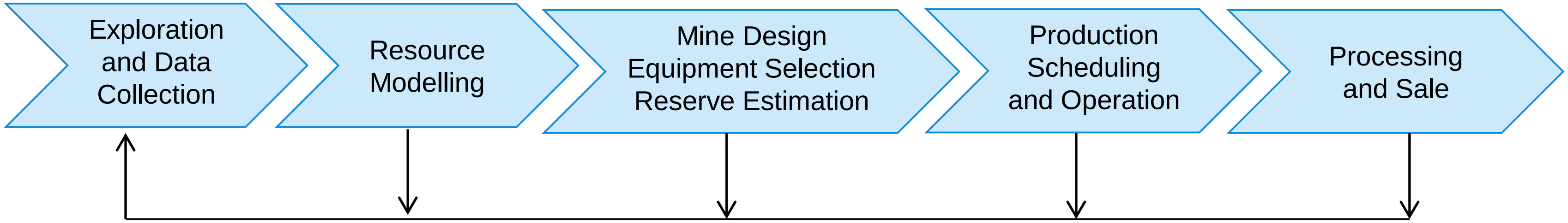
Application of the Ensemble Kalman Filter for Improved Mineral Resource Recovery

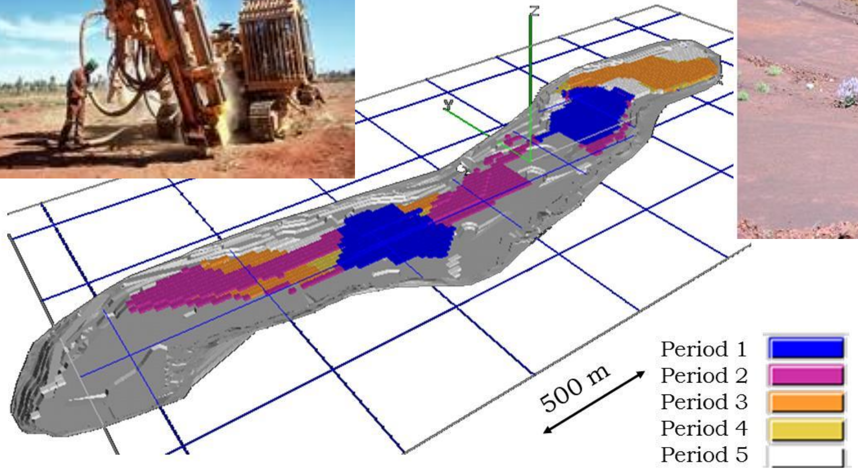
C. Yüksel, M.Sc.

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

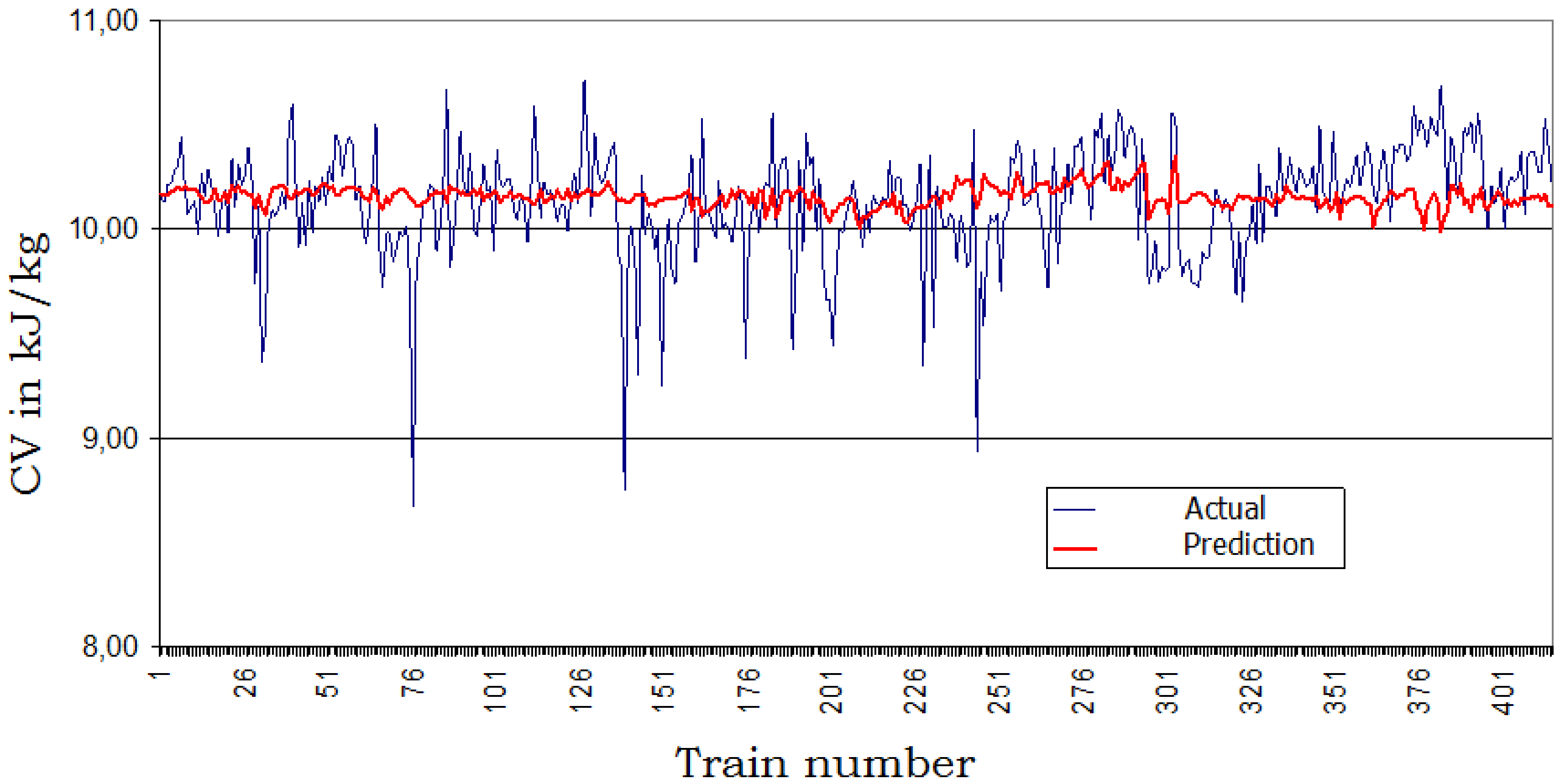
Department of Geoscience & Engineering, Delft University of Technology, Delft, the Netherlands

The Flow of Information

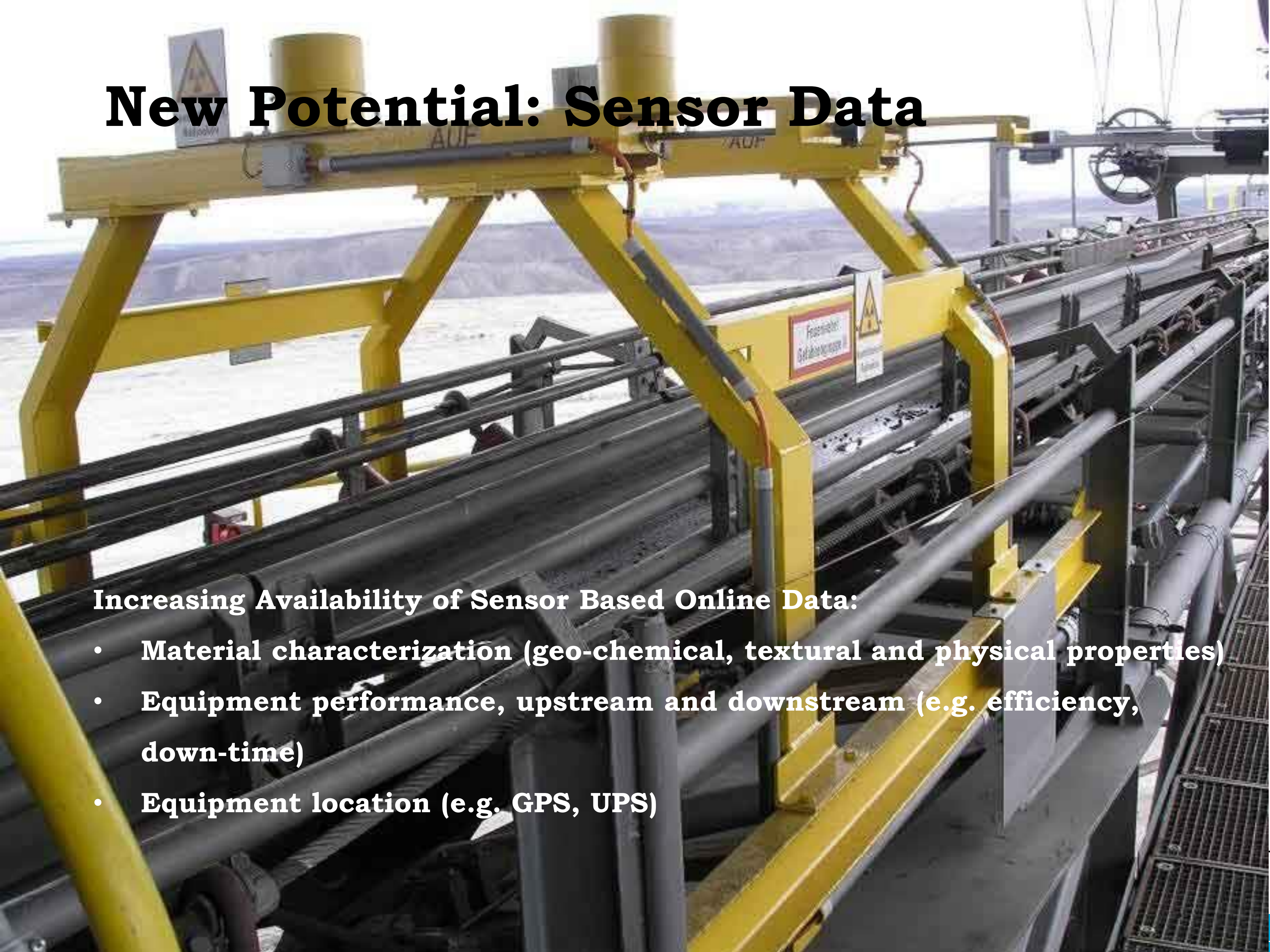




Uncertainty in Model-based Prediction



New Potential: Sensor Data



Increasing Availability of Sensor Based Online Data:

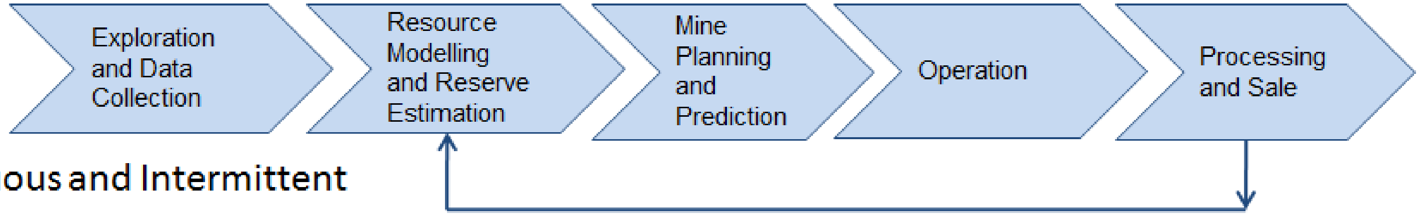
- **Material characterization (geo-chemical, textural and physical properties)**
- **Equipment performance, upstream and downstream (e.g. efficiency, down-time)**
- **Equipment location (e.g. GPS, UPS)**

Content

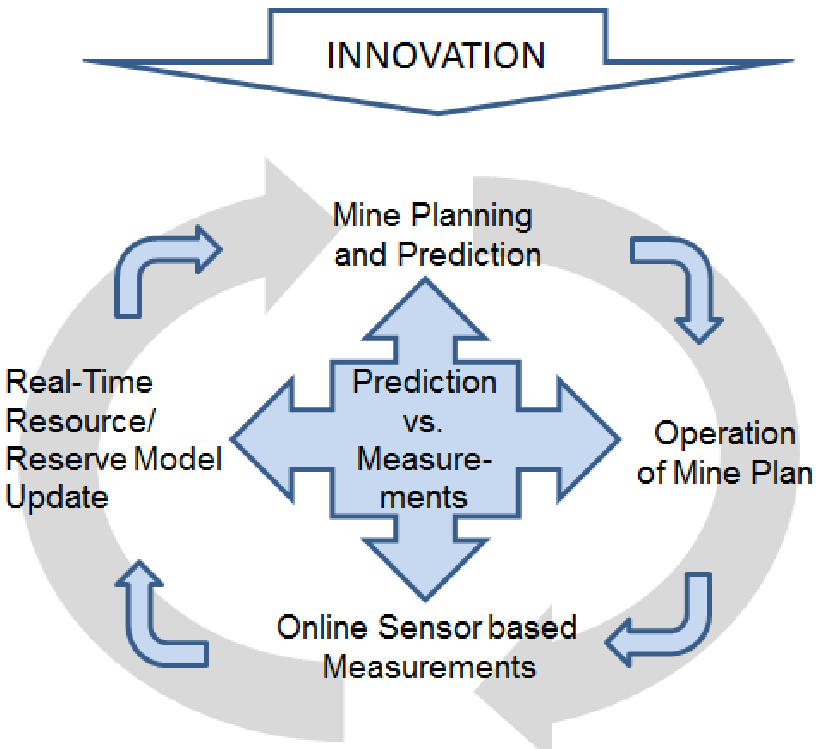
How can we make best use of the available data?

- 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

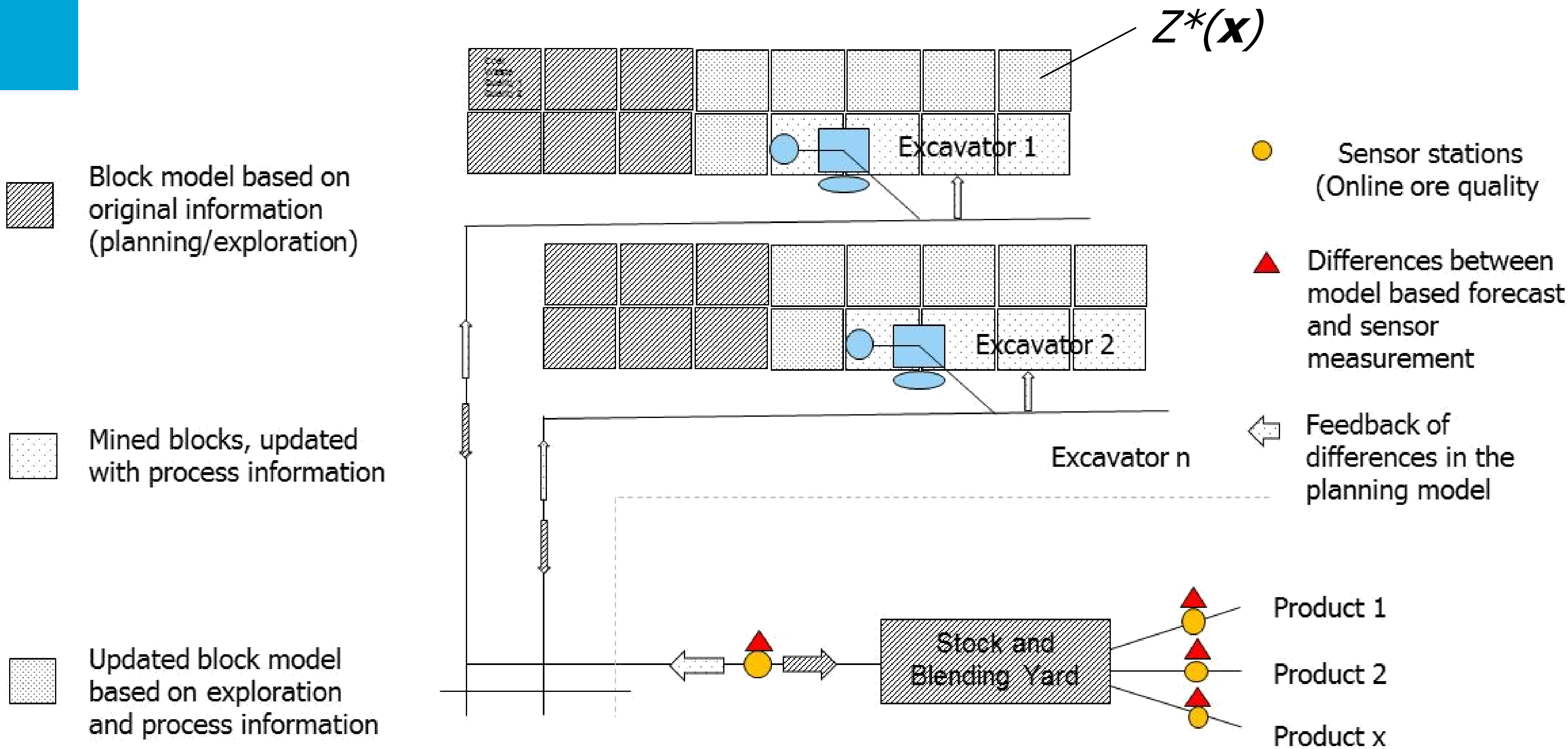


Discontinuous and Intermittent Process Monitoring and Decision Making

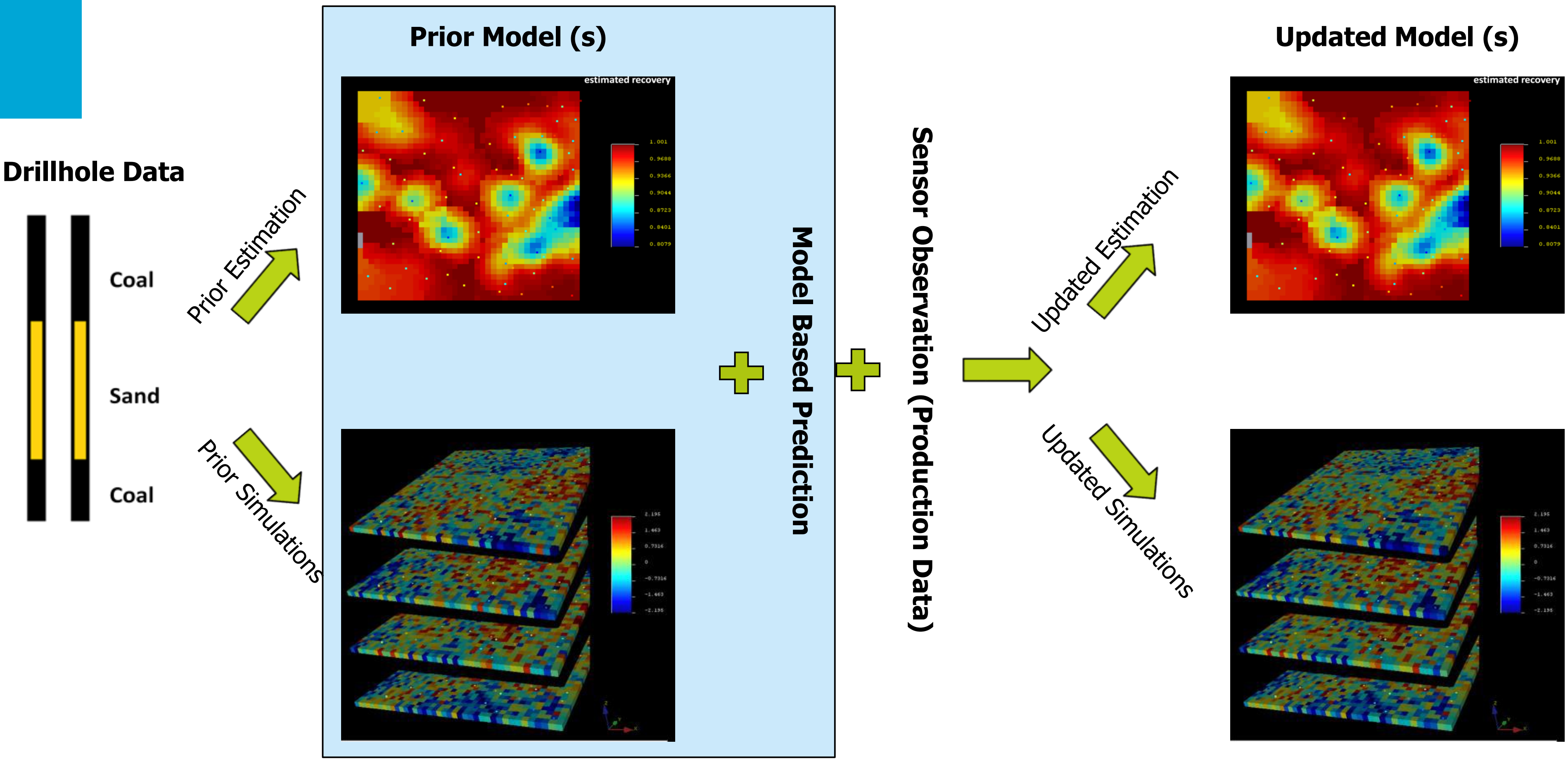


Near-Continuous Process Control and Optimization

Towards Closed-Loop Management



Towards Closed-Loop Management

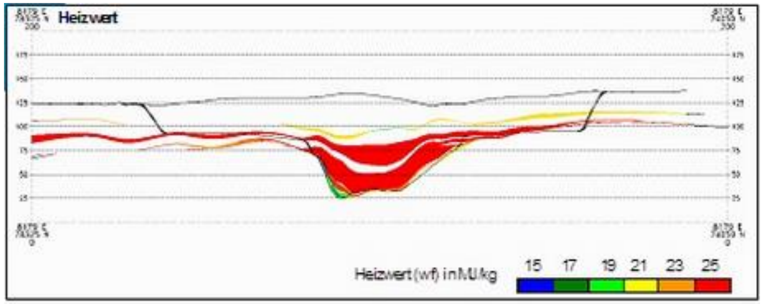


Resource Model

Generation of Prior Models

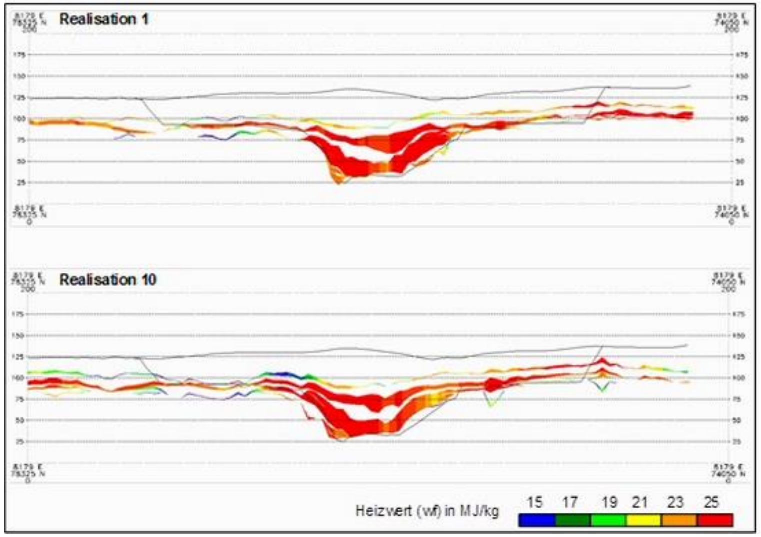
Interpolation (Kriging)

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



Simulation Realisation 1&10 (Conditional Simulation)

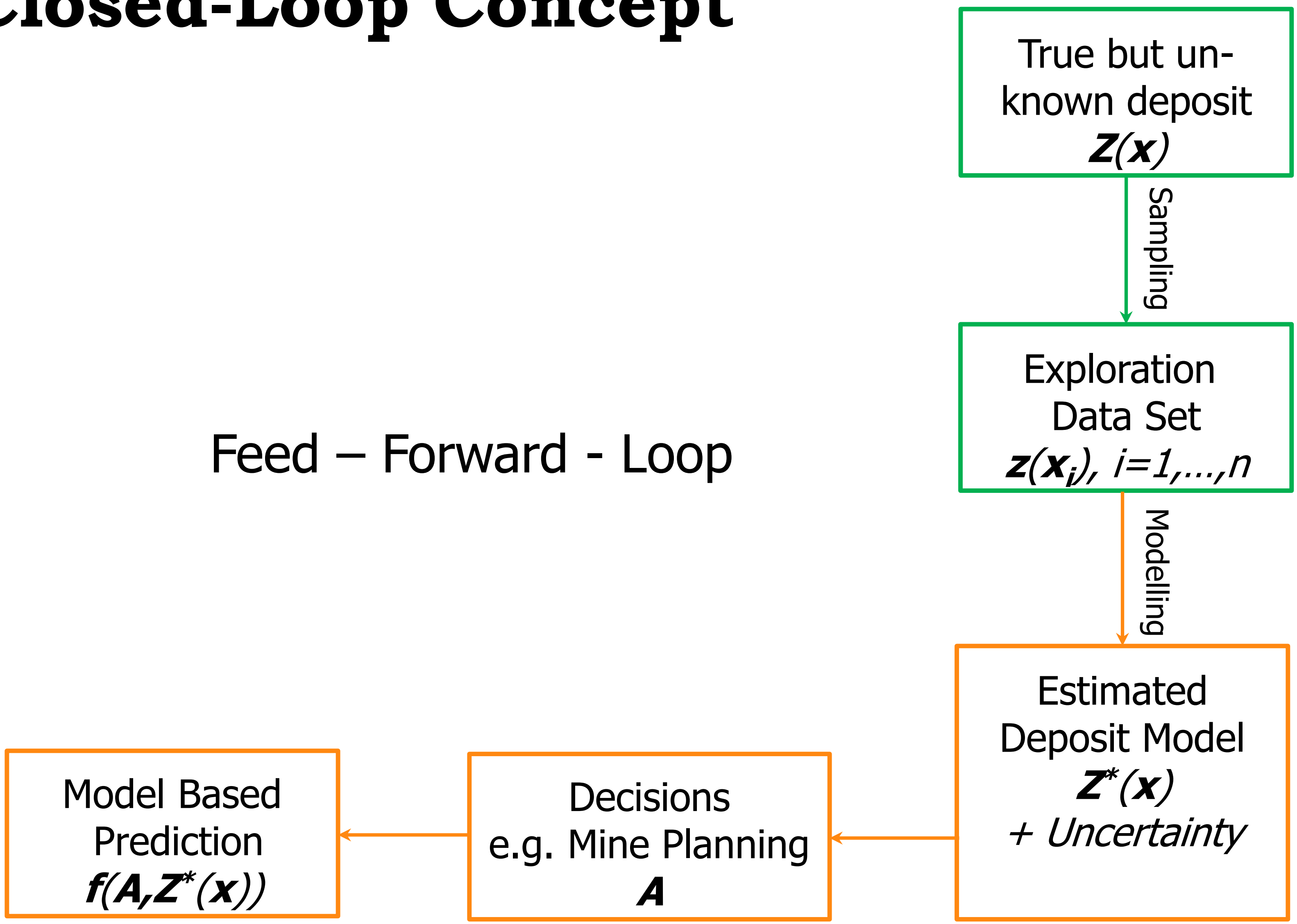
- Represent possible scenarios about the deposit,
- Represent structural behavior of data (in-situ variability),
- Modelled by many different realizations,
- Differences between realizations capture uncertainty



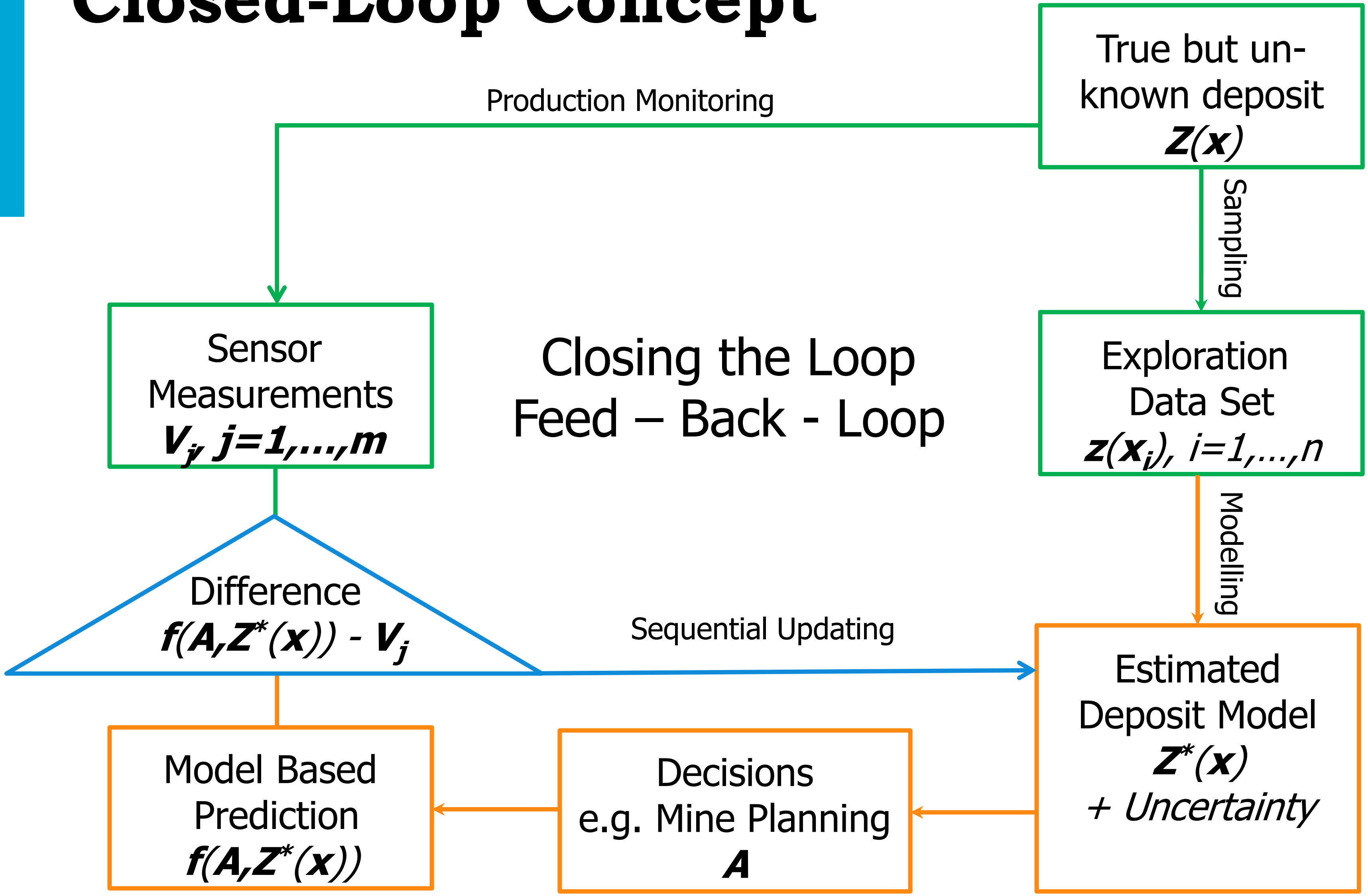
Seam Geometry and CV

(Benndorf 2013)

Closed-Loop Concept

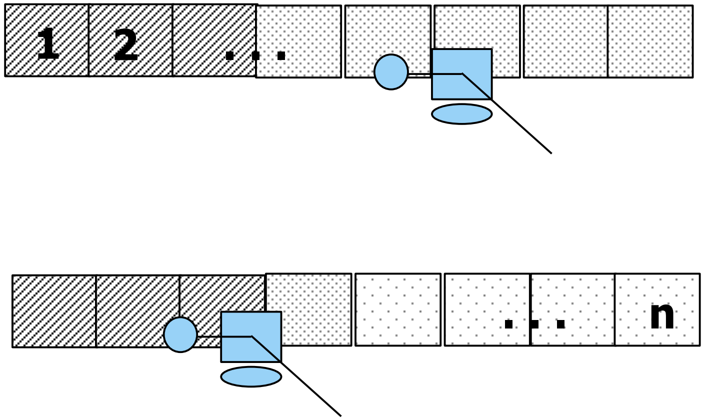


Closed-Loop Concept



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_i



*Production sequence – Matrix **A***

$$\begin{array}{cc} & \textit{Mining Blocks} \\ \rotatebox{90}{\textit{Observations}} & \begin{bmatrix} a_{1,1} & \cdots & a_{1,m} \\ \vdots & \ddots & \vdots \\ a_{n,1} & \cdots & a_{n,m} \end{bmatrix} \end{array}$$

Resource Model Updating

Sequential Model Updating - A Kalman Filter Approach

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

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

$\boldsymbol{Z}^*{}_{\boldsymbol{0}}(\boldsymbol{x})$ … prior block model based (without online sensor data)

v … vector of observations (sensor signal at different points in time t)

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

K … updating factor (Kalman-Gain)

Resource Model Updating

Sequential Model Updating – A “BLUE”

Estimation error:

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

Estimation variance to be minimized:

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

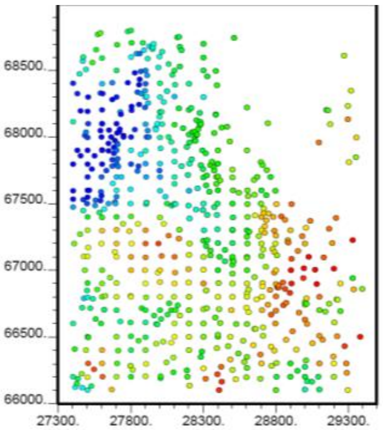
Updating factor:

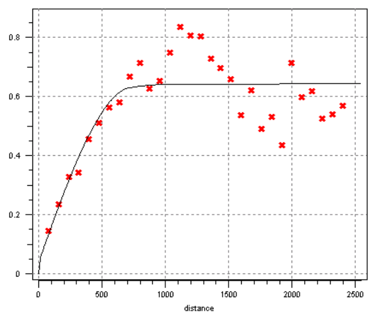
$$\boxed{\boldsymbol{K} = \boldsymbol{C}_{t,t}\boldsymbol{A}^{\boldsymbol{T}}(\boldsymbol{A}\boldsymbol{C}_{t,t}\boldsymbol{A}^{\boldsymbol{T}} + \boldsymbol{C}_{v,v})^{-\mathbf{1}}}$$

Resource Model Updating

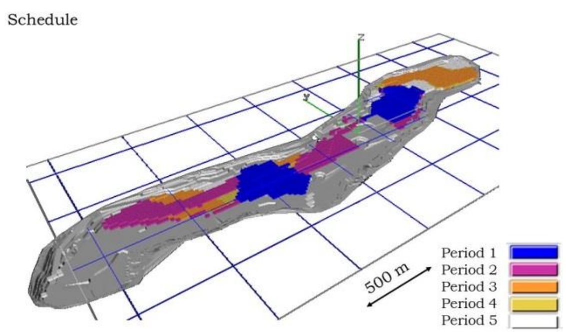
Sequential Model Updating – The Integrative Character

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





Model Uncertainty



Extraction Sequence

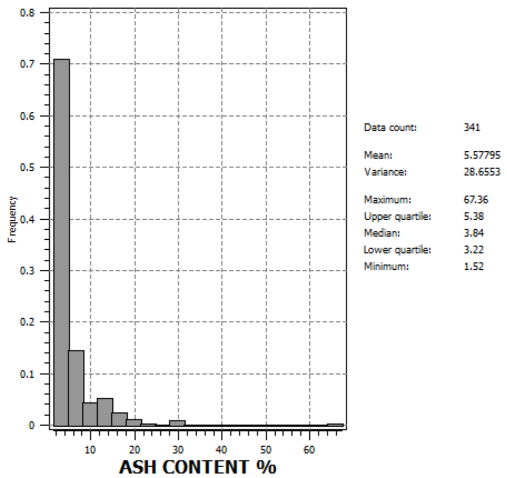
Sensor Precision

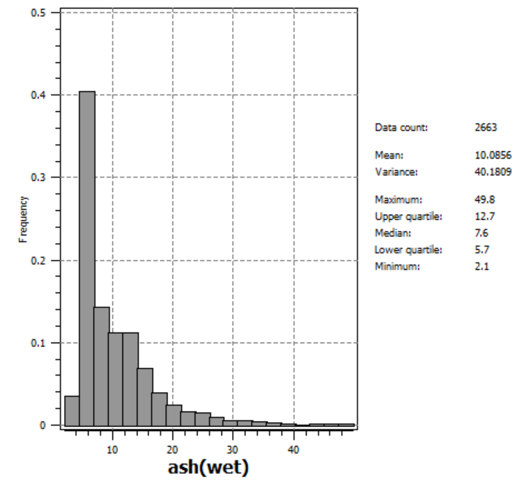
Resource Model Updating

Sequential Model Updating

Main challenges:

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

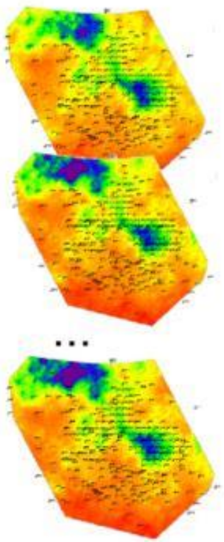




Resource Model Updating

Sequential Model Updating
A Non-Linear Version – The Ensemble Kalman Filter

n realizations
(Ensamble)



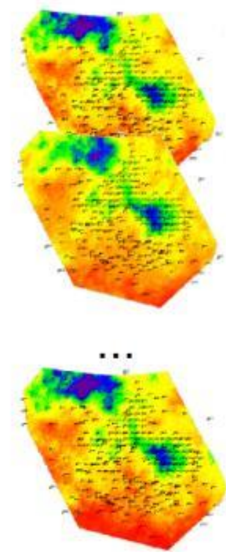
Model based prediction $AZ_0(x)$

Observations l

Difference $(l - AZ_0(x))$

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

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

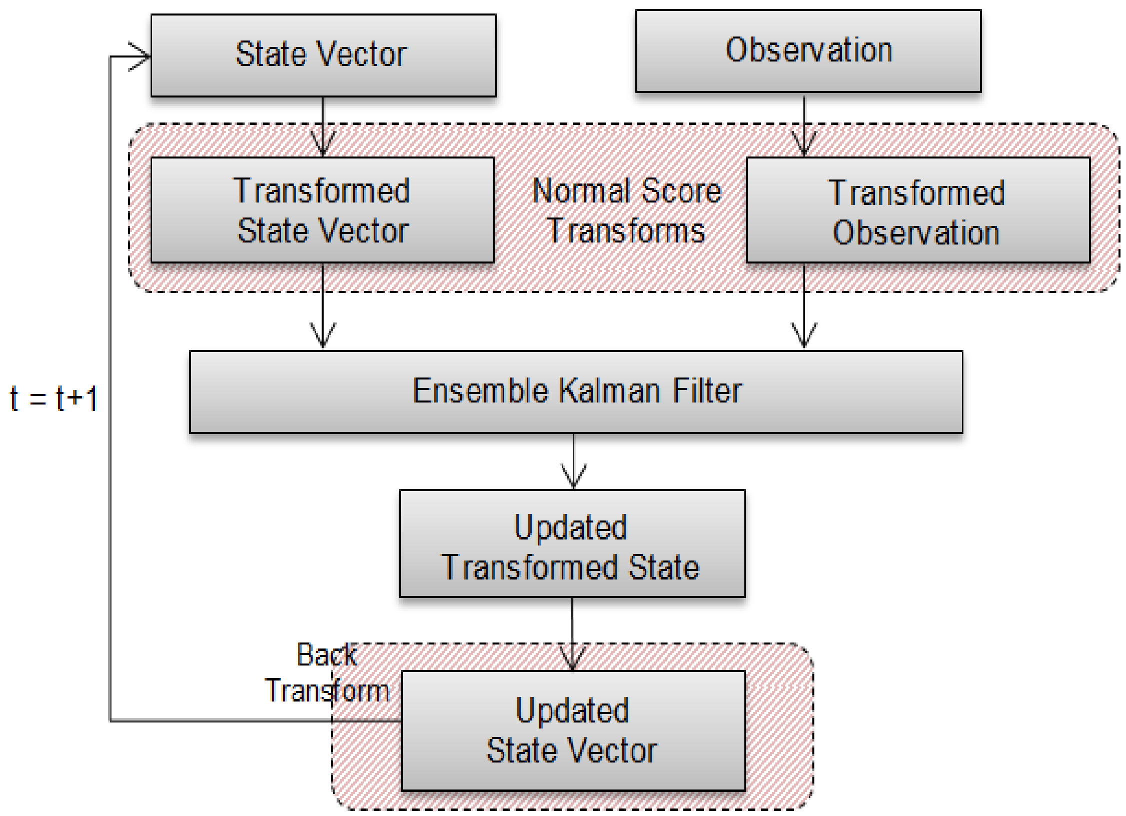


(Reproduced after Geir Evensen 1993)

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

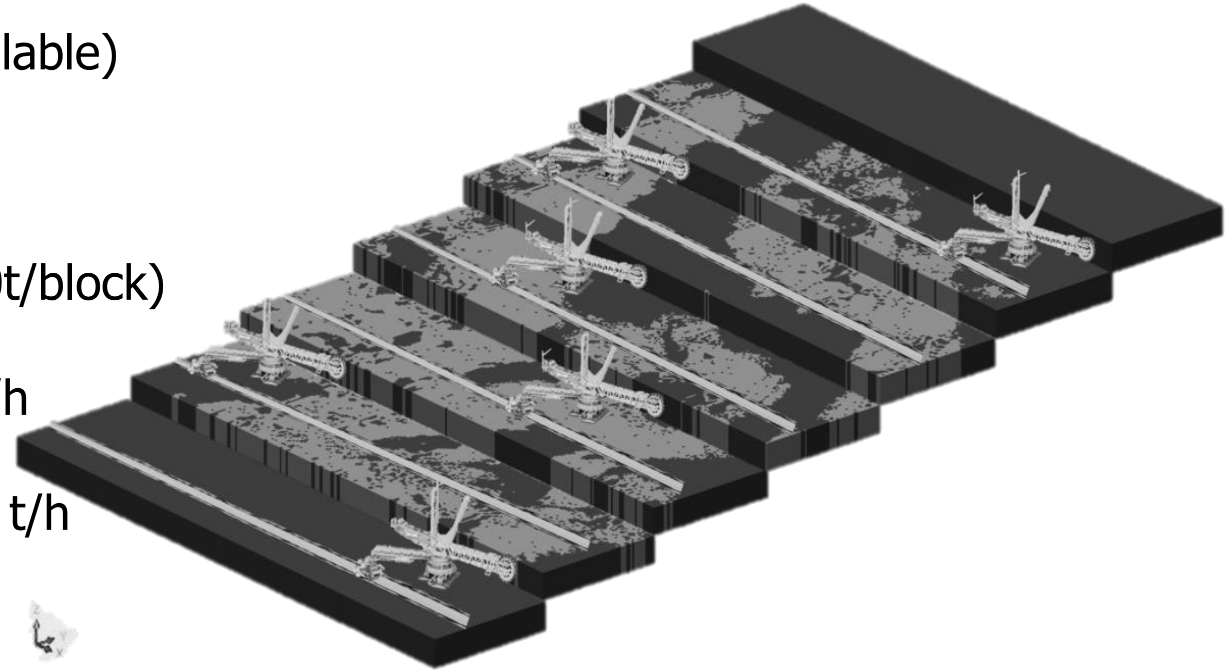
Updating the Calorific Value in a Large Coal Mine

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

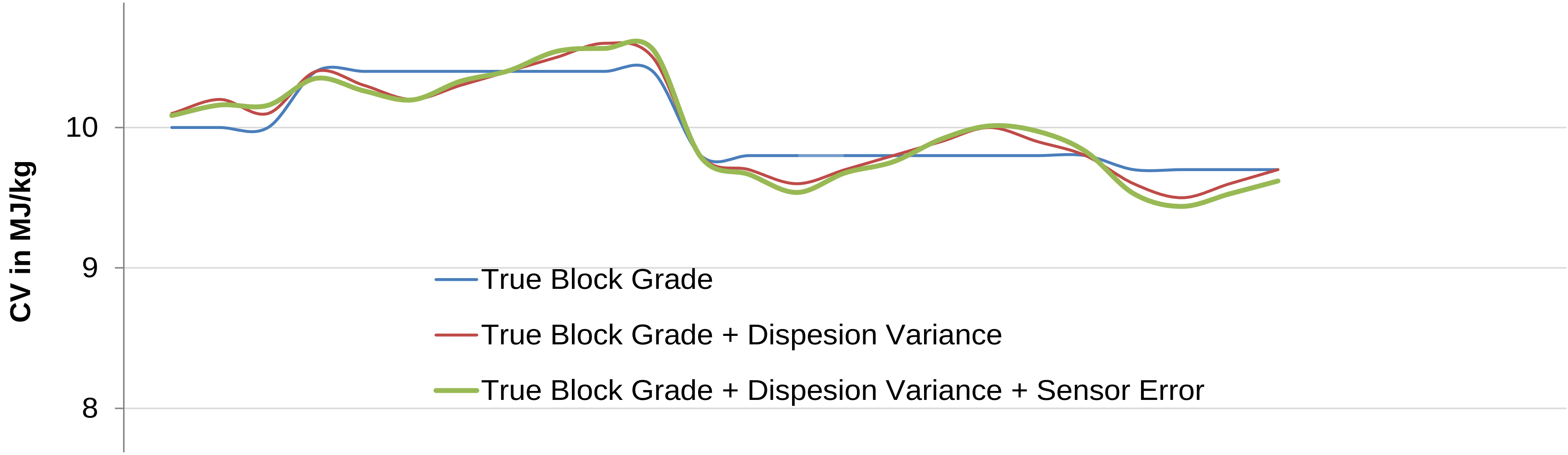


Illustrative Case Study

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

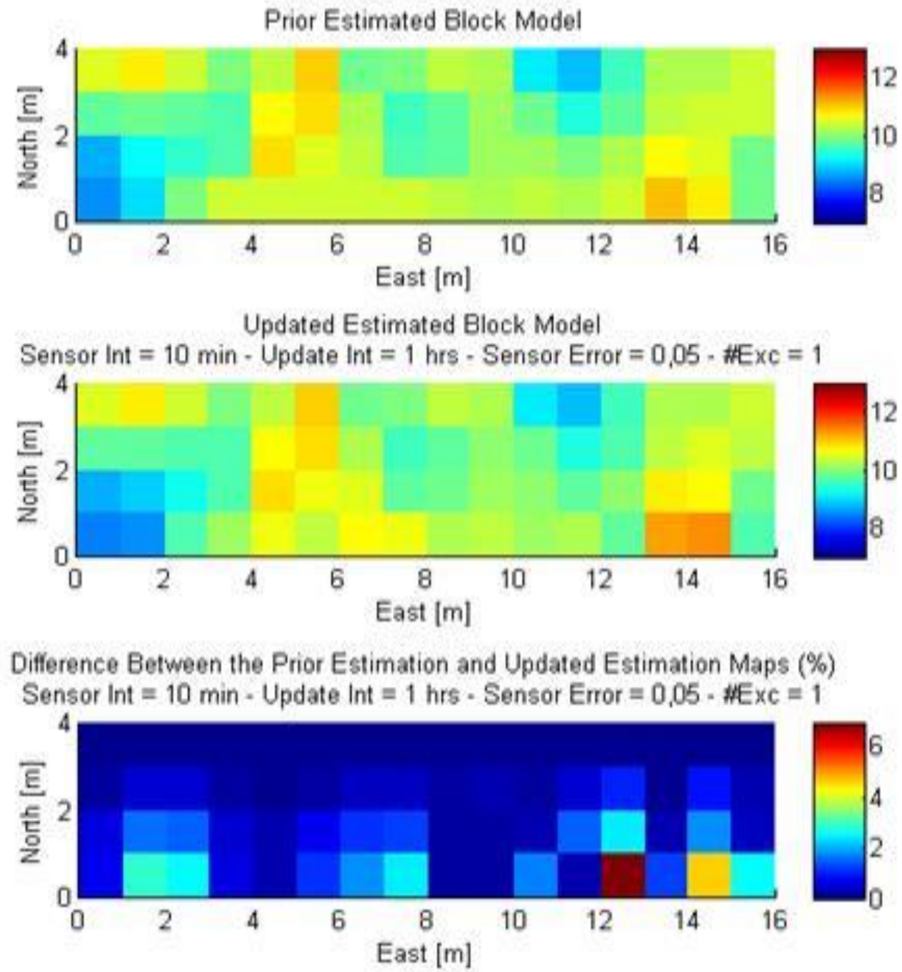


Illustrative Case Study

Prior Block Model
based on Exploration Data

Updated Block Model
Integrating Sensor Data

Differences

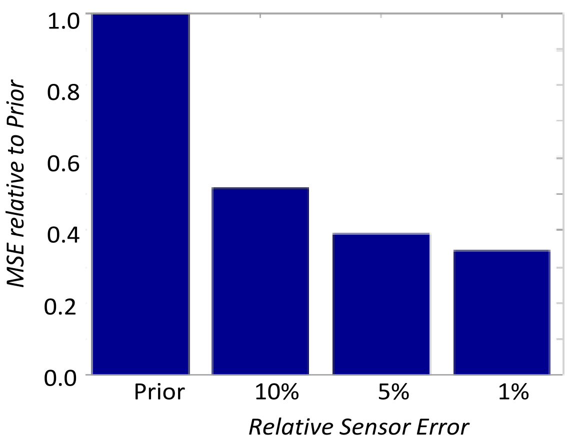


Illustrative Case Study

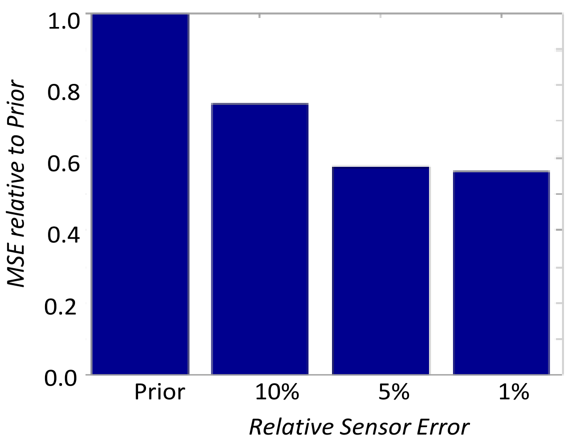
Comparison to Reality

Kalman-Filter: 2 Excavators

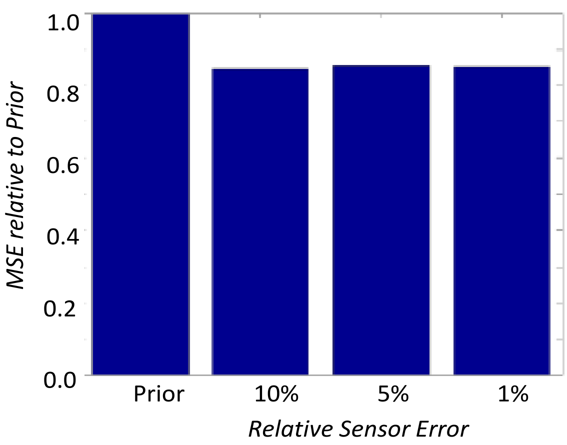
MSE-mined



MSE- adjacent blocks



MSE- 2 blocks away



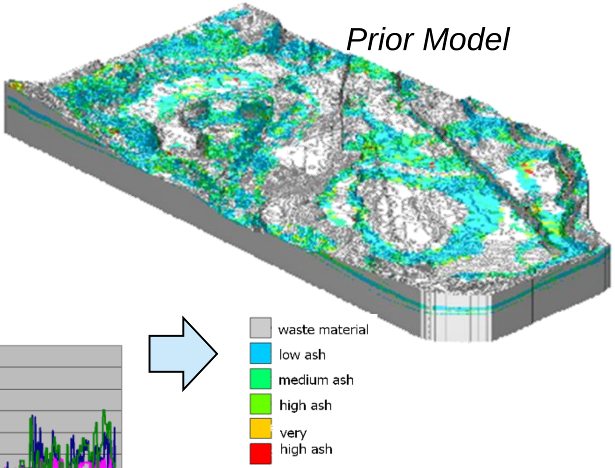
$$\mathrm{MSE} = \frac{1}{N}\sum_{i=1}^{N}(z^*(\mathbf{x}_i) - z(\mathbf{x}_i))^2$$

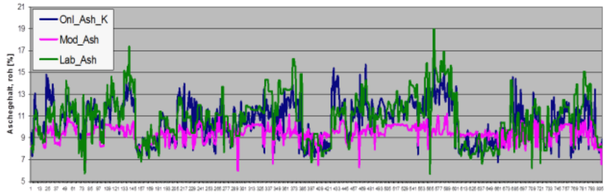
Illustrative Case Study - Results

- 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 RTRO-Coal**





with partners: TU Delft Delft University of Technology, AGH, Bergakademie Technische Universität Freiberg, MIBRAG, 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