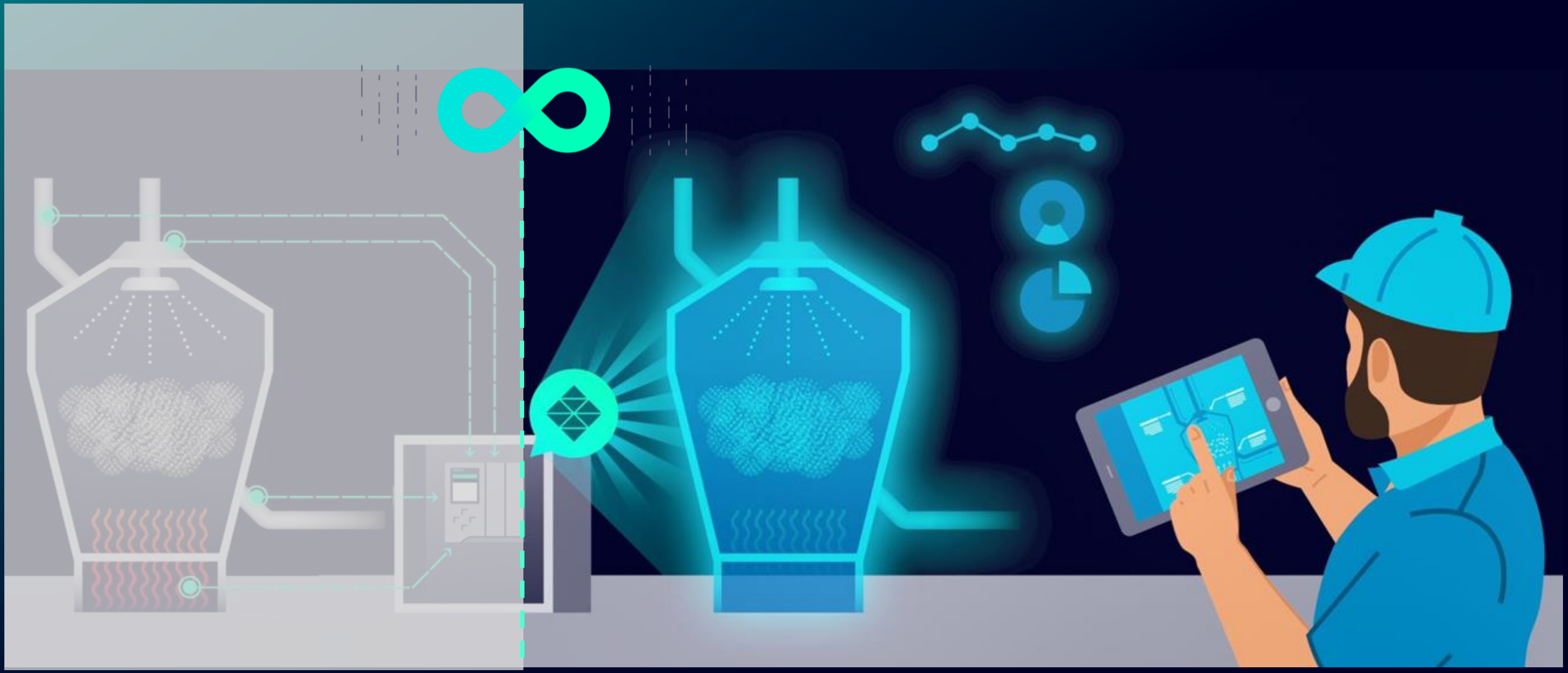
A new path for the food and beverage industry

Status quo is insufficient to achieve production excellence, **digital transformation** is required.



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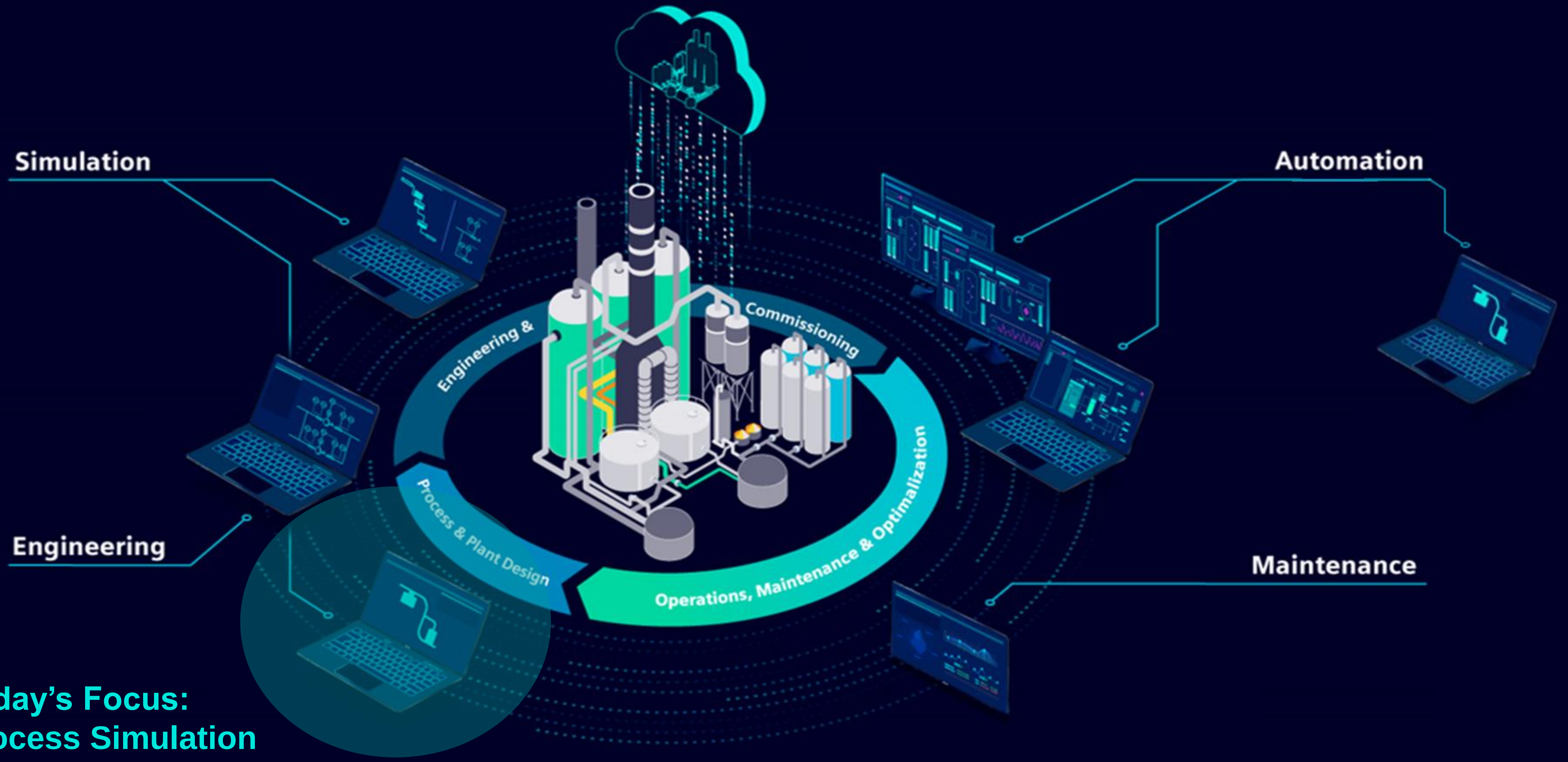
Digital Twins – Not only process models



Today's Focus:
Process Simulation

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Overcome innovation barriers to sustainable F&B production with digital process twins

Current situation:

- Cost pressure means that over **65%** of companies are prioritizing product innovation and process efficiency.
- Corporate responsibility targets drive energy, water & waste reduction.
- Consumer quality demands are increasing.
- **Result:** F&B companies risk needing to invest **€ millions** to stay competitive

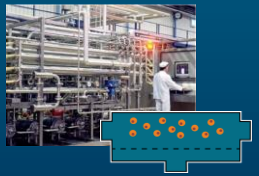
Typical benefits:

Increase process line uptime by up to **10%** to untap **€3-5 M** annual revenue

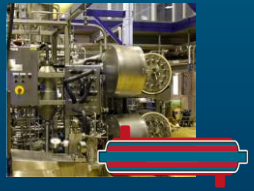
Avoid **€15-20 M** CAPEX spend in multi-factory process upgrades

Reduce water and evaporation energy demand by >**50%** to remove impurities

What questions might be asked to increase your company's speed of innovation and competitiveness?



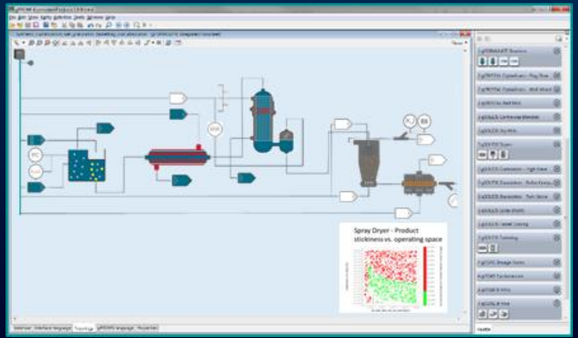
How can I increase run time of a protein concentration process to meet market demand?



How can I design a safe process for multiple products with no more than necessary CAPEX spend?

How can I design an impurity removal process with minimal water & energy usage?

How can I produce many high quality recipes with a shorter batch time to differentiate my product in the market?



The solution: Digital design of Food & Beverage processes using physics-based process digital twins

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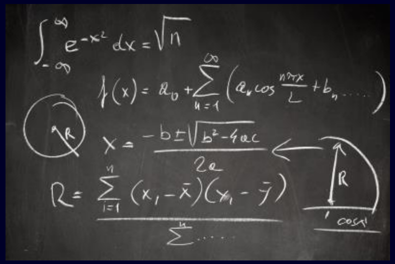
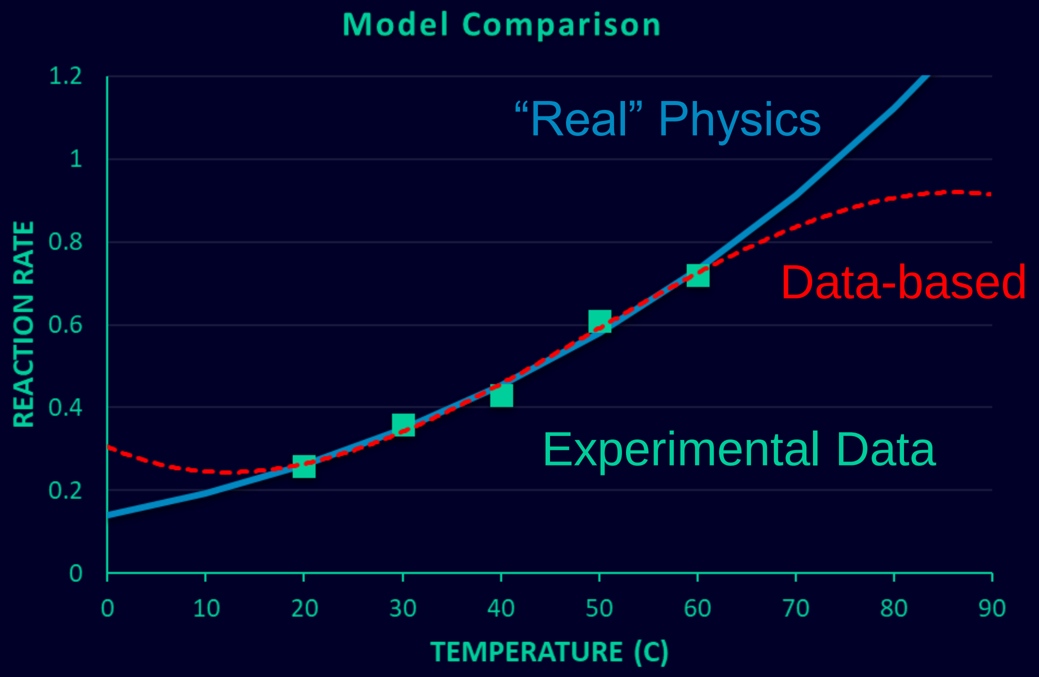
Advantages of physics-based process modelling

- Two types of modelling:

Data-driven

Physics-based





- Physics-based modelling:
  - Requires less experimental data
  - Can be used outside of data range
  - Transfers better to other scales/equipment
  - Takes advantage of well-known phenomena

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Membrane System Modelling

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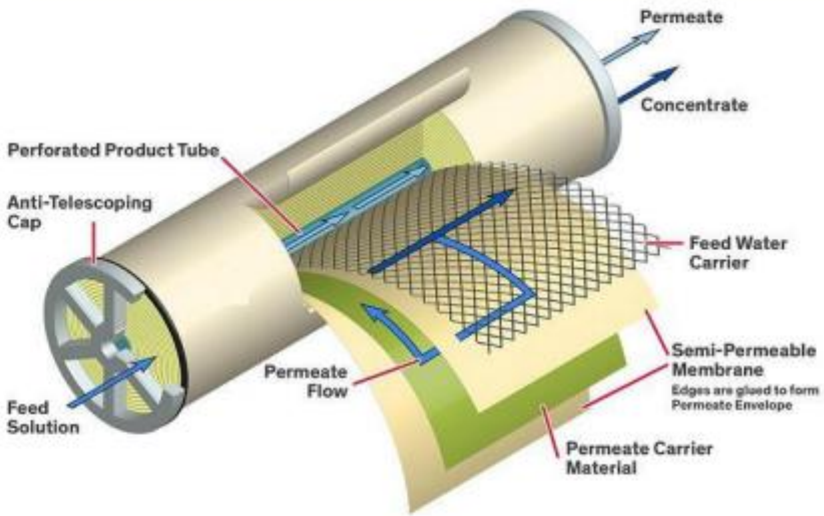
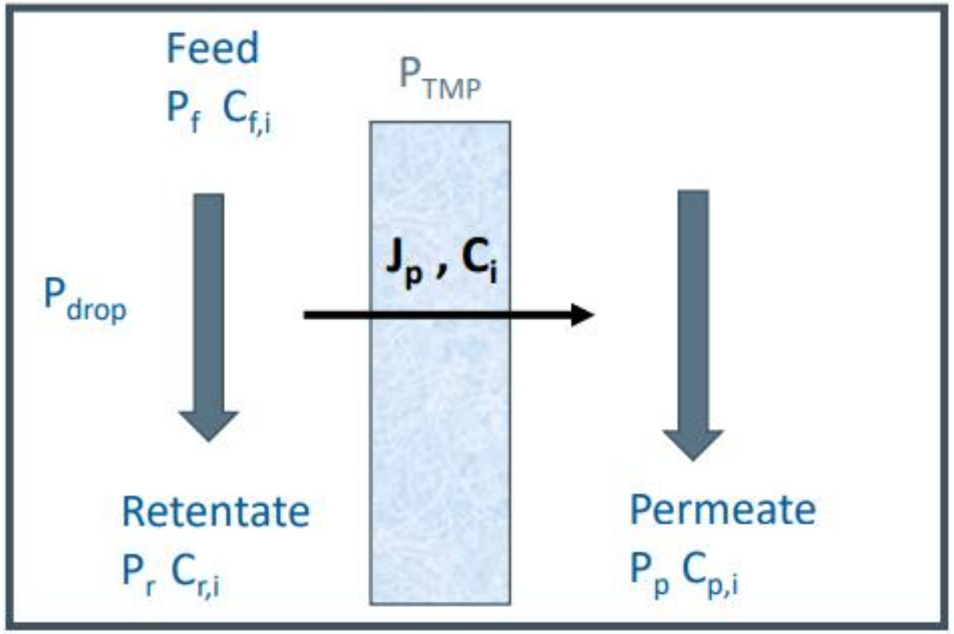
TANGENTIAL FLOW MEMBRANE





Membrane flux

$$J_p = \frac{P_{TMP}}{R}$$

Notation

J_p	Membrane flux to permeate	kg m^{-2} s^{-1}
P_{TMP}	Transmembrane pressure	Pa
R	Membrane resistance, $R = R_{dyn} + R_{stat}$	Pa m^2 s^{1}kg^{-1}

Membrane pressures

$$P_{TMP} = P_f - \frac{P_{drop}}{2} - P_p$$

Notation

P_{TMP}	Transmembrane pressure	Pa
P_f	Feed stream pressure	Pa
P_p	Permeate pressure	Pa
P_{drop}	Pressure drop	Pa

Rejection coefficient

$$f_{rej,i} = 1 - \frac{C_{p,i}}{C_{f,i}} \quad i \in active\ components - water$$

Notation

$f_{rej,i}$	Rejection coefficient	-
$C_{p,i}$	Mass concentration of component i in permeate stream	kg/m^3
$C_{f,i}$	Mass concentration of component i in feed stream	kg/m^3

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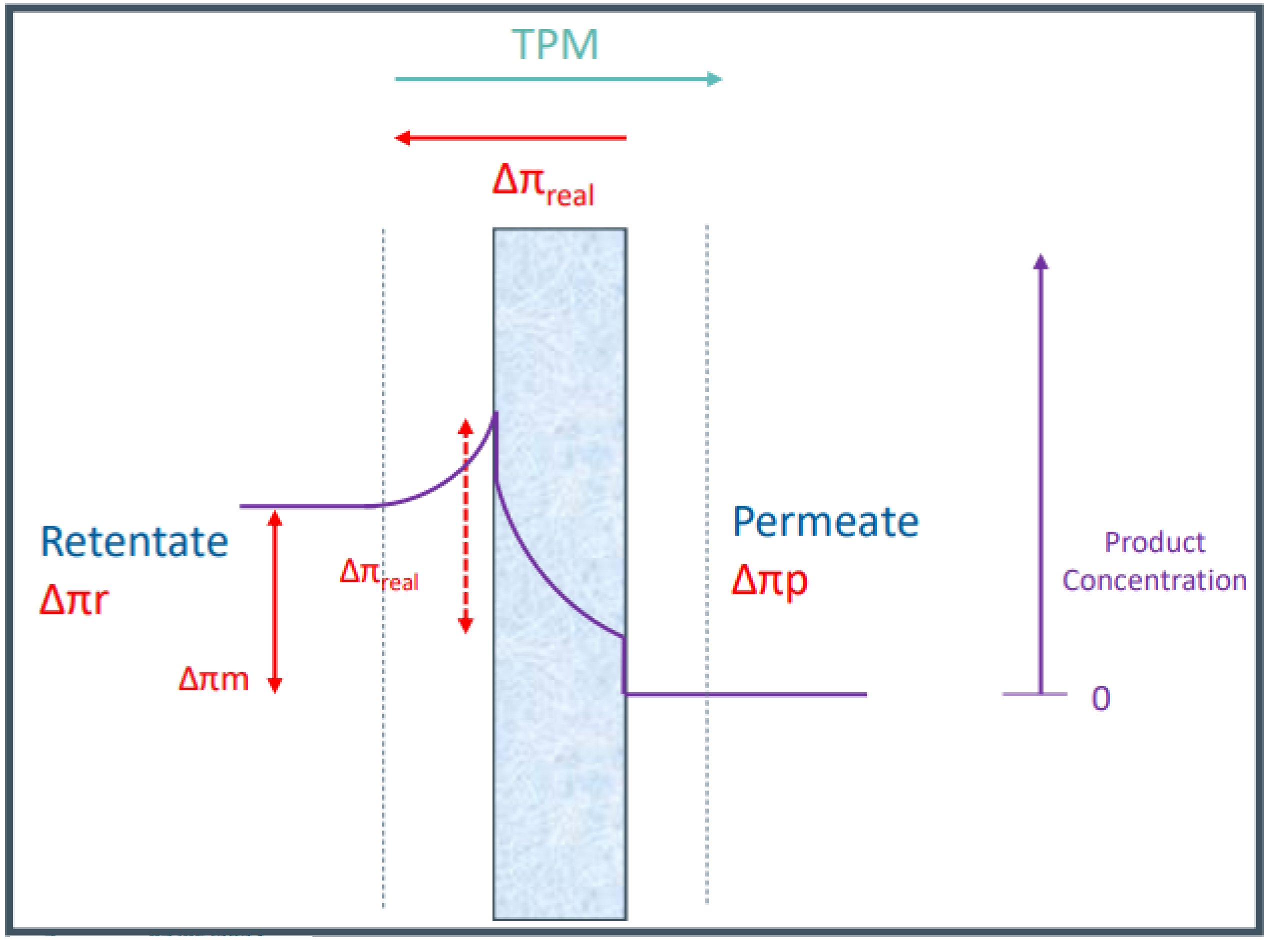
FLUX MODELING

Jp Permeate flux $\left[\frac{kg}{m^2.s}\right]$

P_{TMP} Transmembrane pressure $[Pa]$

R Membrane resistance $\left[\frac{m^2.Pa.s}{kg}\right]$

$$J_p = \frac{P_{TMP}}{R} = L_p\,.\,(P_{TMP} - \Delta\pi_{real})$$



$$R = R_{water}.R_{product}$$

$$R_{water} = \frac{1}{L_p}$$

$$R_{product} = \left(1 - \sigma.\left(\frac{\Delta\pi_m}{P_{TMP}}\right)^p\right)^n$$

$$J_p = \frac{P_{TMP}}{\frac{\left(1 - \sigma.\left(\frac{\Delta\pi_m}{P_{TMP}}\right)^p\right)^n}{L_p}}$$

L_p water membrane permeability $\left[\frac{kg}{m^2.Pa.s}\right]$

$Rwater$ water membrane resistance $\left[\frac{m^2.Pa.s}{kg}\right]$

$Rproduct$ product membrane resistance

$\Delta\pi m$: osmotic pressure membrane difference $[Pa]$

σ reflexion coefficient

n & p reflexion coefficient parameters

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FLUX MODELING

Water activity & Osmotic pressure

$$\Delta\pi = -\left(\frac{RT}{Vm}\right).\ln aw$$

$\Delta\pi$ *osmotic pressure* $[Pa]$

$R = 8314 \left[\frac{l.Pa}{mol.K}\right]$

Vm *molar volume(water)* $18{,}07.10^{-3}\left[\frac{l}{mol}\right]$

$T\ [°K]$

$$\ln(aw) = \frac{-\xi m}{55.1}$$

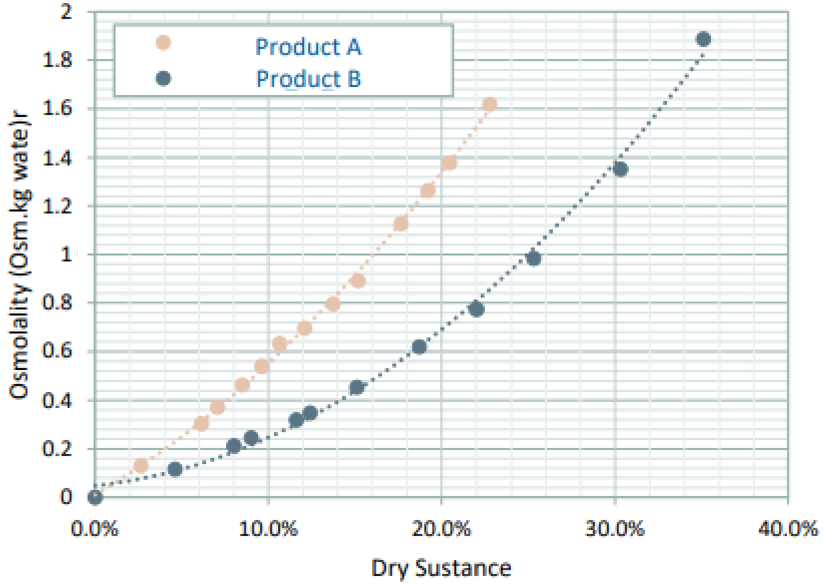
$$aw = e^{\left(\frac{-\xi m}{55.1}\right)}$$

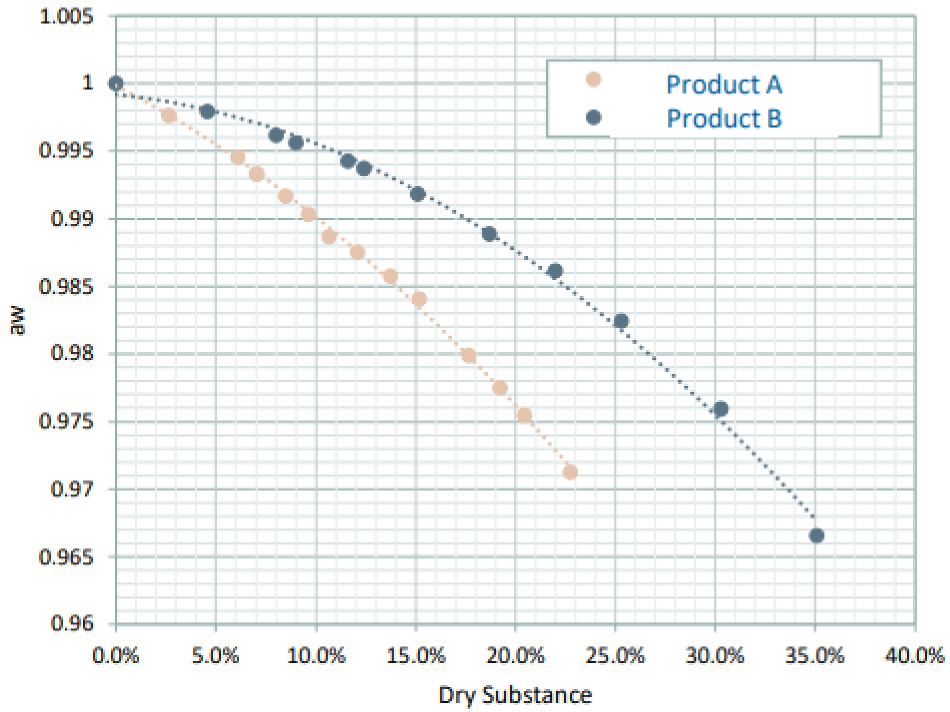
aw *water activity*

ξm *Osmolality* $\left[\frac{Osm}{kg\ water}\right]$

OSMOMAT 3000

Osmolality ξm (mOsm/kg water)





$$aw = aw2.DS^2 + aw1.DS + aw0$$

Coefficient	PRODUCT B	PRODUCT A
aw2	-2.134E-01	-2.106E-01
aw1	-1.496E-02	-7.615E-02
aw0	1	1

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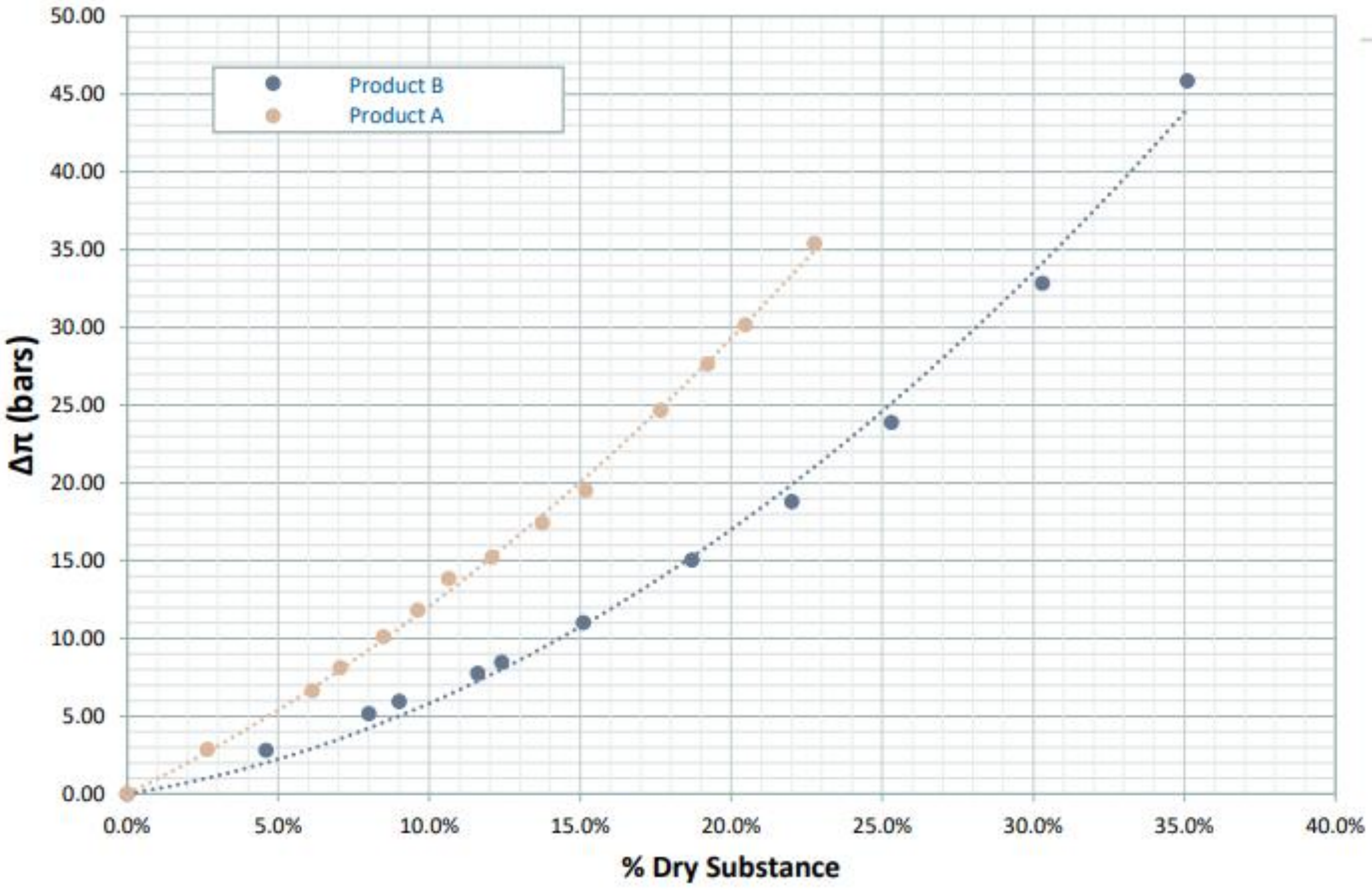
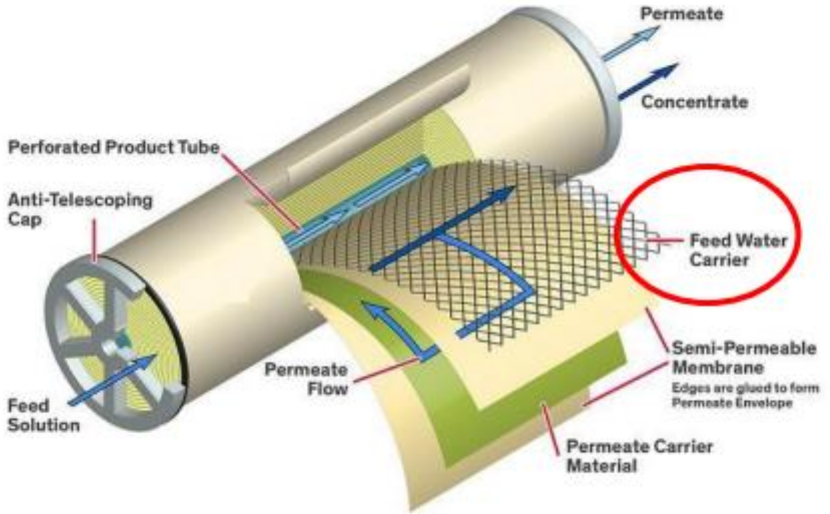
OSMOTIC PRESSURE Δπ



Designation	Characteristics	NaCl rejection
RO90	Thinfilm composite	≥ 90%**

** measured on 2000 ppm NaCl, 9 bar, 25ºC

Part No.	Element type	Area m2	(sqft)	Lp (kg/m²/Pa/s)
527977	RO90-8038/30	38	(409)	1.20E-08
525510	RO90-8038/48	28.1	(302)	1.40E-08



Overview Case Studies

Whey protein concentrate (WPC) production –
Improve uptime of ultrafiltration process to meet demand

Customer challenge

- To **reduce protein fouling** in a WPC ultrafiltration process to **increase process uptime** & **reduce CIP frequency**
- To meet **product specification** and **capacity requirements**

Solution

- Configure and calibrate **physical science-based process model** of ultrafiltration process
- Use optimisation techniques to identify operating conditions which reduce rate of fouling and increase run time

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Customer benefits

Reduced membrane fouling delivering up to **10% increase** in process runtime

Higher productivity and reduced CIP

Streamlined experimentation and process upscaling to engineering and operations

CAPEX savings

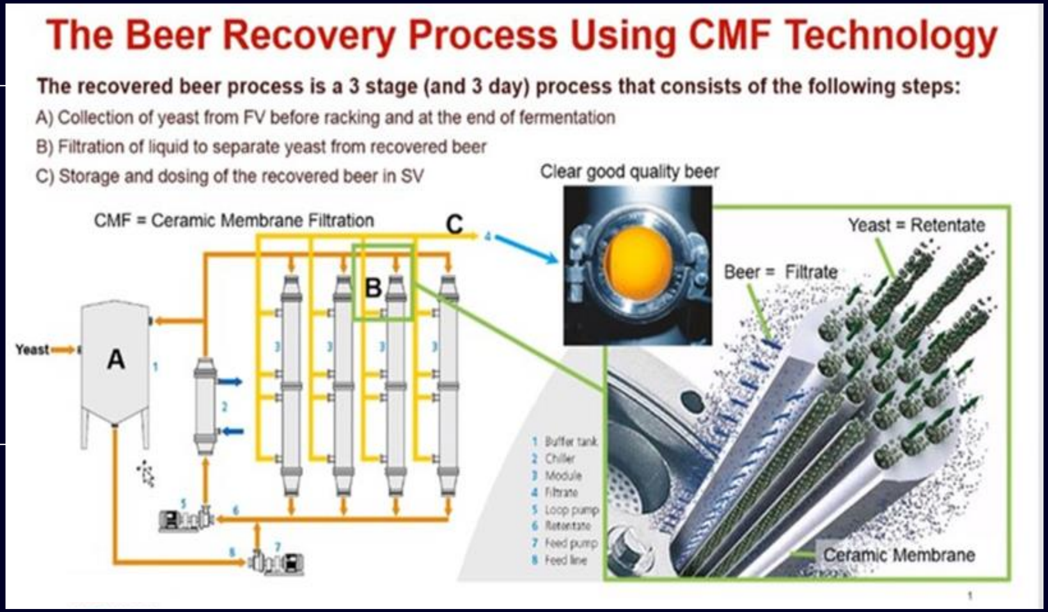
Recovery of beer from yeast slurry –
Improve process understanding and consistency

Customer challenge

- Yeast slurry after beer fermentation contains a significant amount of good beer
- Equipment exists to separate beer from yeast, but process **know-how** is lacking

Solution

- Apply membrane models to calibrate the process and develop better process understanding
- Deploy models to aid in process prediction and operational decision-making



Customer benefits

Reduce operator efforts in process control

Improve beer removal from 60% to 80%

Financial benefit of $50-200k per annum, depending on brewery size

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Plant-based ingredient production –
Sustainable design of reverse osmosis impurity removal process

Customer challenge

- **Sustainable** process design – performance evaluation of different configurations
- **Minimize energy and water consumption** in process
- Improve quality of product given varying feed impurity levels

Solution

- Configure and calibrate **physical science-based process model** of the reverse osmosis process in **SIEMENS gPROMS FormulatedProducts**
- Performance analysis using global system analysis
- Use optimisation techniques in gPROMS to identify optimum operating conditions

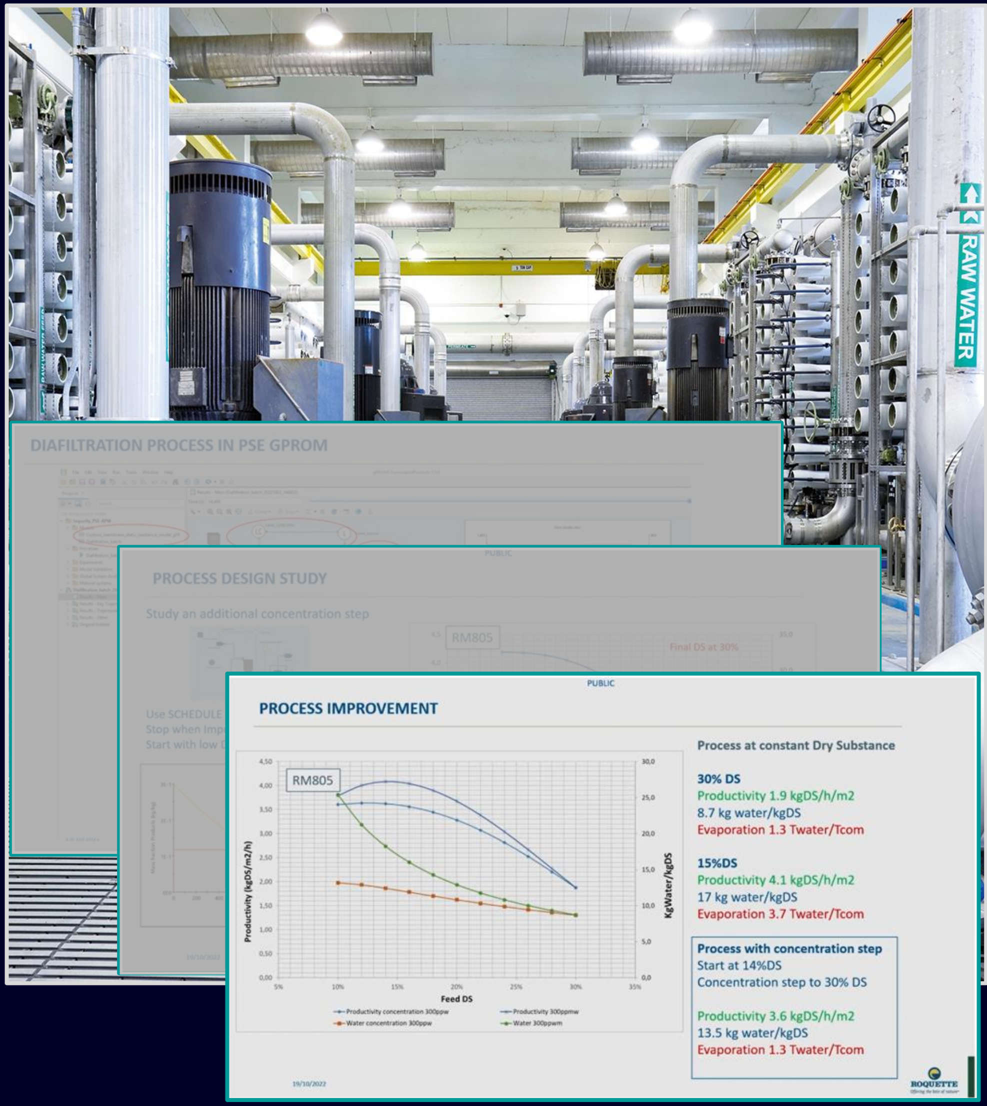
Customer benefits

Better, leaner and more competitive designs

20% reduction in diafiltration water consumption

65% reduction in evaporation energy

Operating space discovery for optimal and consistent product quality



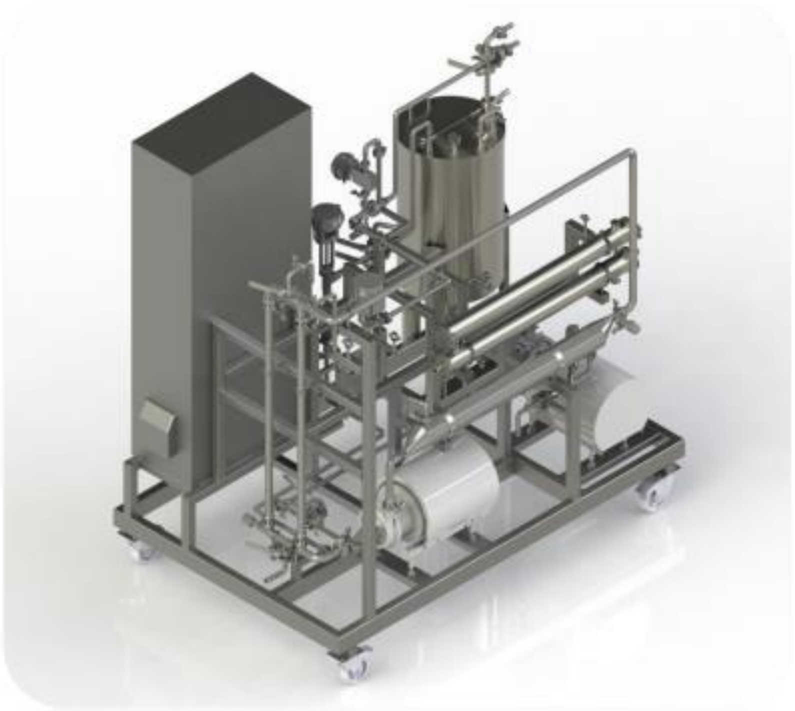
Reverse Osmosis Process Design

SCOPE OF STUDY

Quality improvement of our products

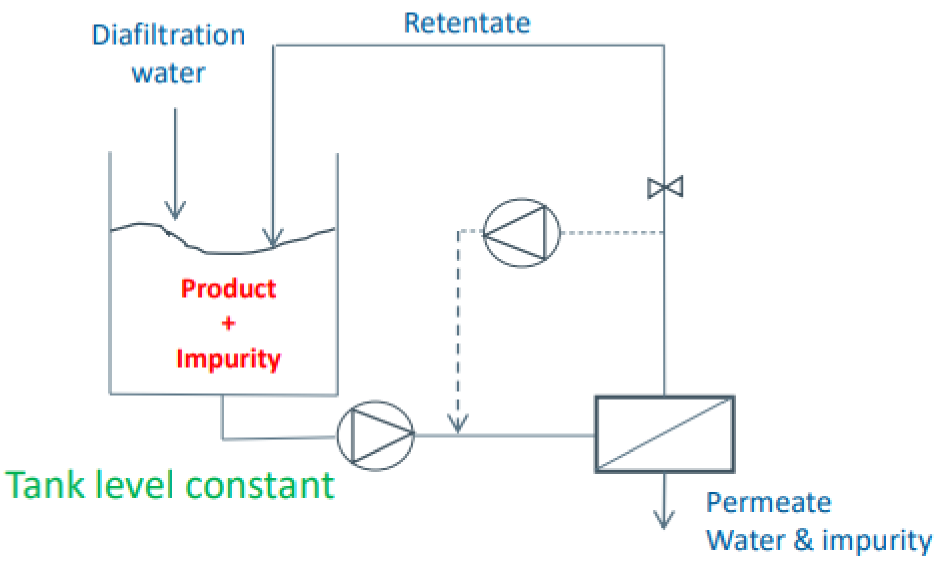
Remove impurity with a new membrane process

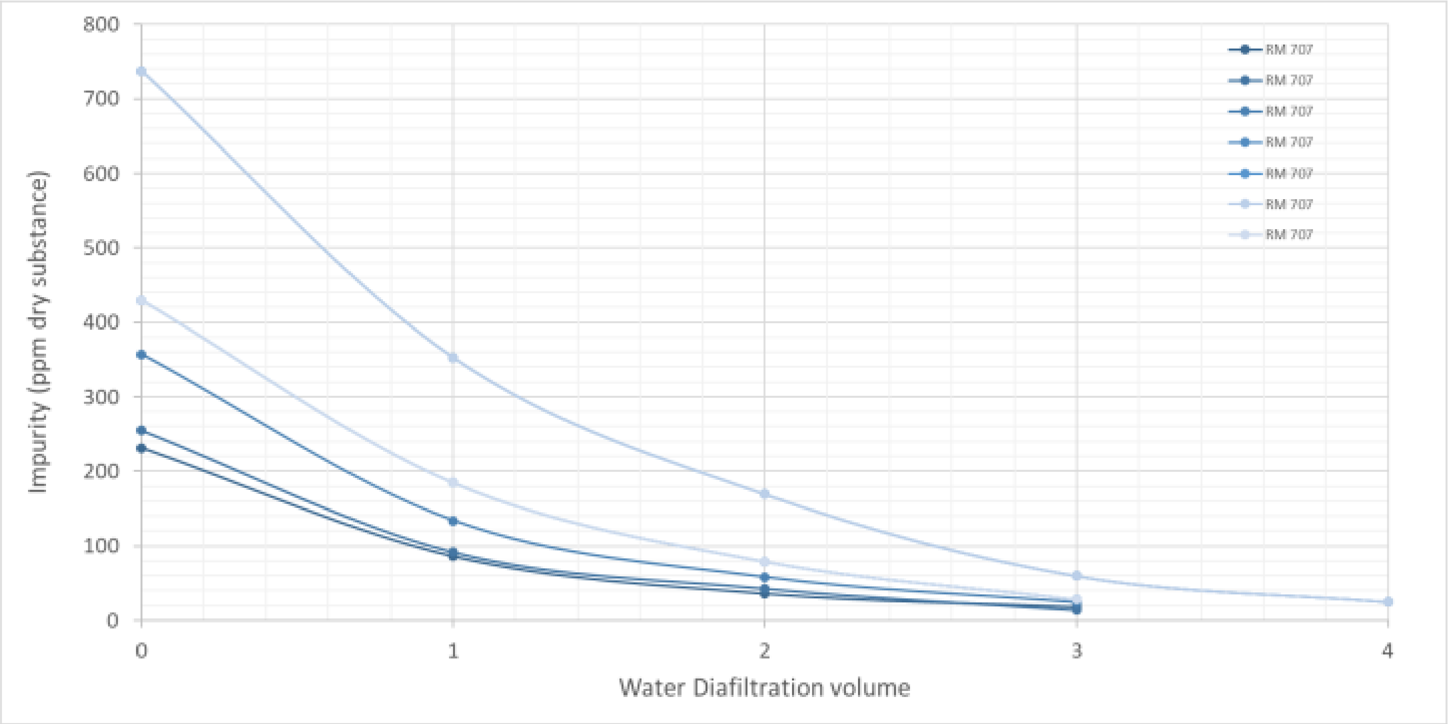
Development of modeling tool
- New model for NF/RO
- Batch system
- Experiment at pilot scale



Tool for process performance evaluation and scale-up

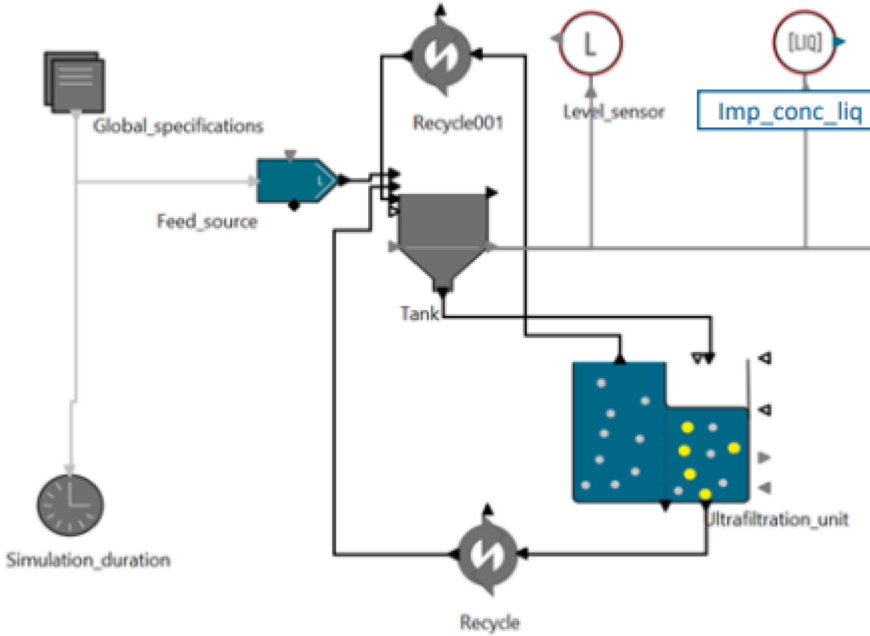
PROCESS PILOT SCALE

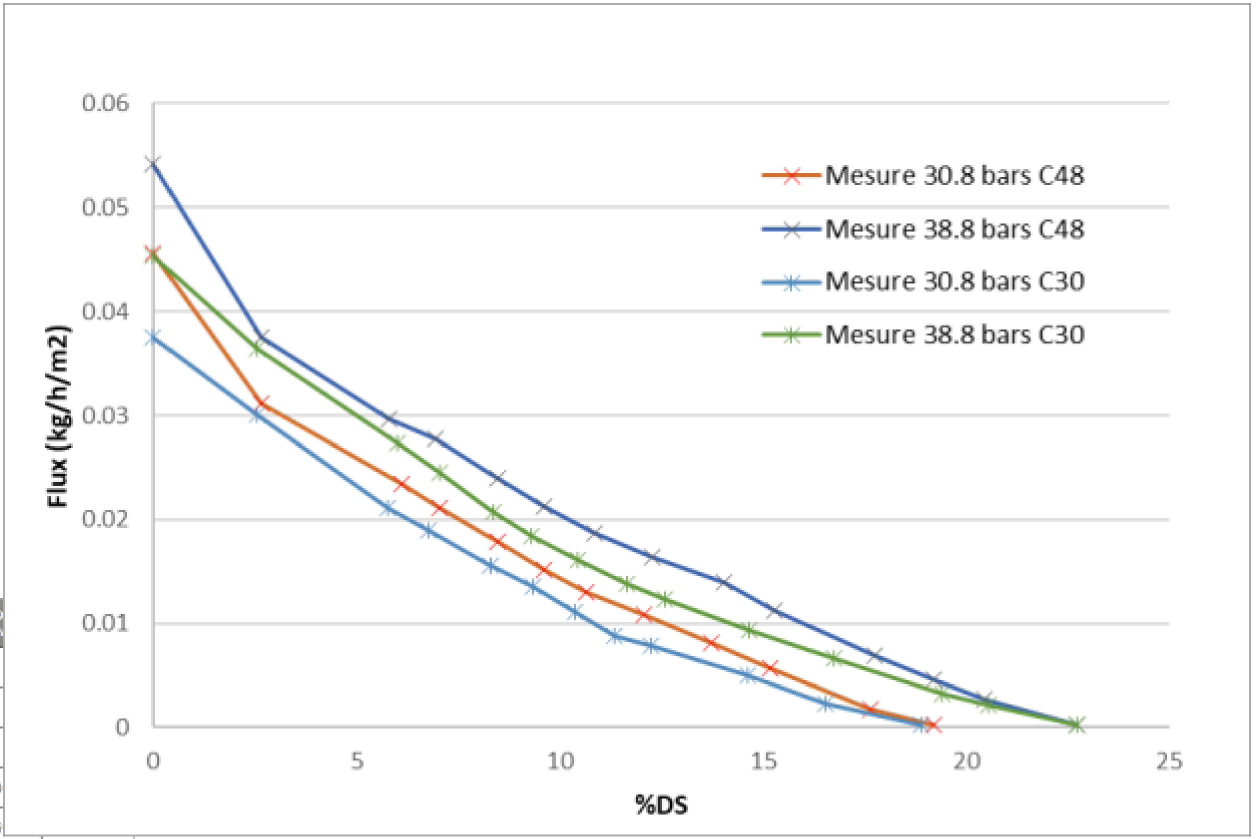




Scale-up to continuous ?

FLUX MODELING – MODEL VALIDATION





Model Parameters

- Probability of parameter lying between (Final Value -α% Confidence Interval) and (Final Value +α% Confidence Interval) = α%
- The t-value shows the percentage accuracy of the estimated parameters, with respect to the 95% confidence intervals

Model Parameter	Final Value	Initial Guess	Lower Bound	Upper Bound	Confidence Interval			9 t-v	
					90%	95%	99%		
Ultrafiltration_unit Static resistance: Custom empirical model - Custom resistance parameters (aw0)	1.00000	1.00000	1.00000*	1.00000*					
Ultrafiltration_unit Static resistance: Custom empirical model - Custom resistance parameters (aw1)	-0.0149600	-0.0149600	-0.0149600*	-0.0149600*					
Ultrafiltration_unit Static resistance: Custom empirical model - Custom resistance parameters (aw2)	-0.213360	-0.213360	-0.213360*	-0.213360*					
Ultrafiltration_unit Static resistance: Custom empirical model - Custom resistance parameters (n)	-1.61506	-1.61506	-2.00000	-1.00000	0.00349131	0.00418167	0.00556622	38	
Ultrafiltration_unit Static resistance: Custom empirical model - Custom resistance parameters (sigma_cst)	0.835206	0.835206	0.00000	1.00000	0.000811576	0.000972054	0.00129390	85	
Ultrafiltration_unit Static resistance: Custom empirical model - Custom resistance parameters (sigma_power)	0.520874	0.520874	0.00000	1.00000	0.000490829	0.000587884	0.000782532	886.016	0.000293467
								Reference t-value (95%):	1.67252

Click here to use above final values in future calculations

*a parameter that lies at one of its bounds is excluded from the statistical analysis

FLUX MODELING

$$J_p = L_p.\frac{P_{TMP}}{\left(1-\sigma.\left(\frac{\Delta\pi_m}{P_{TMP}}\right)^p\right)^n}$$

Model	Model Osmolalityalfalaval RO90-48		Model Osmolalityalfalaval RO90-30	
Lp (kg/m²/Pa/s)	1.40E-08		1.20E-08	
Produit	PRODUCT B	PRODUCT A	PRODUCT B	PRODUCT A
σ	0.835	0.924	0.835	0.924
p	0.521	0.566	0.524	0.571
n	-1.61	-1.20	-1.61	-1.20
MAPE(%)		8.5		

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** measured on 2000 ppm NaCl, 9 bar, 25ºC

Part No.	Element type	Area m2	Area (sqft)
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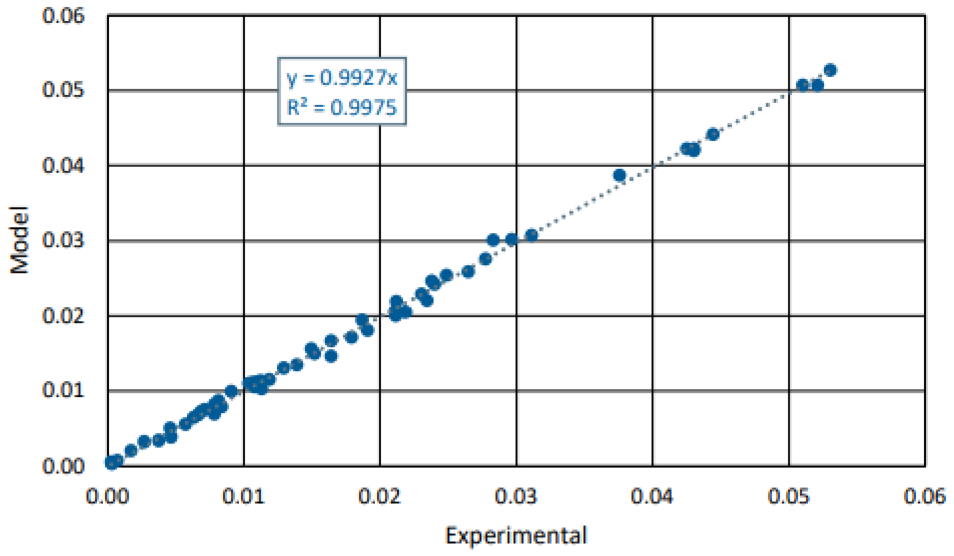
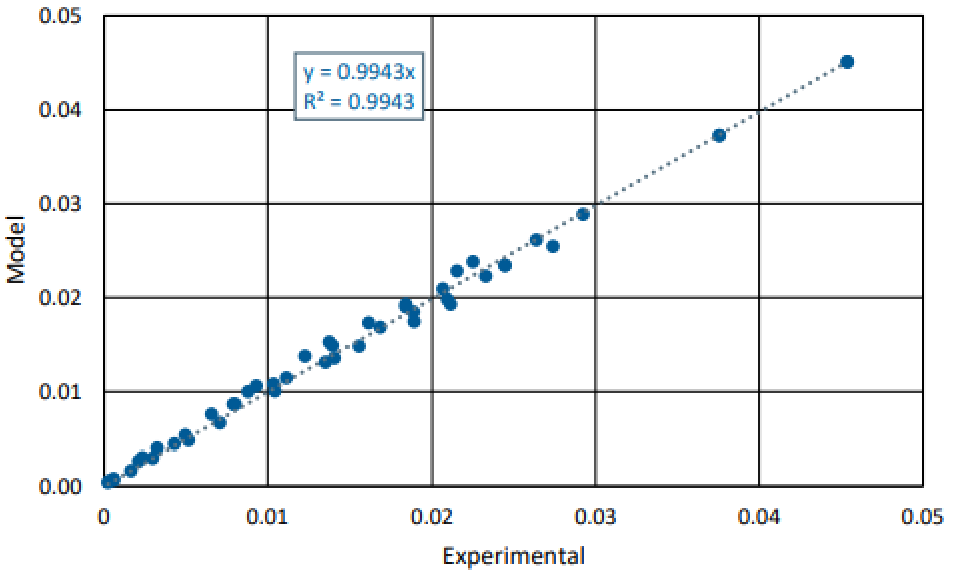
525510	RO90-8038/48	28.1	(302)

Parity plot RO90-8038/48



Parity plot RO90-8038/30



FLUX MODELING

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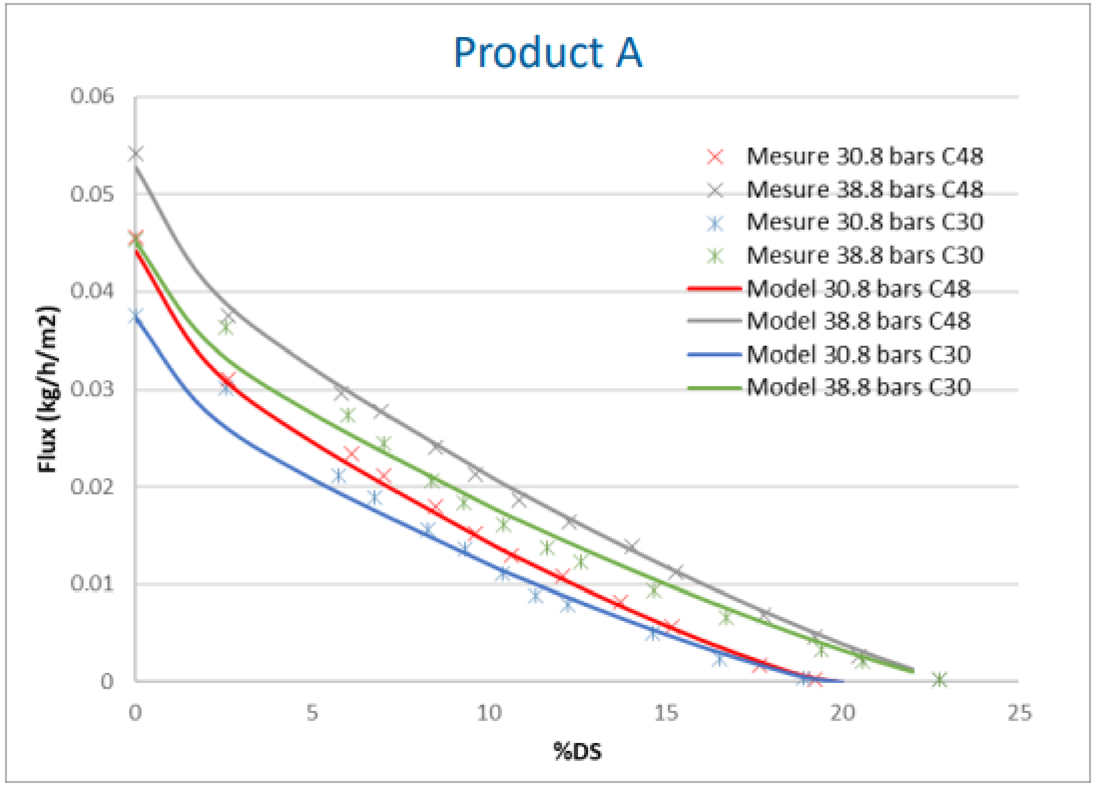

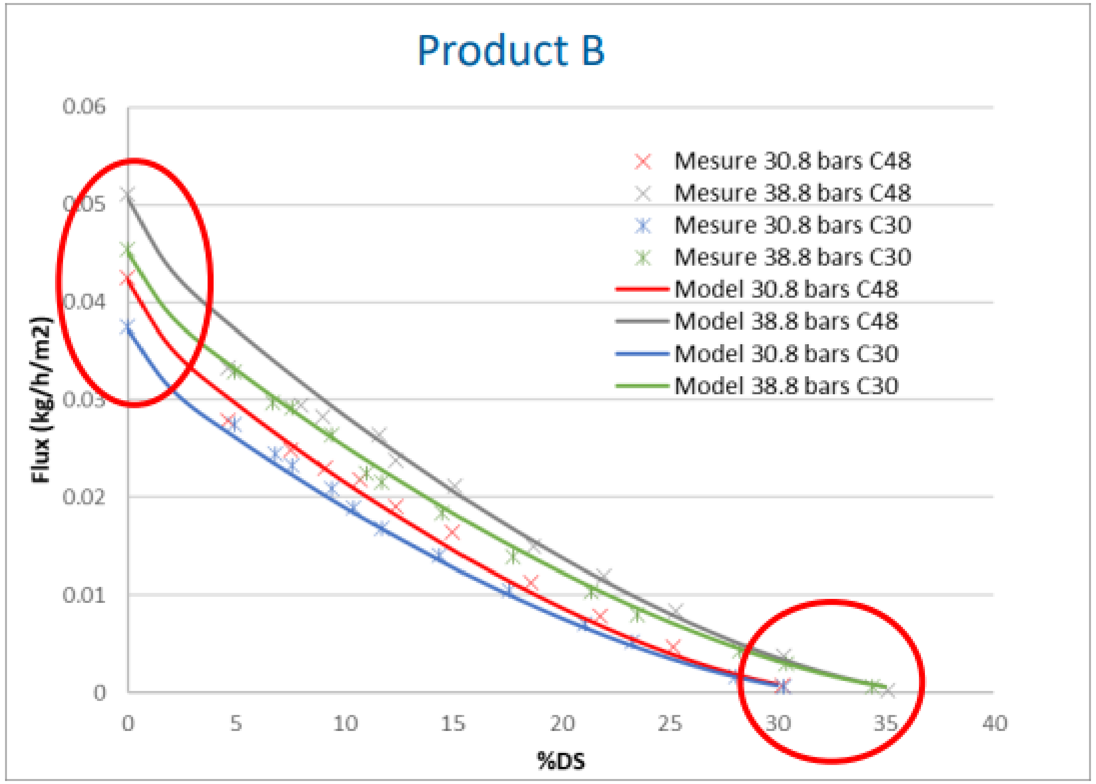

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REJECTION MODELING

$$f_{rej,i} = 1 - \frac{C_{p,i}}{C_{f,i}}$$

$$f_{rej,i} = \frac{1}{1 + a_i . Jv^{b_i}}$$

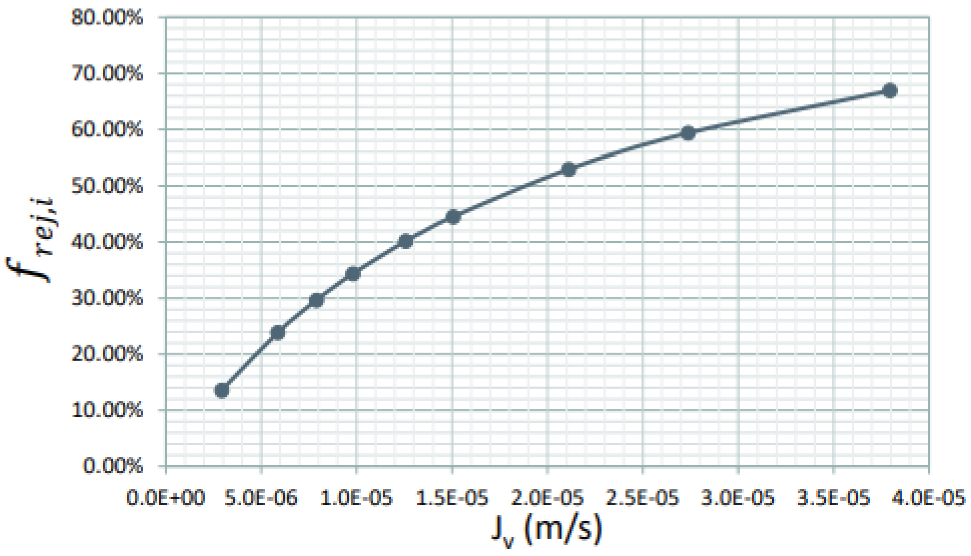
$C_{p,i}$ Mass concentration of component i in permeate stream $\left[\frac{kg}{m^3}\right]$

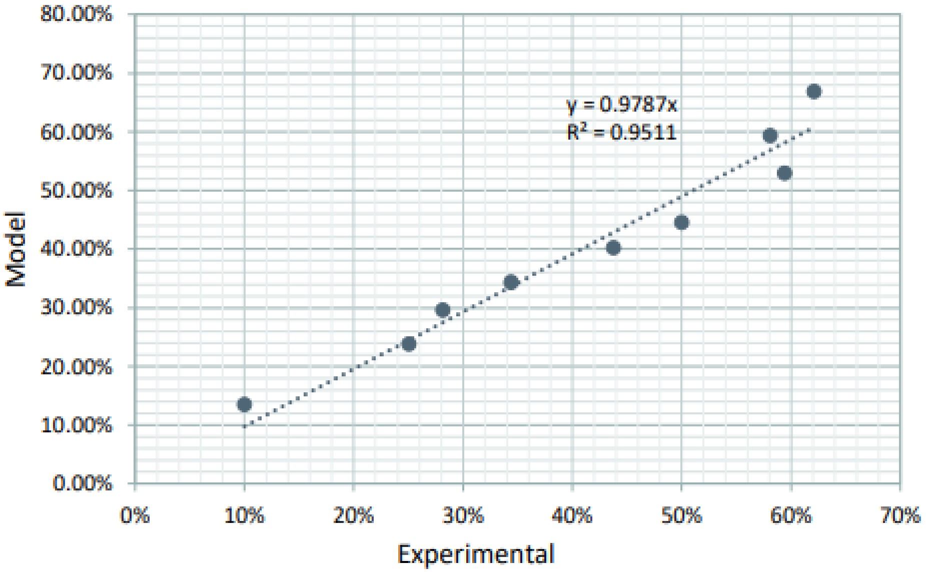
$C_{f,i}$ Mass concentration of component i in feed stream $\left[\frac{kg}{m^3}\right]$

Jv Membrane permeate linear velocity $\left[\frac{m}{s}\right]$

a_i & b_i Rejection coefficient of component i at temperature Ti

Coefficient	Impurity	Product
ai	1.8749E-05	0
bi	-1	1





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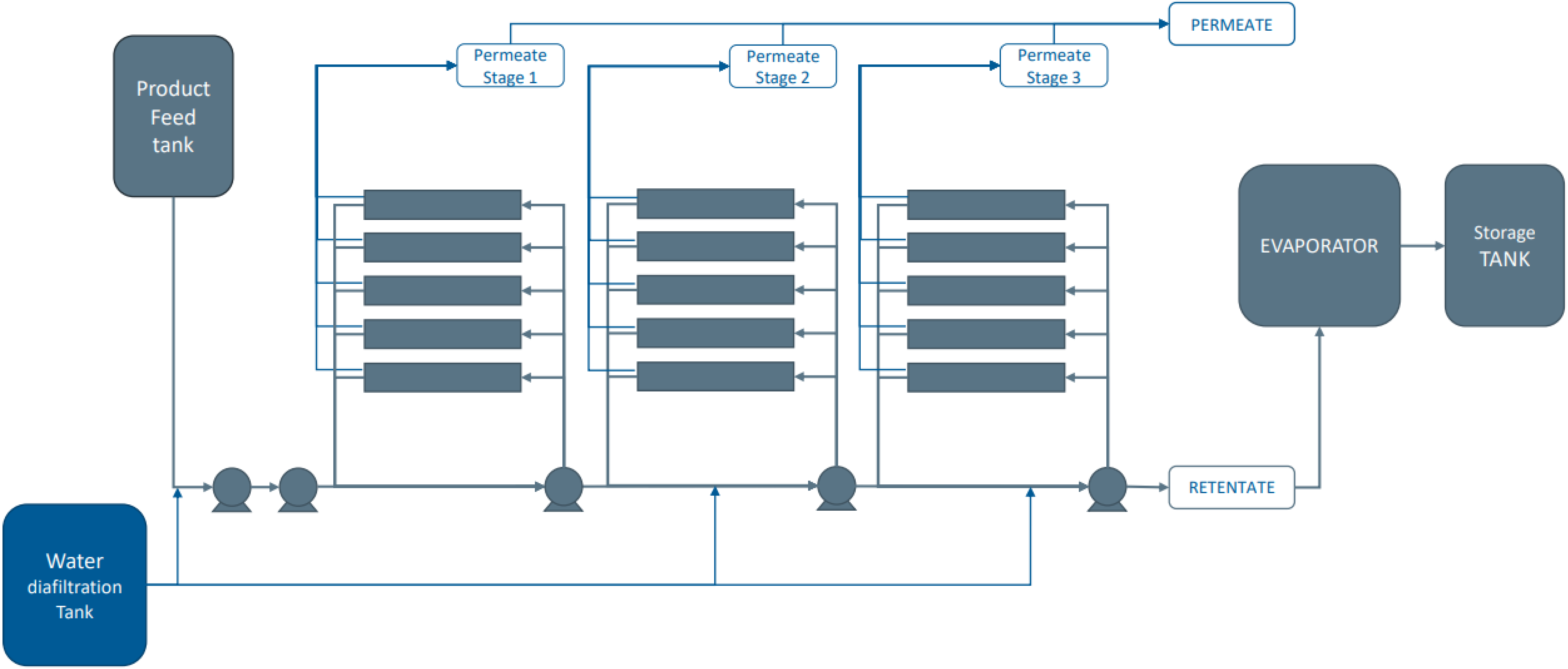
PROCESS OVERVIEW



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NANOFILTRATION CONTINUOUS

Continuous 3 stages of 5*4 membranes, total 60 membranes

Designation	Characteristics	NaCl rejection
RO90	Thinfilm composite	≥ 90%**

** measured on 2000 ppm NaCl, 9 bar, 25ºC

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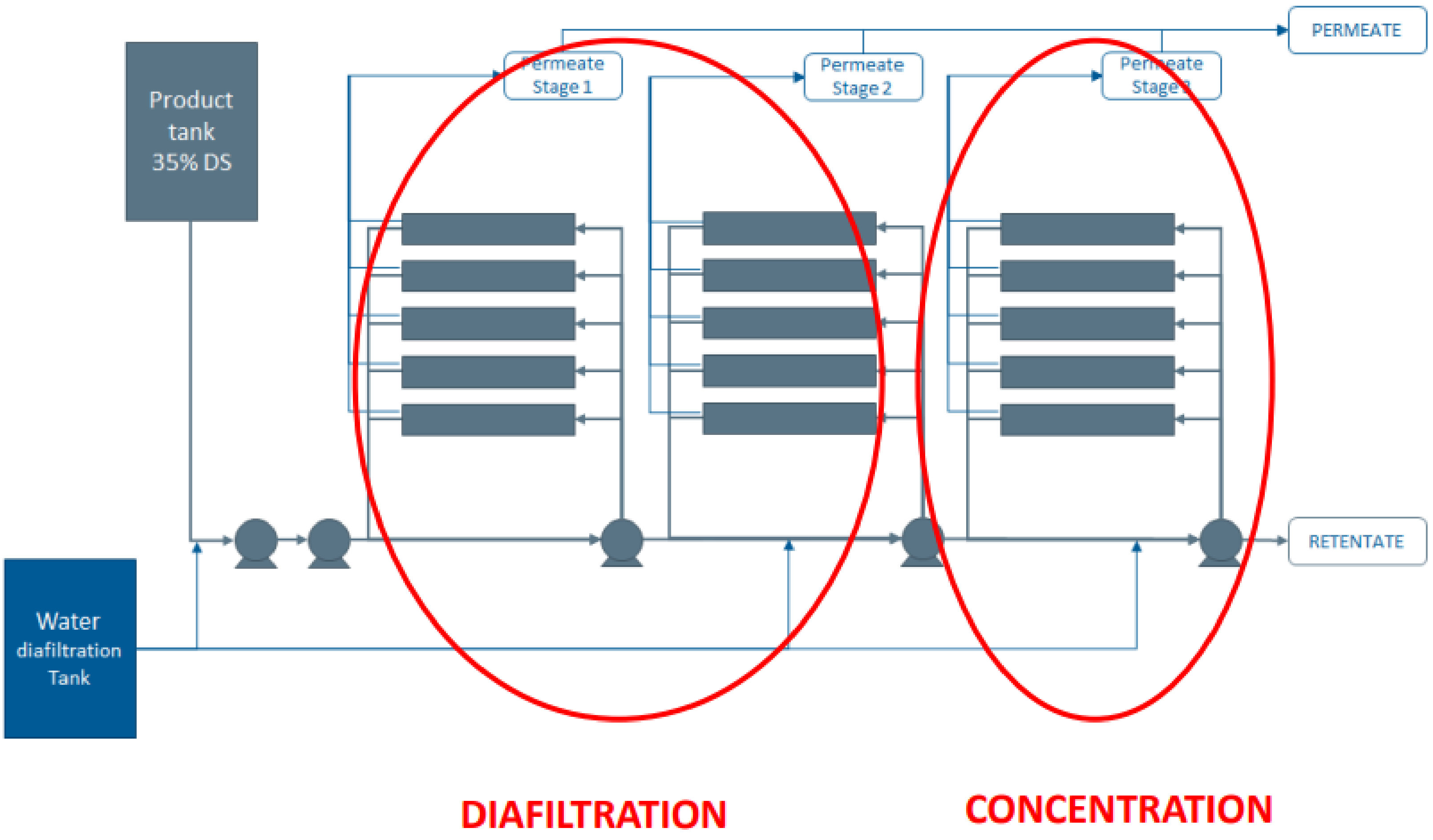

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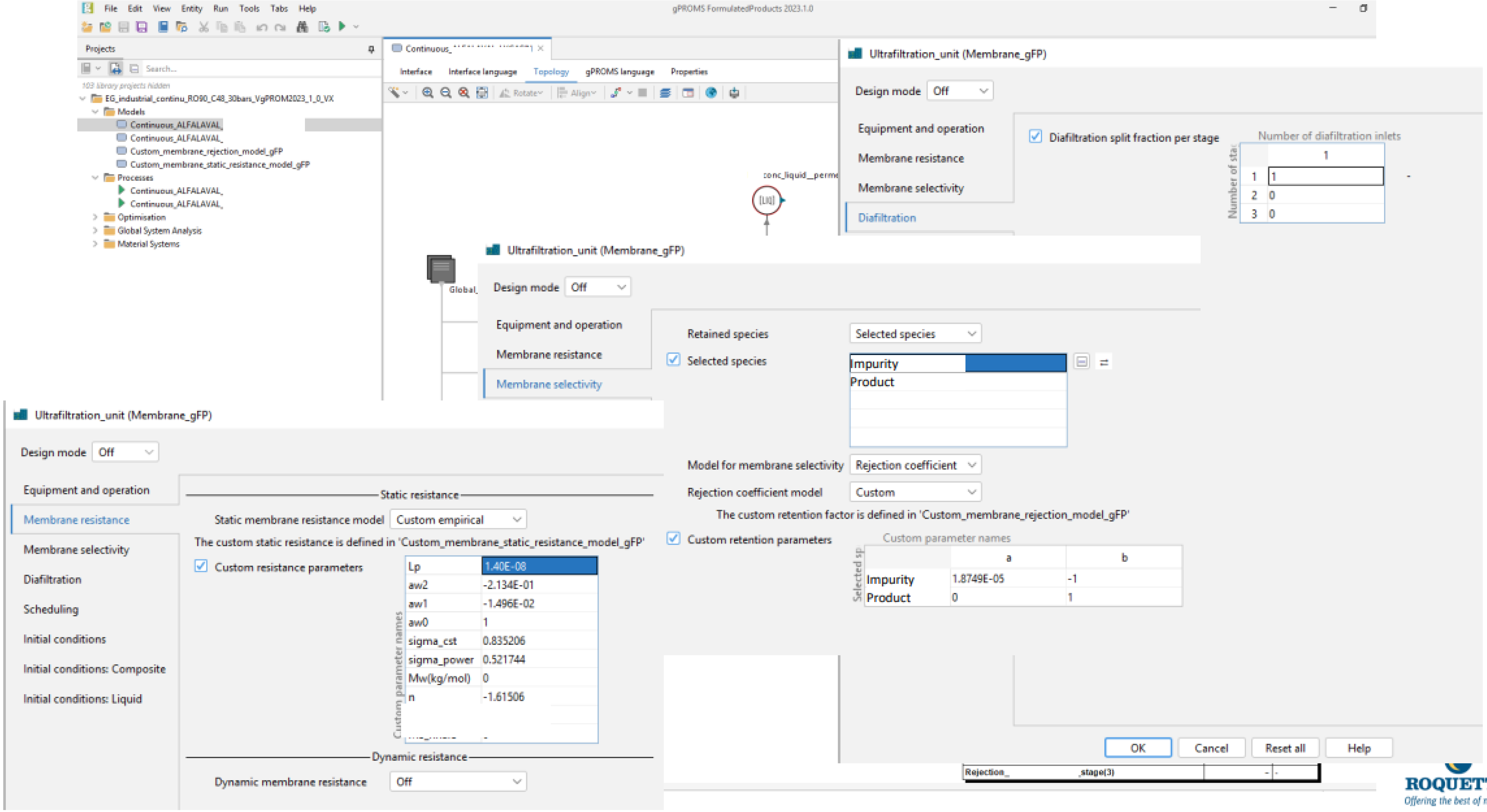
PROCESS SIMULATION



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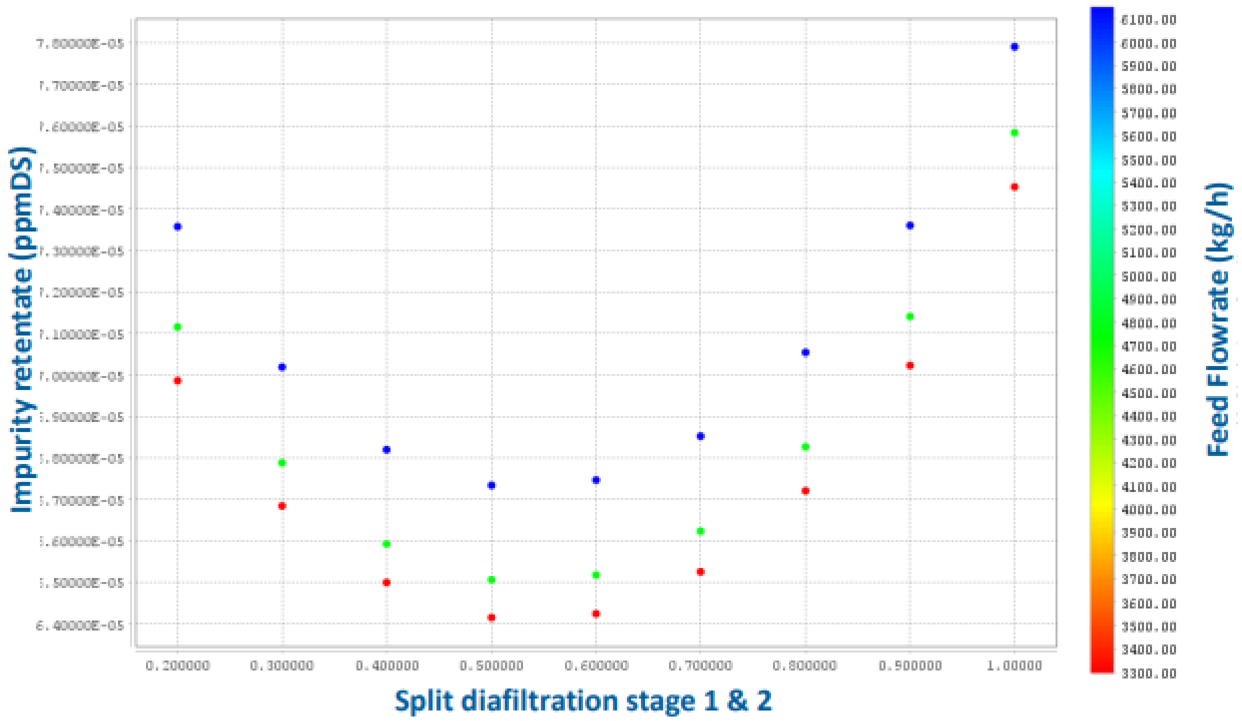
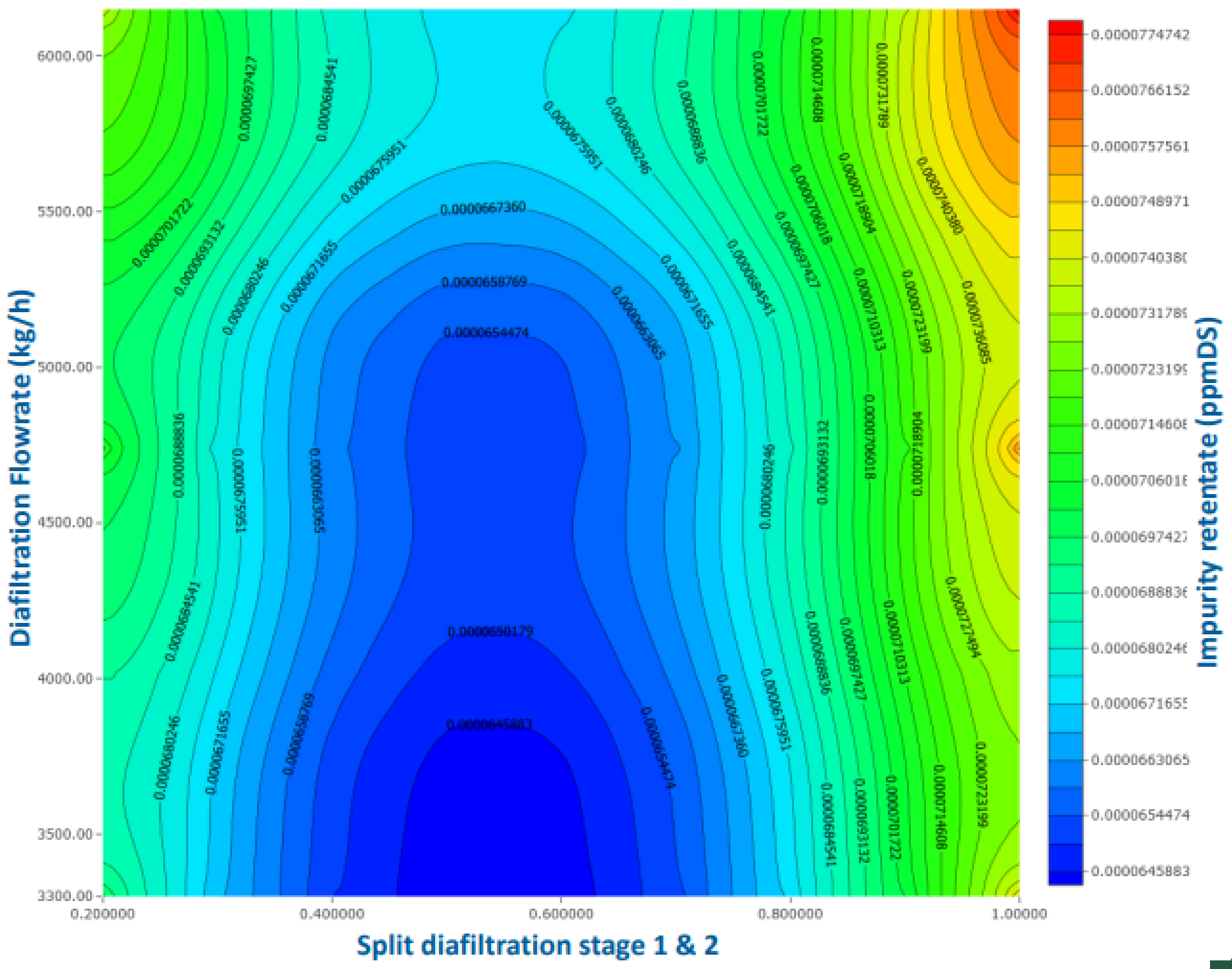
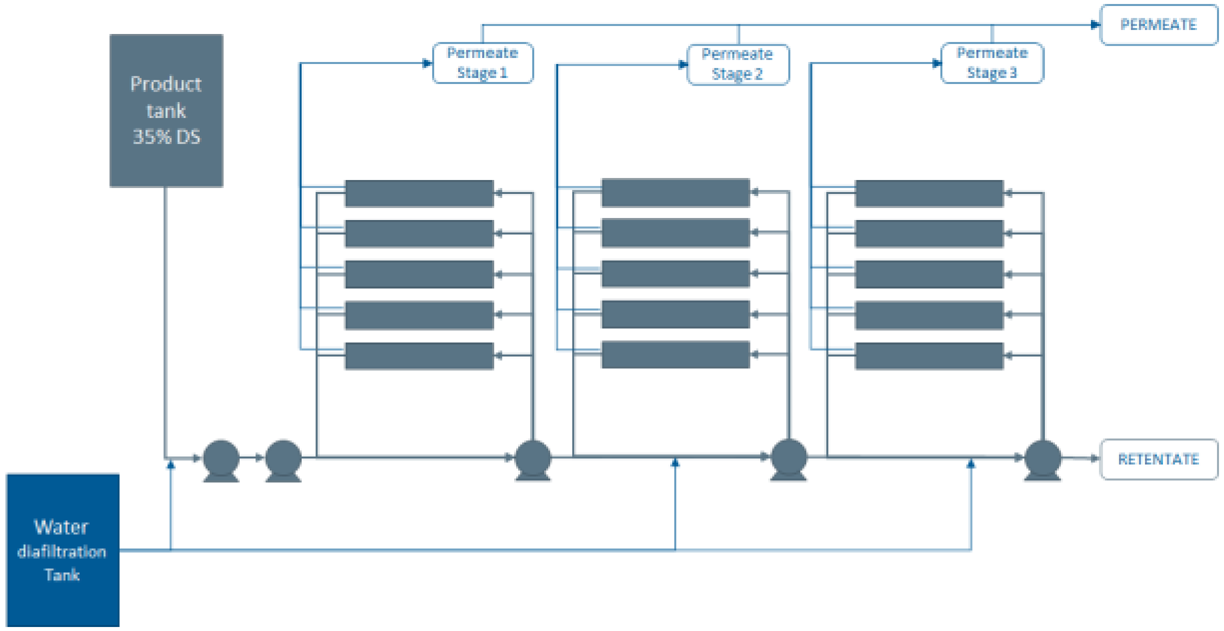
PRODUCTIVITY OPTIMISATION - GSA





PRODUCTIVITY AND WATER CONSUMPTION OPTIMIZATION

Membrane surface (m2)	2280	TPM (bars)	29
Membrane	RO90-8038/30	m2	38.0
PRODUCT A Configuration split	1 on stage 1	0.4 stage 1 0.6 on stage 2	
Productivity	2438 Tcom/year	8063 Tcom/year	
Productivity	0.23 TMS/h	0.75 TMS/h	
Water comsuption	129.5 kgeau/kDS	24.7 kgeau/kDS	
Evaporation rate	0.9 T/h	3.0 T/h	
PRODUCT B Configuration split	1 on stage 1	0.5 stage 1 0.5 on stage 2	
Productivity	18375 Tcom/year	17813 Tcom/year	
Productivity	1.72 TMS/h	1.66 TMS/h	
Water comsuption	6.7 kgeau/kDS	4.4 kgeau/kDS	
Evaporation rate	3.0 T/h	3.0 T/h	



Split diafiltration water on stage 1 & 2 is more efficient

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CONCLUSION

- New model approach for nanofiltration and reverse osmosis with osmotic pressure measurement method for complex product
- Easy implementation through custom model interface
- Parameters estimation tool for model validation
- GSA tool for scale-up and Quality by Design approach

In summary

- Food and beverage industries face a host of challenges including:
  - Cost pressures and supply chain uncertainty
  - Sustainability
  - Changing consumer demands
- Digitalization and digital twin creation is a growing trend
- Process modelling is a key part of digitalization which can help:
  - Scale up confidently
  - Improve process efficiency
  - Maintain product quality
  - Manage uncertainty

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