

## Application of the Ensemble Kalman Filter for Improved Mineral Resource Recovery (PPT)

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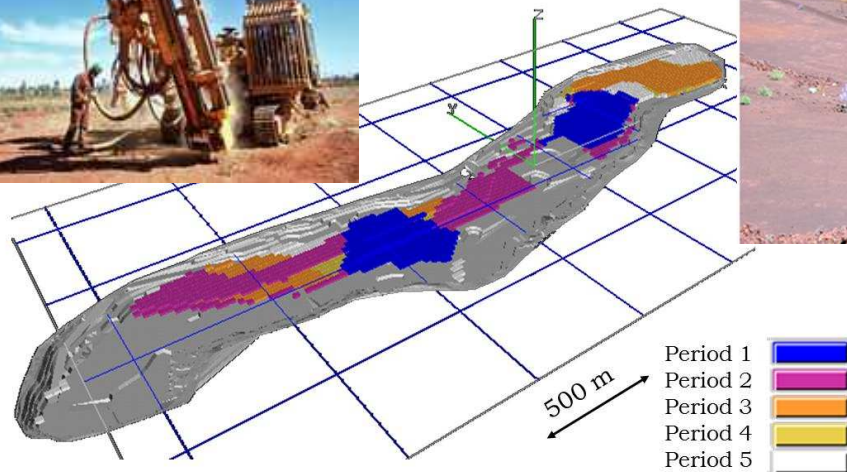
# Application of the Ensemble Kalman Filter for Improved Mineral Resource Recovery

C. Yüksel, M.Sc.

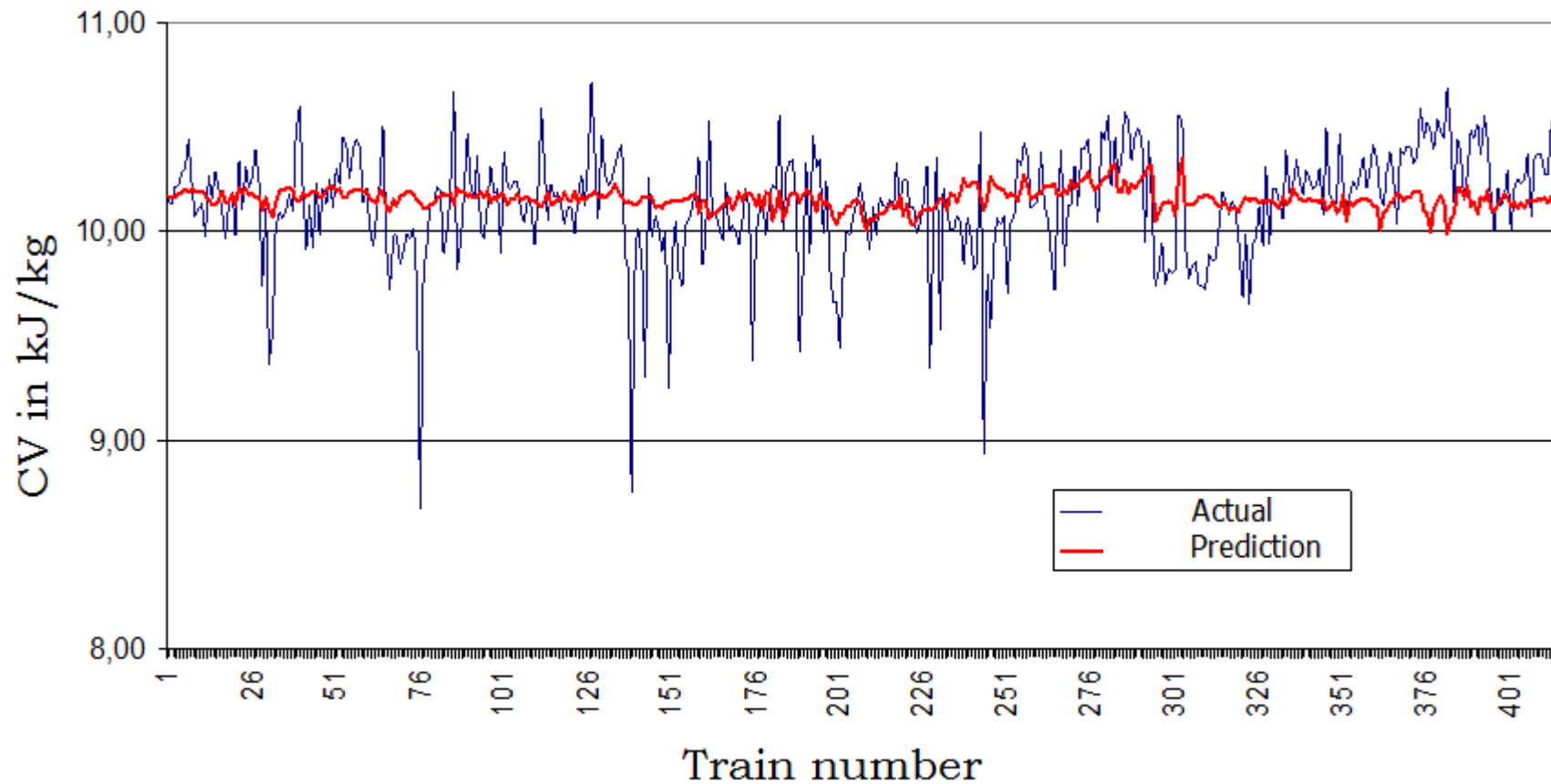
J. Benndorf, PhD, MPhil, Dipl-Eng.

*Department of Geoscience & Engineering, Delft University of Technology, Delft, the Netherlands*

# The Flow of Information



# Uncertainty in Model-based Prediction





# New Potential: Sensor Data



## Increasing Availability of Sensor Based Online Data:

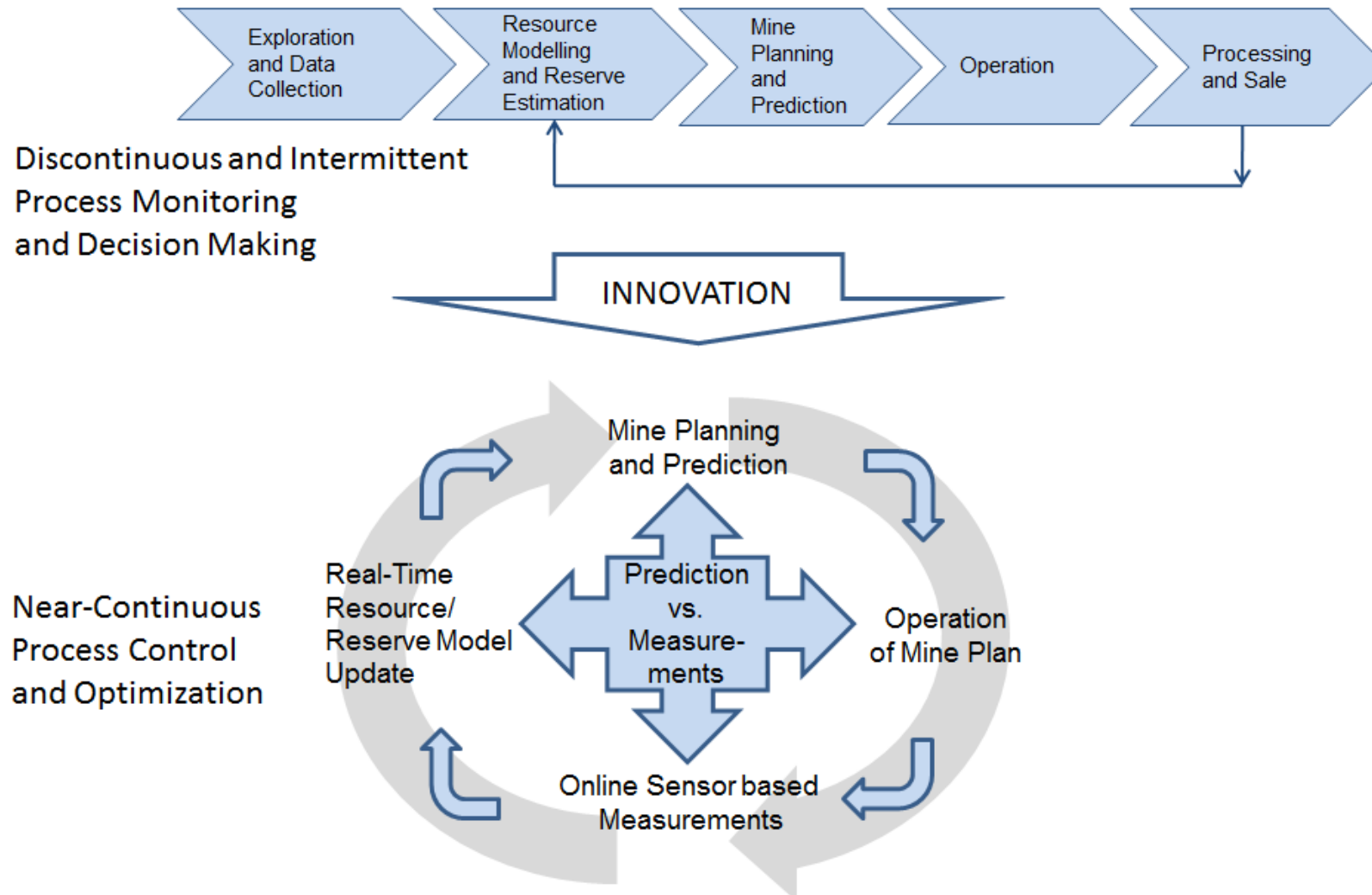
- Material characterization (geo-chemical, textural and physical properties)
- Equipment performance, upstream and downstream (e.g. efficiency, down-time)
- Equipment location (e.g. GPS, UPS)

# Content

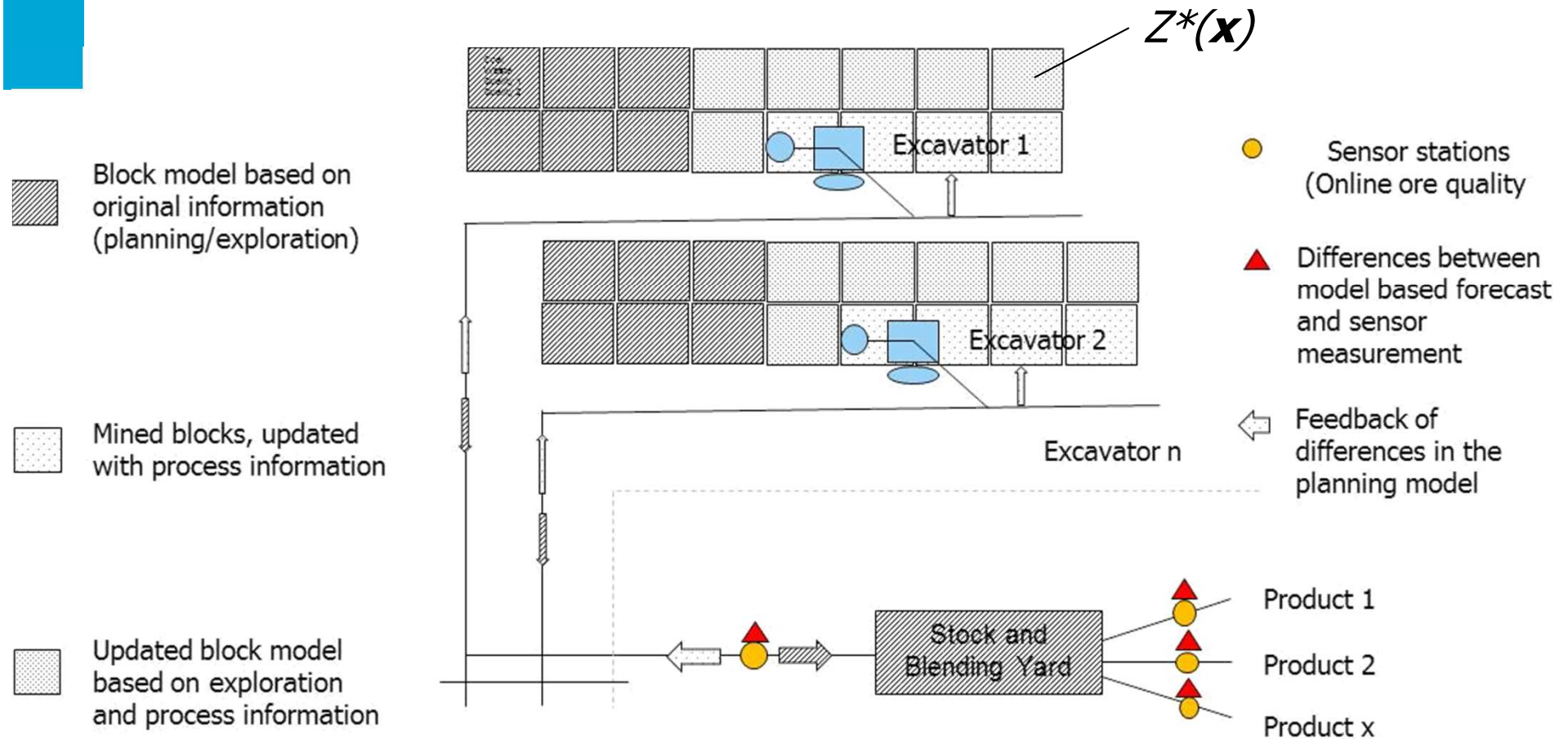
## How can we make best use of the available data?

- Closing the Loop: A feed-back framework for Real-Time Resource Model  
Updating
  - A Kalman Filter Approach
- Using Online Data for Improved Production Control
- Illustrative Case Study: Coal

# Towards Closed-Loop Management

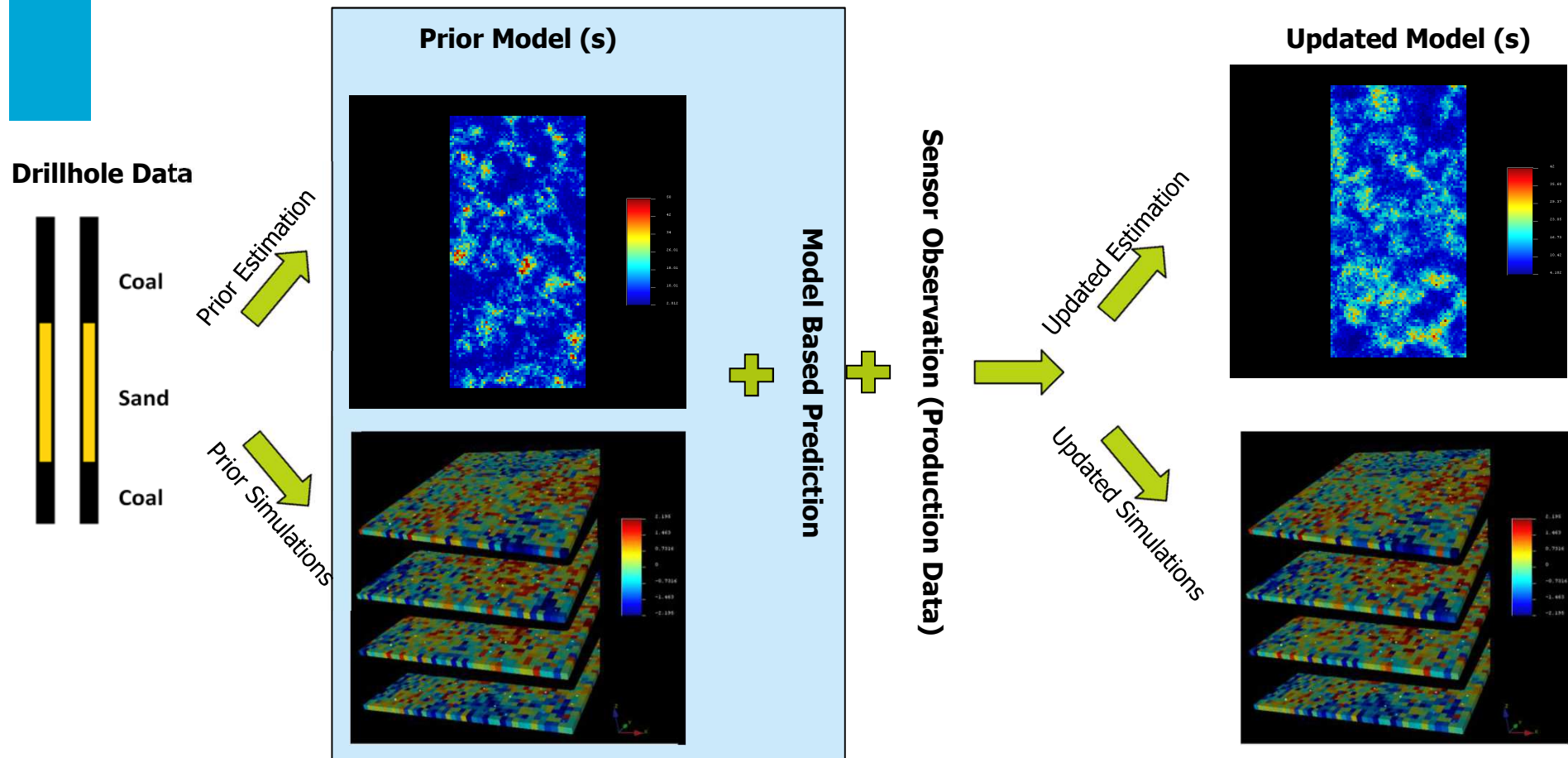


# Towards Closed-Loop Management





# Towards Closed-Loop Management

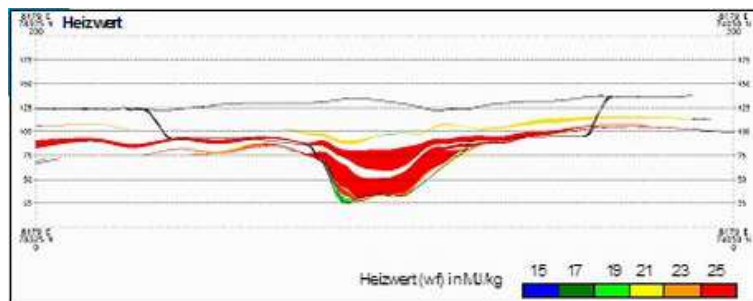


# Resource Model

## Generation of Prior Models

### Interpolation (Kriging)

- Best local estimation,
- Minimization of error-variance estimate.

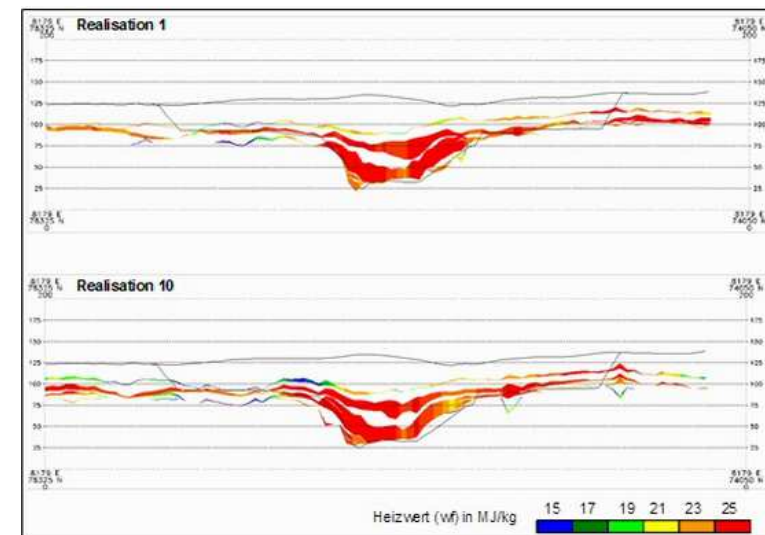


Seam Geometry and CV

(Benndorf 2013)

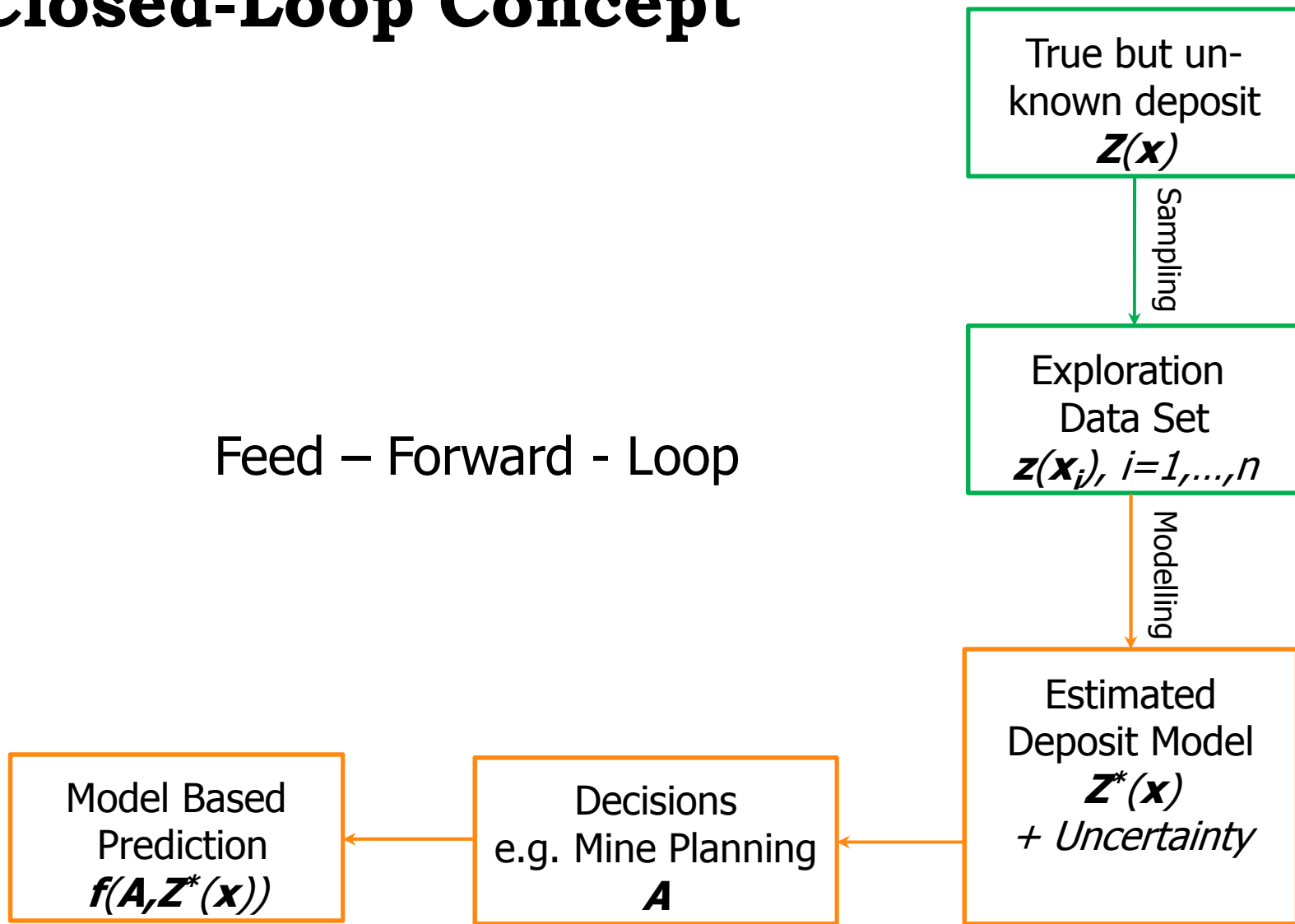
### Simulation Realisation 1&10 (Conditional Simulation)

- Represent possible scenarios about the deposit,
- Represent structural behavior of data (in-situ variability),
- Modelled by many different realizations,
- Differences between realizations capture uncertainty

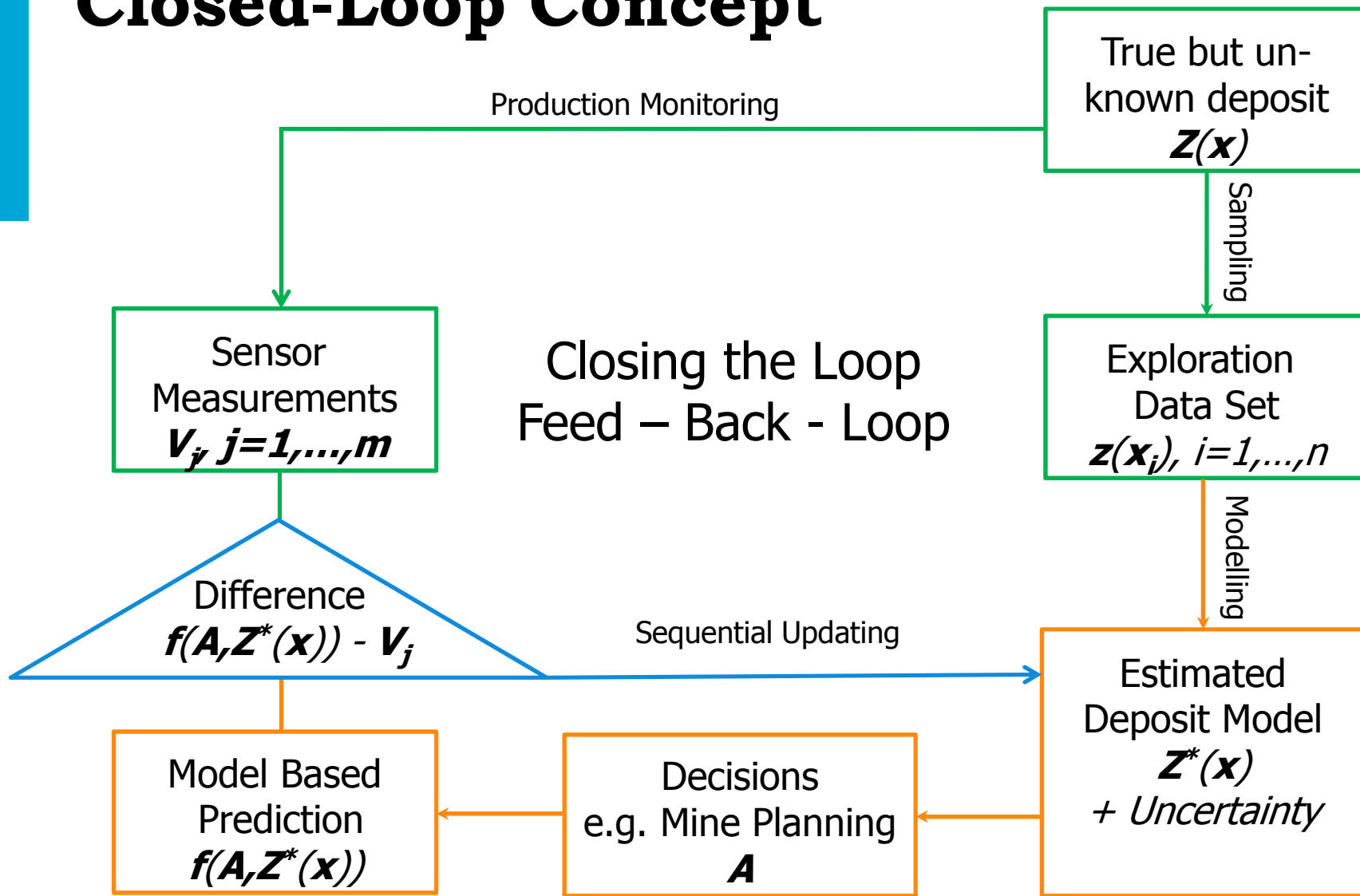


# Closed-Loop Concept

Feed – Forward - Loop

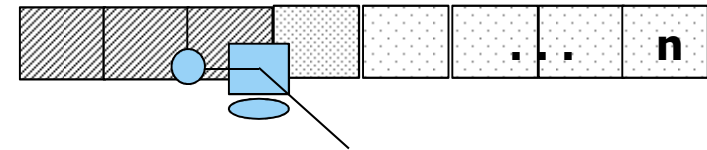
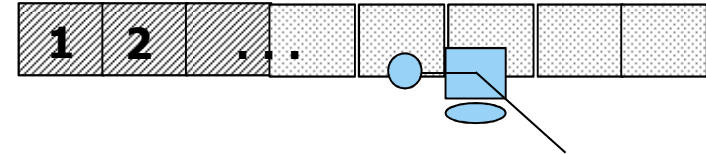


# Closed-Loop Concept



# Linking Model and Observation

- $n$  mining blocks
- each of the blocks contributes to a blend, which is observed at a sensor station at time  $t_i$
- $m$  measurements are taken
- $a_{i,j}$  proportion block  $i$  contributes to the material blend, observed at time  $j$  by measurement  $l_j$



*Production sequence – Matrix A*

$$\begin{array}{c} \text{Observations} \end{array}
 \begin{array}{c} \text{Mining Blocks} \\ \left[ \begin{array}{ccc} a_{1,1} & \cdots & a_{1,m} \\ \vdots & \ddots & \vdots \\ a_{n,1} & \cdots & a_{n,m} \end{array} \right] \end{array}$$



# Resource Model Updating

## Sequential Model Updating - A Kalman Filter Approach

$$\mathbf{Z}^*(\mathbf{x}) = \mathbf{Z}_0^*(\mathbf{x}) + \mathbf{K} (\mathbf{v} - \mathbf{A}\mathbf{Z}_0^*(\mathbf{x}))$$

$\mathbf{Z}^*(\mathbf{x})$  ... updated short-term block model (a posteriori)

$\mathbf{Z}_0^*(\mathbf{x})$  ... prior block model based (without online sensor data)

$\mathbf{v}$  ... vector of observations (sensor signal at different points in time  $t$ )

$\mathbf{A}$  ... design matrix representing the contribution of each block per time interval to the production observed at sensor station

$\mathbf{K}$  ... updating factor (Kalman-Gain)

# Resource Model Updating

## Sequential Model Updating – A “BLUE”

Estimation error:

$$\mathbf{e}(\mathbf{x})_{t+1} = \mathbf{z}(\mathbf{x})_{t+1} - \mathbf{z}^*(\mathbf{x})_{t+1}$$

Estimation variance to be minimized:

$$\mathbf{C}_{t+1,t+1} = E\left[ \mathbf{e}(\mathbf{x})_{t+1} \mathbf{e}(\mathbf{x})_{t+1}^T \right]$$

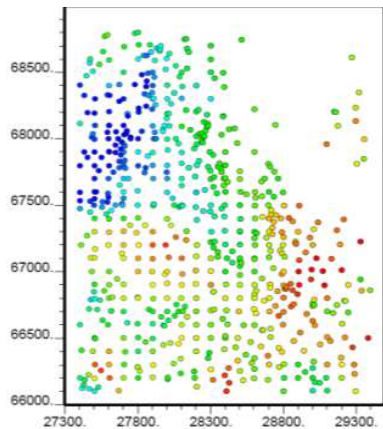
Updating factor:

$$\mathbf{K} = \mathbf{C}_{t,t} \mathbf{A}^T (\mathbf{A} \mathbf{C}_{t,t} \mathbf{A}^T + \mathbf{C}_{v,v})^{-1}$$

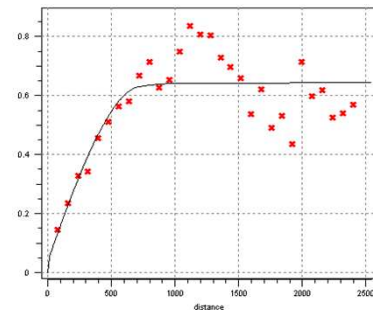
# Resource Model Updating

Sequential Model Updating – The Integrative Character

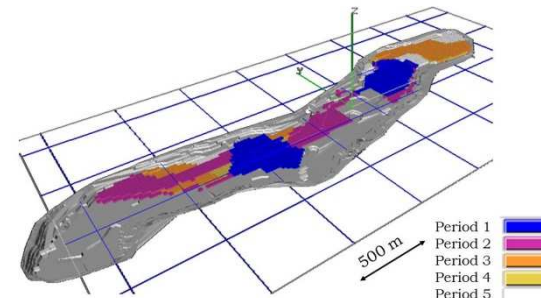
$$K = C_{t,t} A^T (A C_{t,t} A^T + C_{v,v})^{-1}$$



*Model Uncertainty*



Schedule



*Extraction Sequence*



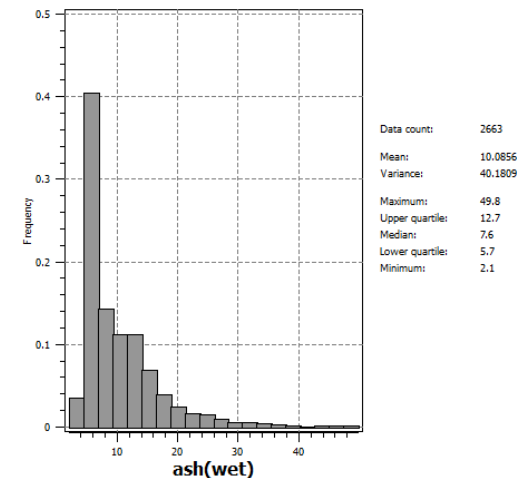
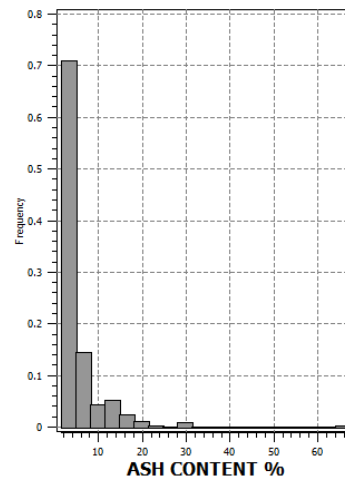
*Sensor Precision*

# Resource Model Updating

## Sequential Model Updating

### Main challenges:

- Large grids
  - Industrial Case: 4,441,608 blocks
- Non-linear relationships between model and observation
- Non-Gaussian data

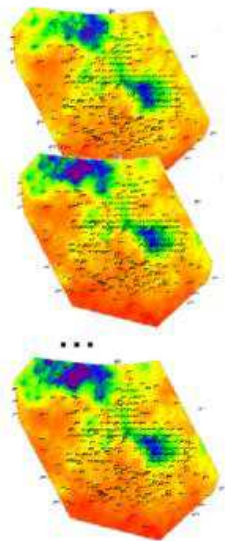


# Resource Model Updating

## Sequential Model Updating

### A Non-Linear Version – The Ensemble Kalman Filter

*n* realizations  
(Ensamble)



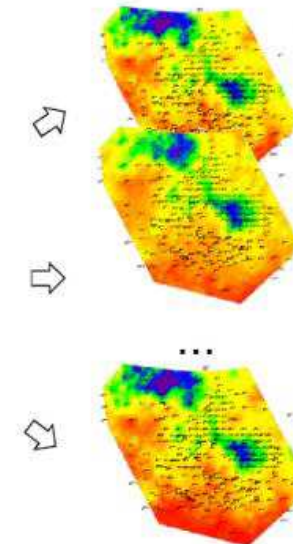
Model based prediction  $AZ_0(x)$

Observations  $l$

Difference  $(l - AZ_0(x))$

$$Z^*(x) = Z_0(x) + K(l - AZ_0(x))$$

*n* **updated** realizations  
(**updated** Ensamble)



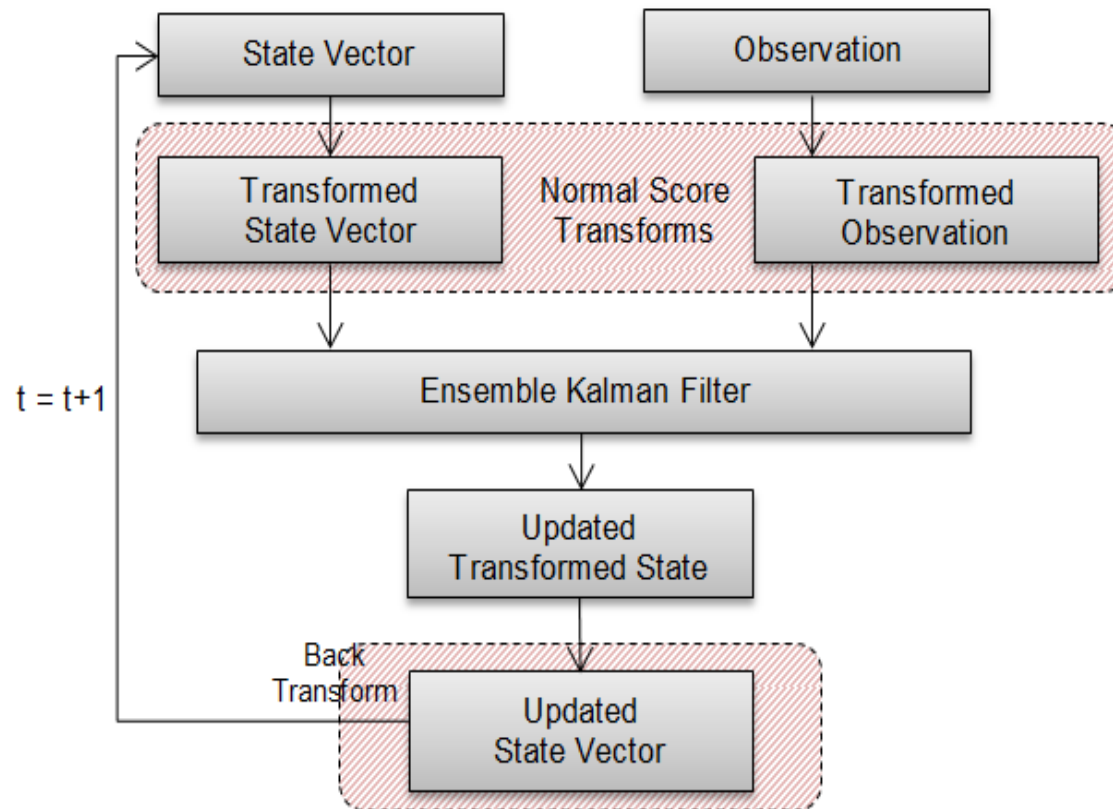
(Reproduced after Geir Evensen 1993)



# Resource Model Updating

Sequential Model Updating

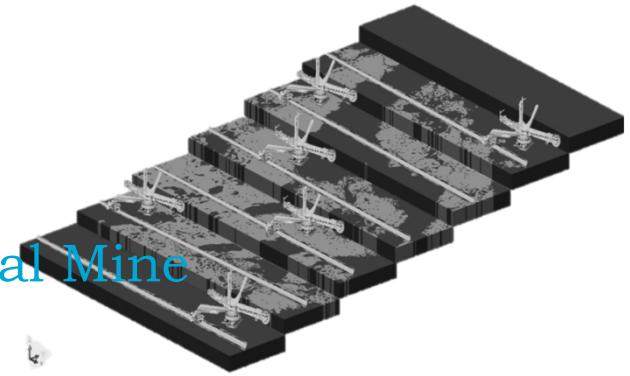
To handle Non-Gaussian Data... N-Score-Ensemble Kalman Filter\*



\*Z Haiyan, J J Gomez-Hernandez, H H Franssen, L Li. 2011. An approach to handling non-Gaussianity of parameters and state variables. *Advances in Water Resources*, 844-864.

# Illustrative Case Study

## Updating the Calorific Value in a Large Coal Mine

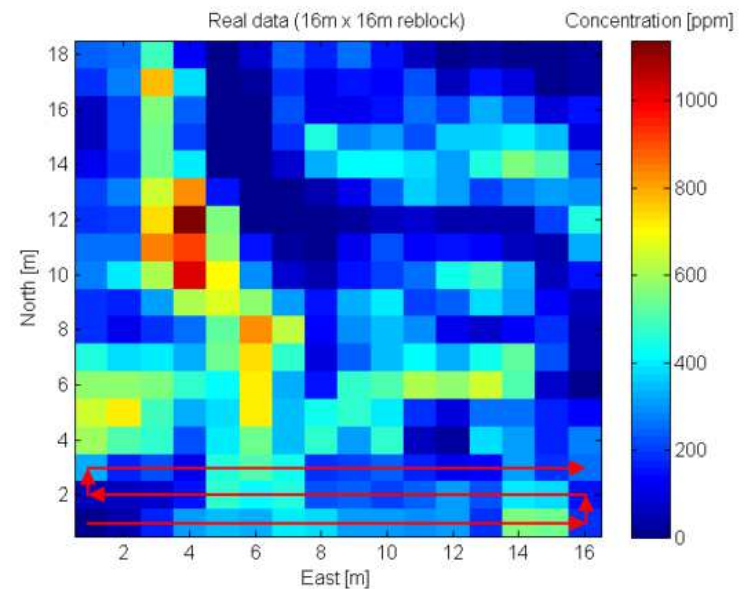


### Case Study: Walker Lake Data Set

(Exhaustive "true" data are available)

### Model based prediction:

- Estimated block model (5200t/block)
- Capacity Excavator 1: 500 t/h
- Capacity Excavator 2: 1.000 t/h

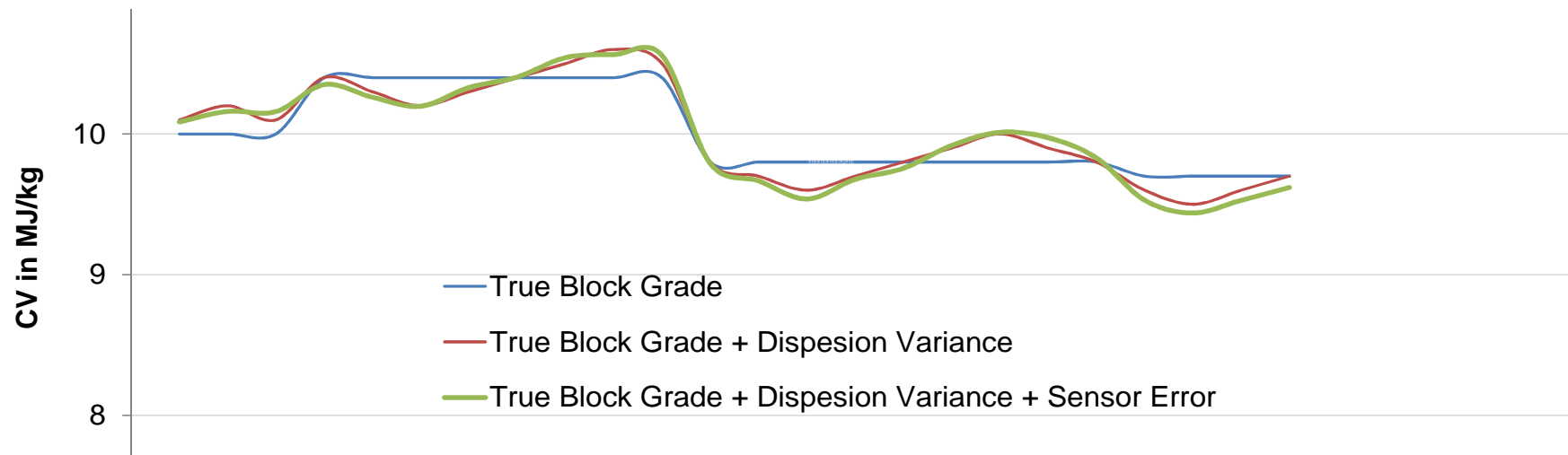


# Illustrative Case Study

## Updating the Calorific Value in a Large Coal Mine

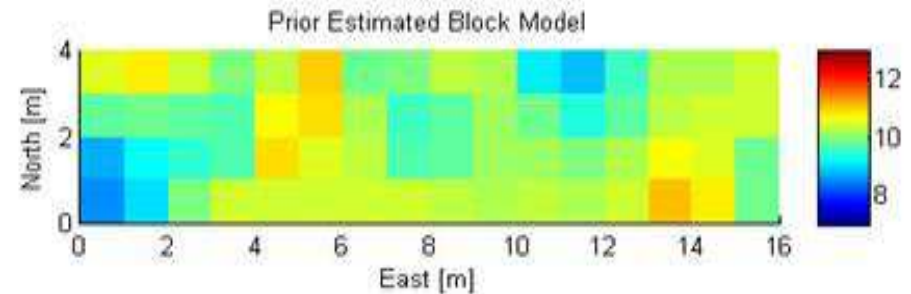
### Sensor Observations:

- Artificial sensor data for a 10 minute average (representing 250 t)
- Relative sensor error is varied between 1%, 5% and 10%
- Sensor data obtained:
  - Model based prediction + dispersion variance + sensor error

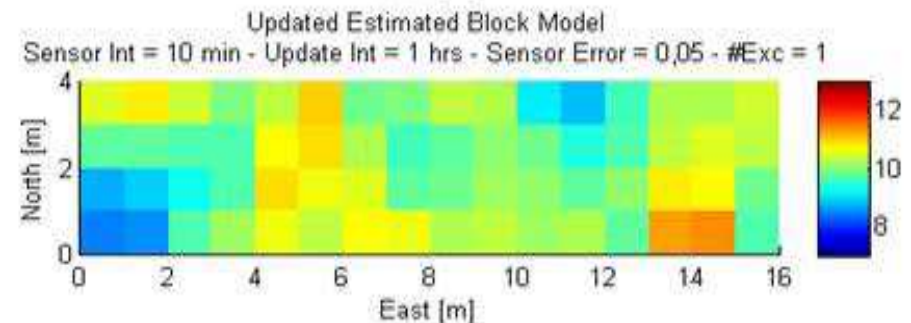


# Illustrative Case Study

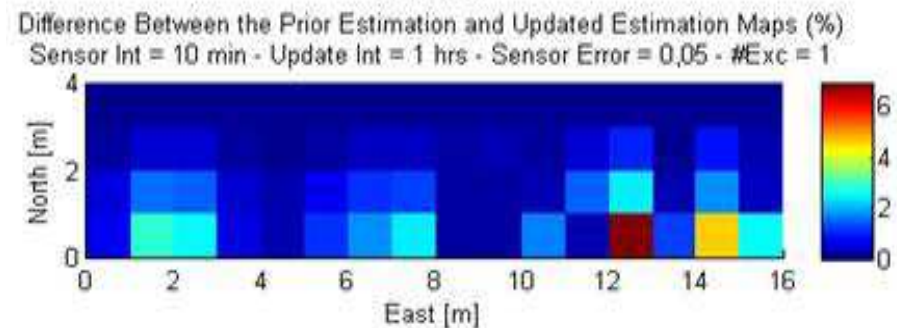
Prior Block Model  
based on Exploration Data



Updated Block Model  
Integrating Sensor Data



Differences

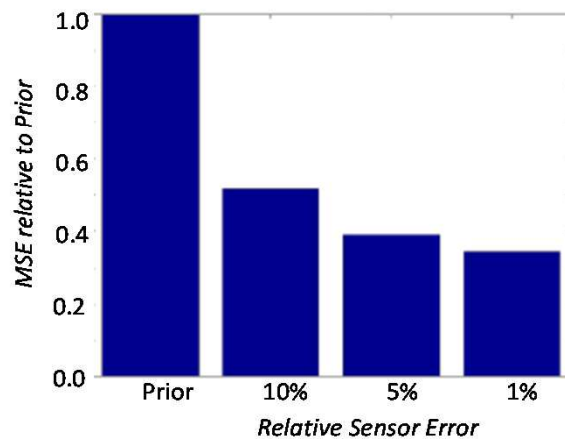


# Illustrative Case Study

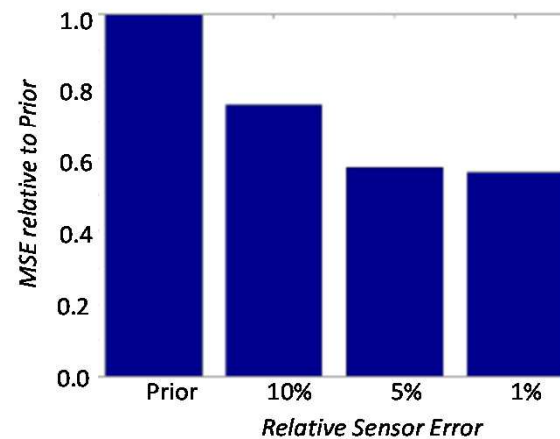
## Comparison to Reality

### Kalman-Filter: 2 Excavators

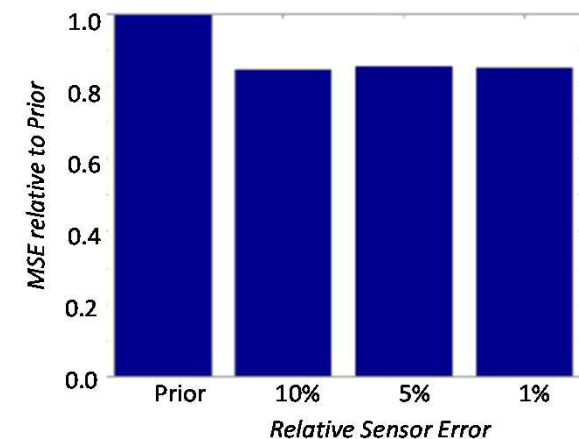
MSE-mined



MSE- adjacent blocks



MSE- 2 blocks away

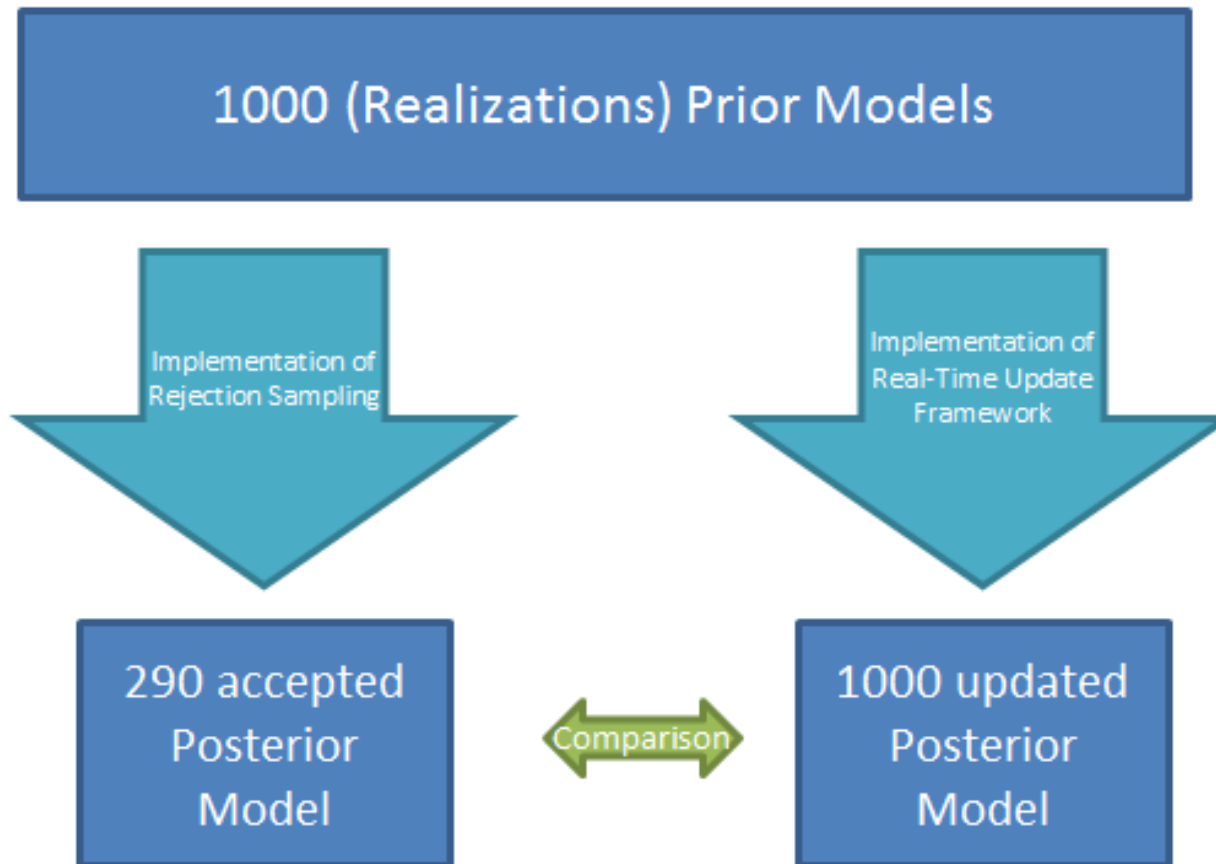


$$\text{MSE} = \frac{1}{N} \sum_{i=1}^N (z^*(\mathbf{x}_i) - z(\mathbf{x}_i))^2$$



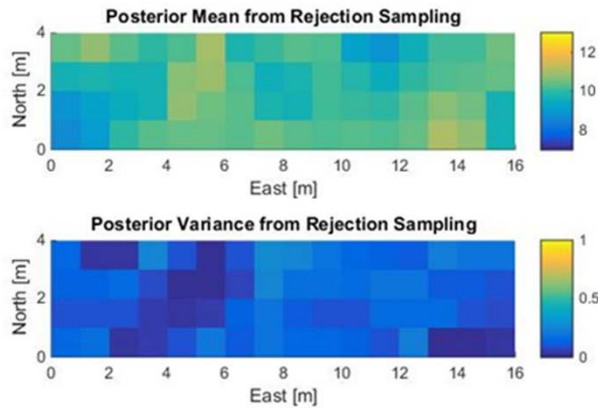
# Illustrative Case Study

## Rejection Sampling

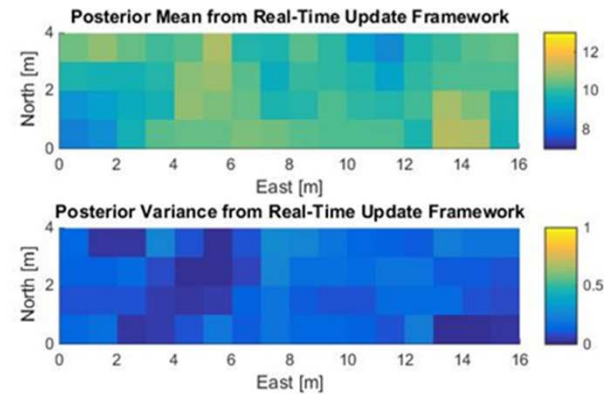


# Illustrative Case Study

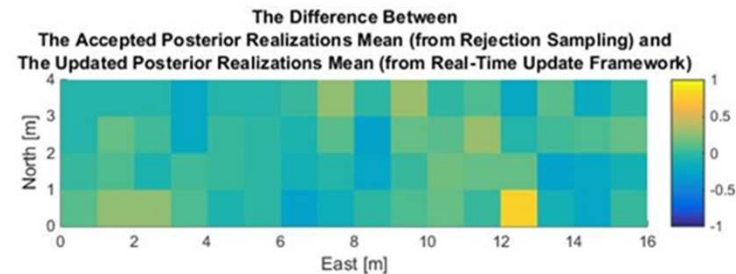
## Rejection Sampling



Average mean and variance maps of 290 posterior realizations accepted according to rejection sampling method



Average mean & variance maps of 1000 posterior realizations updated with EnKF framework



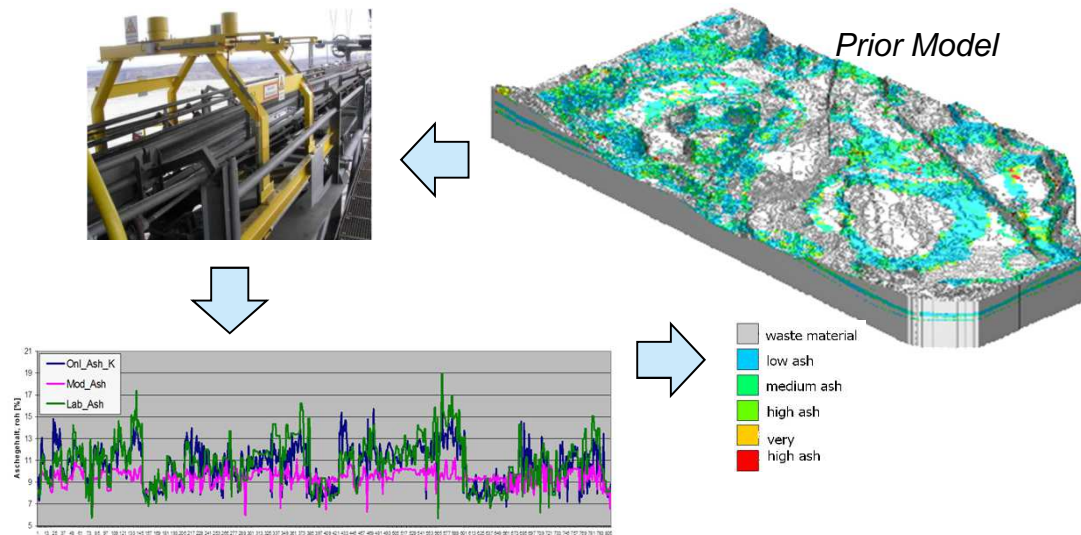
Difference map between the accepted posterior realizations from rejection sampling and updated posterior realizations from real-time update framework

# Illustrative Case Study - Results

- Significant improvement in prediction
- Increased confidence in dispatch decisions
  - Less miss-classified blocks (ore/waste)
  - Less shipped train loads out of spec
- Increased customer satisfaction and revenue
- Magnitude of improvement depends on level of exploration, variability and sensor error

# Current Work

- EU - RFCS funded project RTR0-Coal



with partners:



VORWEG GEHEN

# Conclusions

- Modern ICT provides online data, which can be the basis for (near-) continuous process monitoring at different stages of the mining value chain
- Utilizing these data for (near-) real-time decision making offers huge potential for more sustainable extraction of mineral resource
- Closed Loop Concepts offer:
  - Integration of prediction and process models with data gathering
  - Interdisciplinary and transparent project communication (breaking the silos)
  - More complex use of data for increased resource efficiency



**Thank You for Your Attention**

**Contact: Cansın Yüksel  
C.Yuksel@tudelft.nl**

*Source: RWE*

