



Applying Numerical Optimization Tools to Lime Sludge Kilns

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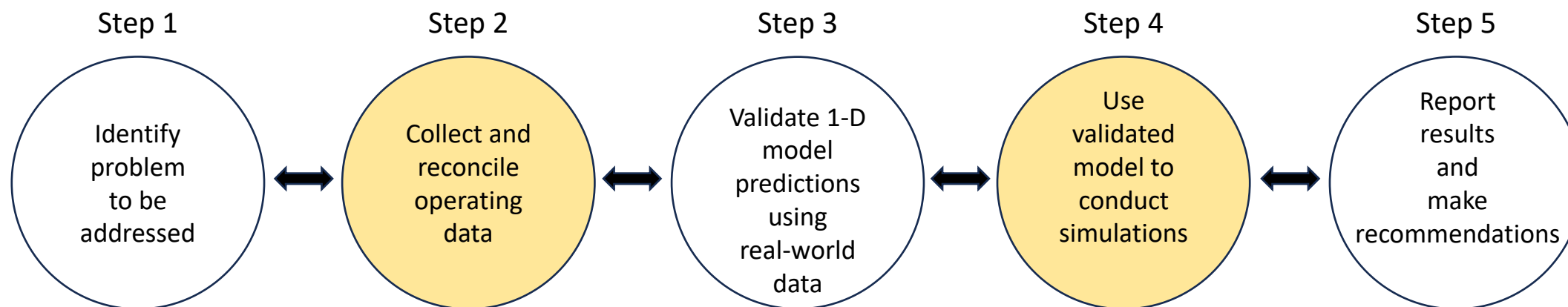
Outline of Presentation

This presentation continues our discussion on the development of numerical optimization tools used to evaluate and optimize kiln operation as presented at the APPTI Workshop on August 13-14, 2024.

Topics for today:

- Steps used to model kilns
- Brief overview of 1-D computer model
- Example case study to lower fuel consumption and replacing natural gas with wood.
- Highlight issues that need to be addressed to shorten the time required for modeling and data collection
- Next steps

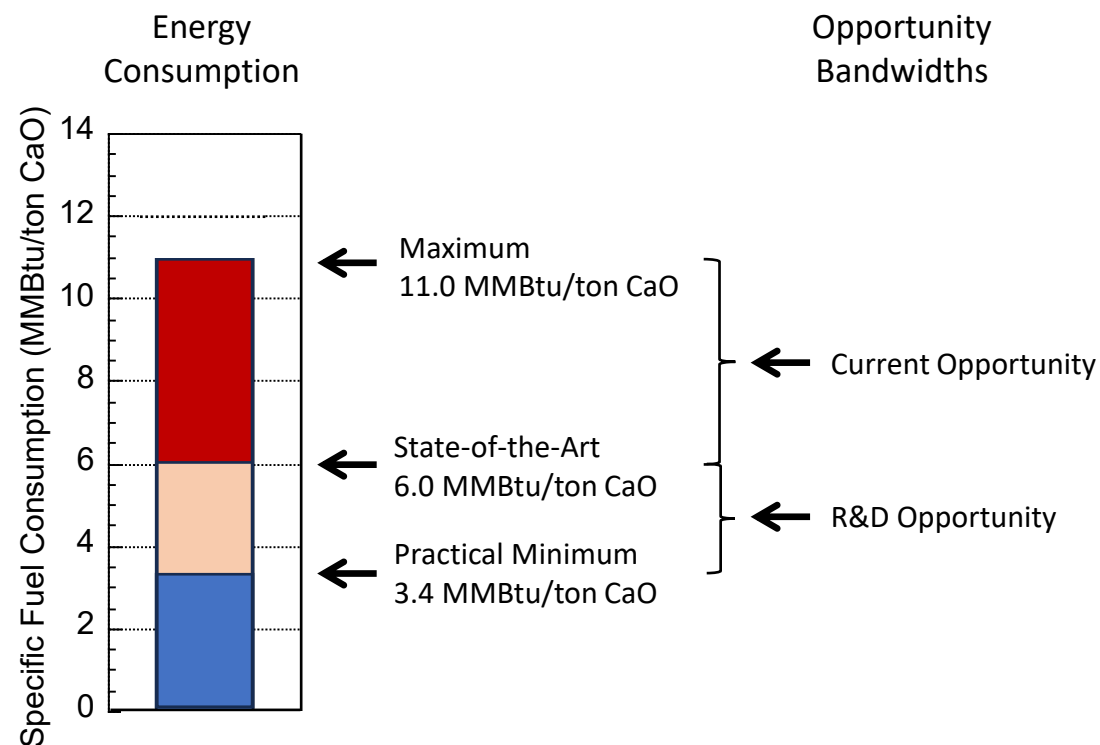
Steps Used to Model Kilns



Steps 2 and 4, highlighted in yellow, normally require the most time to complete when modeling kilns. Currently, it takes 2-4 months to complete a study for a single kiln. The focus of this work is to show how numerical optimization tools could speed up steps 2 and 4 with the goal of reducing the overall time to model a kiln from months to weeks.

Validation of the model in Step 3 uses data from the kiln of interest along with data from other kilns. The use of data from multiple kilns helps to validate and improve the accuracy of model predictions used to determine baselines for energy consumption, CO₂ emissions and other variable(s) of interest. Quantitative data, that is numerical, measurable and reproduceable, plays a key role in validating models to provide factual insights that drive informed decisions. In today's data-driven world, the industry must not only collect vast amounts of operational data but also ensure its accuracy, consistency, and completeness through robust validation practices that include modeling. This is an opportunity for the industry.

Energy Consumption for Lime Kilns in the Pulp and Paper Industry



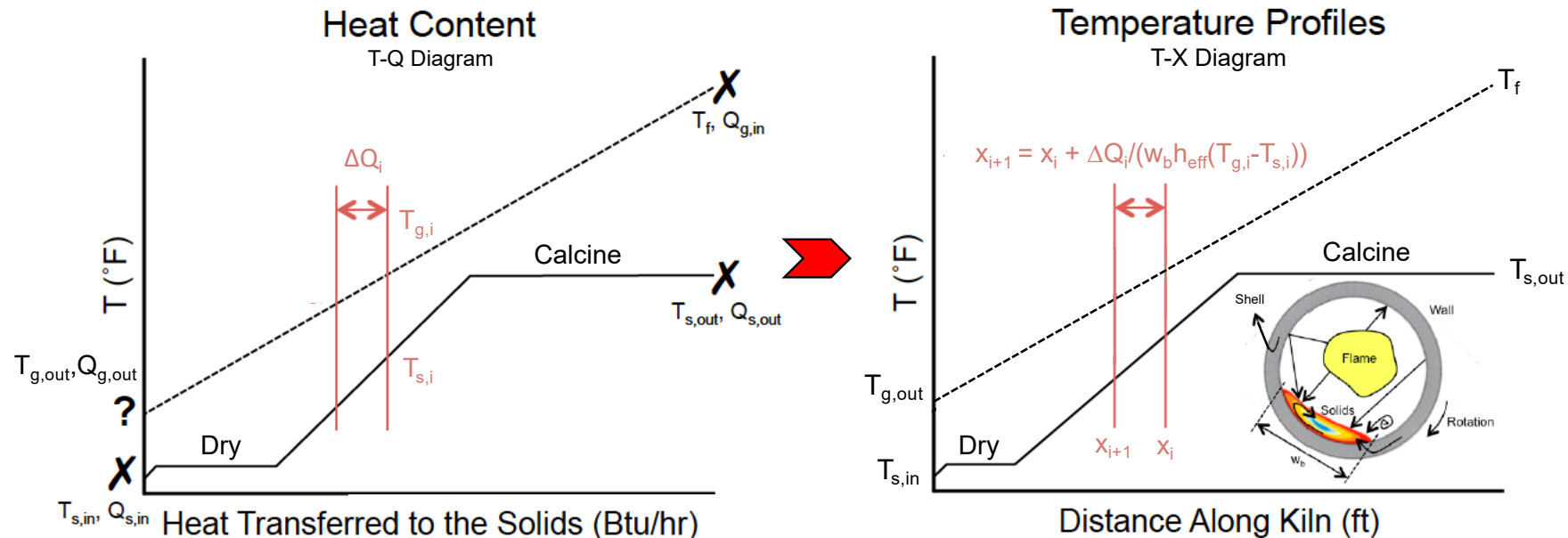
The specific fuel consumption for kilns in the pulp and paper industry runs from 6 to 11 MMBtu/ton CaO. As a first step toward optimizing operations, mills should update equipment and SOPs to reach the state-of-the-art for energy consumption for their kilns. Ultimately, the specific fuel consumption could be reduced to 3.4 MMBtu/ton CaO by moving from long-wet to preheater type kilns.

1-D Computer Model

Computer models of rotary kilns are used to test and evaluate their design and functionality. They are based on a set of assumptions and equations that describe the behavior of the kiln. Keep in mind that models have limitations and cannot “exactly” predict the performance of real-world kilns. The computer models used in this work have been extensively validated using data from operating kilns. The figure below illustrates the overall approach used in the model used in this work.

Major assumptions used in the model:

- Drying and calcination are heat transfer controlled.
- No heat transfer along the kiln axis.
- A modified thermal resistance network can be used to predict heat transfer rates for the kiln.



Independent and Dependent Variables for the Model

Input to model

Kiln geometry:

- Length, diameter, slope, emissivity of shell
- Height dam
- Refractory lining (type and location)
- Product coolers (discharge temperature of solids and efficiency)
- Chain layout (location and amount)

Operating Conditions:

- Ambient conditions (wind speed and temperature)
- Kiln speed
- Flowrate slurry to filter
- Specific gravity of slurry to filter
- Filtrate loss from filter
- Feed rate of dry solids to kiln
- Mud solids off filter
- Inert material in mud
- Temperature mud to kiln
- Dust loss
- Residual carbonate of the product
- Fuel specifications (HHV, ultimate analysis and moisture content)
- Flame characteristics (length, diameter, emissivity)
- Excess air

Output from Model

- Mass Balance
- Energy Balance
- Firing Rate (gross and net)
- Exit gas (composition and volumetric flow rate)
- Temperature profiles (gas, solids, refractory and shell)
- Location of zones (calcining, preheating, drying)
- Moisture content solids exiting chains
- Gas temperature entering chains
- Availability of product

Key Variables Used for Validation

- Production
- Firing Rate
- Exit gas temperature
- Exit gas O₂
- Predicted shell temperatures

Range of Operating Conditions for Kilns

Targeted Range for Operating Conditions:

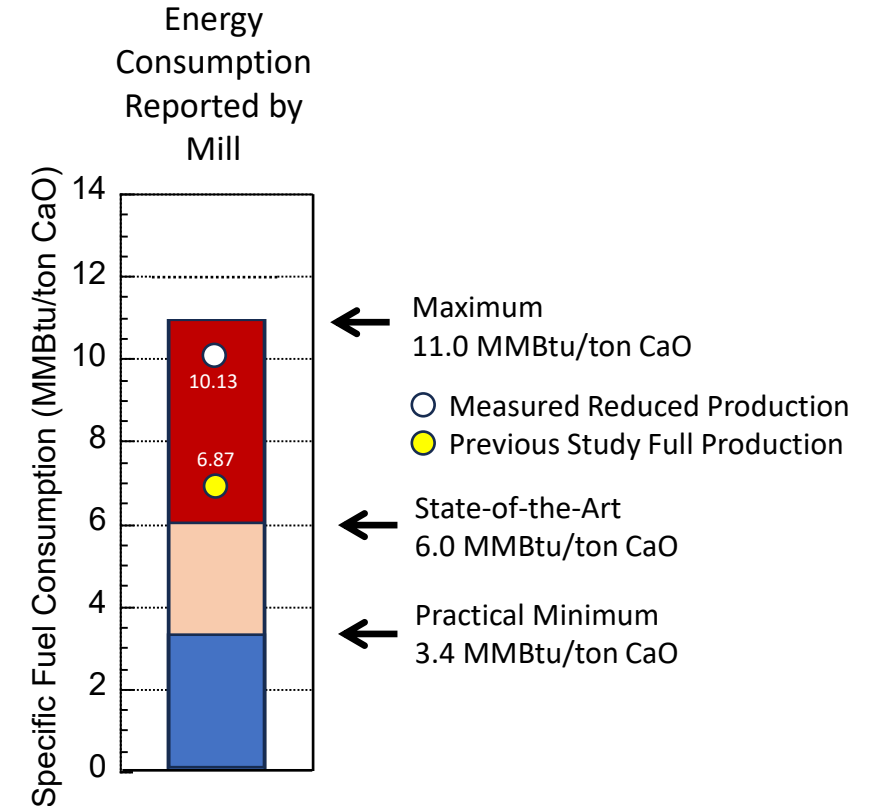
- Specific fuel consumption 6-8 MMBtu NG/ton CaO
- Temperature of solids leaving product coolers 300-350°F
- Residual carbonates 1-5%
- O₂ in the flue gas 1.5-2.0%
- Temperature of exit gas from kiln 300-750°F
- Moisture content of solids exiting the chain section <2%
- Gas temperature of gas entering the chain section <1500°F
- Peak shell temperatures <700°F
- Shell heat loss <15% of total heat output
- Mud solids >70%
- Volumetric production rates 65 to 110 ton/ft³/day for (0.0091 to 0.0154 ft³/ton/day)

Operating Within the Targeted Range is Important for:

- Optimal performance
- Extended run time
- Reduced maintenance costs
- Enhanced safety
- Quality control

Step 1: Problem Statement for Example Study

Lack of wood has forced mill to lower pulp production thereby reducing the demand for lime. After lowering the production of lime by 63%, the mill reports the specific energy consumption of the kiln increased by 47.4%. The mill would like to determine what can be done to bring specific energy consumption at reduced production from 10.13 MMBtu/ton CaO inline with that before dropping production of 6.87 MMBtu/ton CaO.



Step 2: Collect and Reconcile Operating Data for Reduced Production

- Simple mass and energy balances are used to reconcile the operating data.
- There is good agreement between the measured and predicted values for volumetric production. It should be noted that the production is below the typical value of 0.013 ton/ft³/day (75 ft³/ton/day) for kilns with product coolers.
- **There is an 12.9% difference between the measured and reconciled values for specific fuel consumption. It is believed the measurement of flow rate for natural gas was not taken within the designated time for sampling. More investigation is required.**
- 1-D modeling was performed using the reconciled data shown in the table on the right.

Operating Variables	Measured Data	Reconciled Data ¹
Volumetric Production (ton/ft³/day)	0.0043	0.0044
Volumetric Production (ft ³ /ton/day)	230.06	220.98
Mud Solids off Filter (%)	68	68
Excess air (% of stoichiometric)	-	31
Exit Gas O ₂ (%)	3	3
Temperature Mud (°F)	120	120
Dust Loss from Kiln (% of dry feed)	9	9
Availability of Kiln Product (%)	90	90
Residual Carbonate of Product (%)	1.7	1.7
Speed of Rotation (rpm)	1	1
Shell Heat Loss (MMBtu/hr)	-	14.97
Shell Heat Loss (MMBtu/ton CaO)	-	2.42
Exit Gas Temperature (°F)	350.0	350.0
Fuel Consumption (MMBtu NG/hr)	-	54.77
Sp. Fuel Consumption (MMBtu NG/ton CaO)	10.13	8.97
Flow Rate NG (scfm)	950.2	835.1

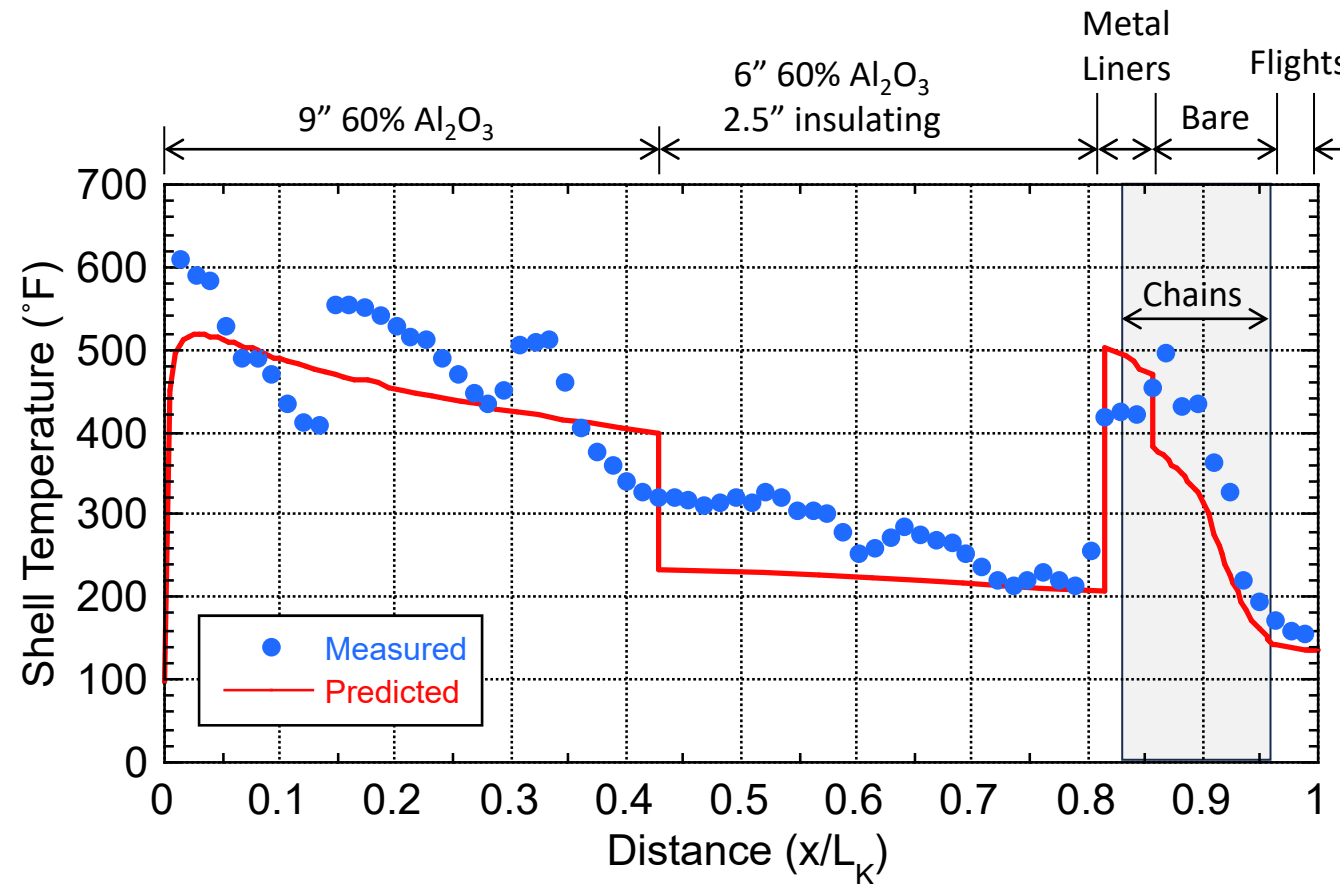
1. Adams, T.N., Lime Kiln Principles and Operations, TAPPI Kraft Recovery Course, St. Petersburg, FL, January 7-10, 2008, pp 2.2 9-15.
<https://www.tappi.org/content/events/08kros/manuscripts/2-2.pdf>

Step 3: Validate 1-D Model

Operating Variables	Reconciled Data	1-D Model Predictions	Difference
Production (ton/ft ³ /day)	0.0045	0.0043	-4.4%
Production (ft ³ /ton/day)	220.98	238.30	
Mud Solids off Filter (%)	68	68	
Excess air (% of stoichiometric)	30	30	
Exit Gas O ₂ (%)	3	3.1	+3.3%
Temperature Mud (°F)	120	120	
Dust Loss from Kiln (% of dry feed)	9	9	
Availability of Kiln Product (%)	90	92.0	+2.2%
Residual Carbonate of Product (%)	1.7	1.7	
Speed of Rotation (rpm)	1	1	
Shell Heat Loss (MMBtu/hr)	14.97	15.04	
Shell Heat Loss (MMBtu/ton CaO)	2.42	2.54	
Exit Gas Temperature (°F)	350.0	333.3	-4.8%
Fuel Consumption (MMBtu NG/hr)	54.77	54.22	
Fuel Consumption (MMBtu NG/ton CaO)	8.97	9.17	+2.2%
Flow Rate NG (scfm)	835.1	828.8	

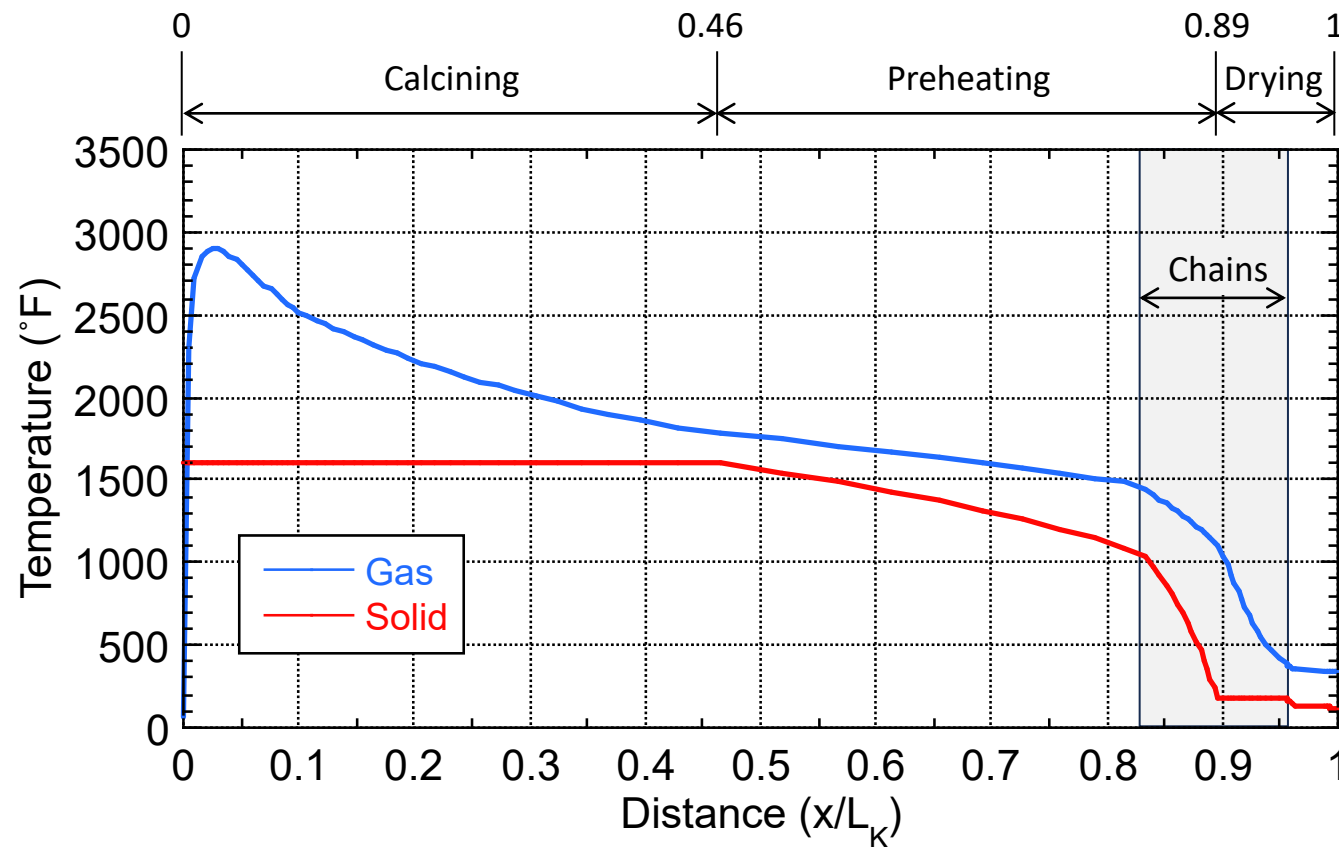
The differences for key operating variables highlighted in yellow for the certified data and the model predictions are less the 5%.

Predicted and Measured Shell Temperatures for Reduced Production



Good agreement between predicted and measured shell temperatures at reduced production.

Temperature Profiles and Zones for Reduced Production



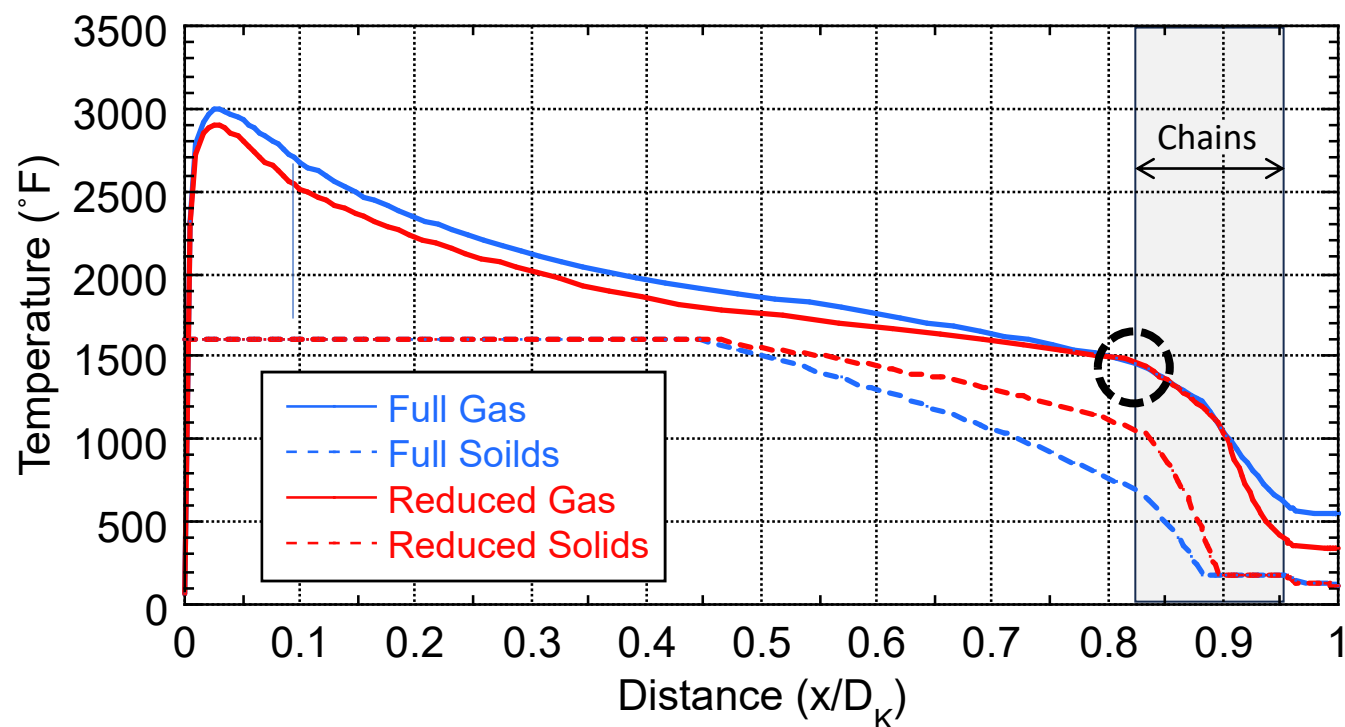
The zones in the kiln are easy to recognize from the bulk solids temperature profile. The calcining zone occupies from one-third to one-half the kiln length. The drying zone is typically the shortest section in the kiln.

Comparison of 1-D Model Predictions for Full and Reduced Production

Operating Data	1-D Model Full Production	1-D Model Reduced Production
Production (ton/ft ³ /day)	0.011	0.0042
Production (ft ³ /ton/day)	90.8	237.7
Mud Solids off Filter (%)	78	68
Excess air (% of stoichiometric)	20	30
Exit Gas O ₂ (%)	2.2	3.1
Temperature Mud (°F)	120	120
Dust Loss from Kiln (% of dry feed)	18	9
Availability of Kiln Product (%)	89.9	92.0
Residual Carbonate of Product (%)	1.7	1.7
Speed of Rotation (rpm)	1	1
Shell Heat Loss (MMBtu/hr)	15.47	15.04
Shell Heat Loss (MMBtu/ton CaO)	0.92	2.54
Exit Gas Temperature (°F)	544.2	333.3
Fuel Consumption (MMBtu NG/hr)	115.56	54.22
Fuel Consumption (MMBtu NG/ton CaO)	6.87	9.17
Flow Rate NG (scfm)	1767.5	828.8

Highlighted in yellow, the 1-D modeling shows dropping the production by 63% increases the specific fuel consumption from 6.87 (previous study) to 9.17 MMBtu/ton CaO, an increase of 33.4%. Less than the 47.4% based on the operating data collected by the mill.

Predicted Temperature Profiles for Full and Reduced Production



All things being equal, lowering the production rate has a minor effect on locations of the start of calcination, end of drying, and gas temperature entering the chain section. Reducing production shifts the start of calcination and end of drying further up the kiln while increasing the temperature of the gas entering the chain section from 1443°F to 1449°F. Still below the recommended maximum gas temperature of 1500°F entering the chains to avoid formation of rings or balls at the hot end of the chain section. Also, reducing production increases the temperature of the solids exiting the chain section from 662°F to 1043°F. The mud is dry leaving the chain section.

Step 4: Case Studies to Lower Specific Fuel Consumption at Reduced Production

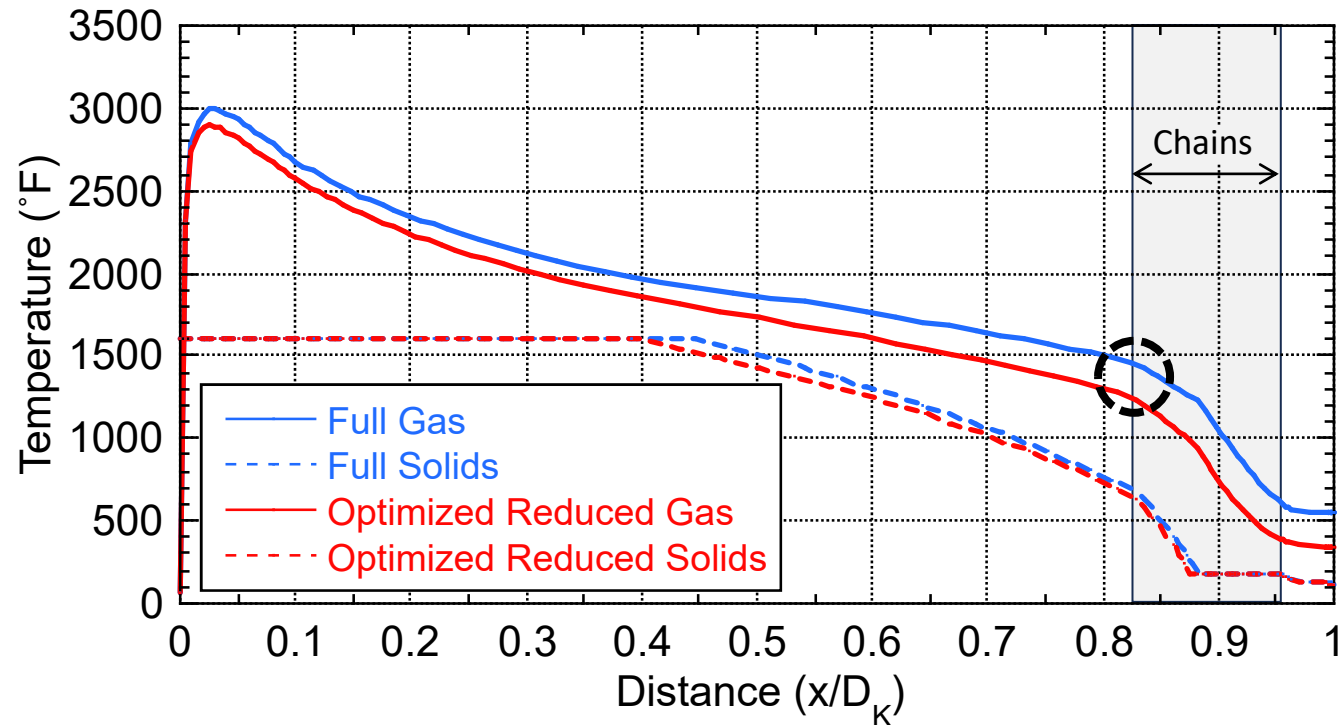
1. Reduce the excess air from 30% to 20% of stoichiometric while simultaneously increasing the mud solids from 68% to 78%. At full production, before dropping production, the excess air and mud solids were 20% and 78%, respectively.
2. Changes in Case 1 plus insulate the first 80' of the kiln with 2.5" of insulating firebrick. The refractory lining in the first 80' of the kiln is currently 9" of uninsulated 60% alumina brick.
3. Changes in Case 1 plus insulate the first 160' of the kiln with 1.5" insulating bricks made with moler, a type of diatomaceous earth, and removing 50% of the chain.

These above cases should not be viewed as a complete list of changes to the configuration and operating conditions of the kiln. There may be other changes to consider.

Model Results for Case Studies

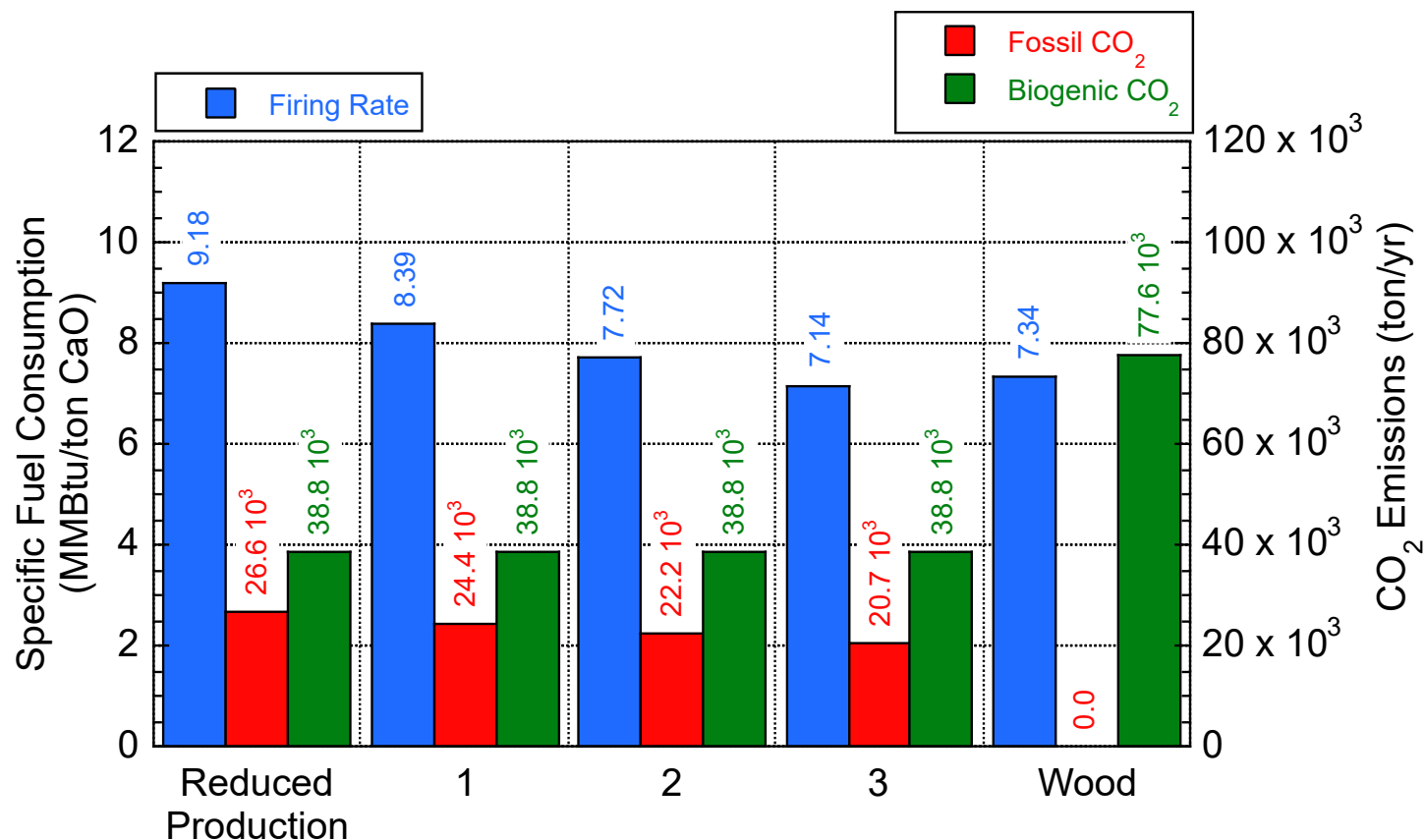
	Full Production	Current Reduced Production	Case 1	Case 2	Case 3 Optimized
			Mud Solids 68% to 78% + excess Air 30% to 20%	Line first 80' of the kiln with 2.5" insulating fireclay bricks over 9" 60% Al ₂ O ₃ bricks	Line first 160' of the kiln with 1.5" moler bricks over 9" 60% Al ₂ O ₃ + remove 50% of the chain
Production (ton/ft ³ /day)	0.012	0.0042	0.0042	0.0042	0.0042
Production (ft ³ /ton/day)	82.5	238.3	238.3	238.3	238.3
Mud Solids (%)	78	68	78	78	78
Excess Air (% stoichiometric)	20	30	20	20	20
Heat In	MMBtu/ton CaO	MMBtu/ton CaO	MMBtu/ton CaO	MMBtu/ton CaO	MMBtu/ton CaO
Gross Heat in Fuel	6.87	9.17	8.38	7.72	7.14
Sensible Heat in Air	0.00	0.00	0.00	0.00	0.00
Sensible Heat in Mud	0.10	0.14	0.10	0.10	0.10
Sensible Heat in Fuel	0.00	0.00	0.00	0.00	0.00
Total	6.97	9.31	8.48	7.82	7.24
Heat Out	MMBtu/tonCaO	MMBtu/ton CaO	MMBtu/ton CaO	MMBtu/ton CaO	MMBtu/ton CaO
Calcination of CaCO ₃	2.56	2.56	2.56	2.56	2.56
Dry Mud	1.14	1.91	1.14	1.14	1.14
H ₂ Loss	0.66	0.88	0.80	0.74	0.68
Sensible Heat Solids	0.47	0.47	0.47	0.47	0.47
Sensible Heat Exit Gas	1.18	0.93	0.93	0.68	0.67
Sensible Heat Dust	0.04	0.02	0.03	0.02	0.02
Shell Heat Loss	0.92	2.54	2.56	2.21	1.69
Total	6.97	9.31	8.48	7.82	7.24
Flow Rate Natural (scfm)	1767.5	828.8	762.7	696.7	645.4
Chain Area (% installed)	100	100	100	100	50
Exit Gas Temperature (°F)	544.2	333.3	395.0	327.1	338.6
Gas Temperature Entering Chains (°F)	1443.5	1449.0	1331.7	1352.1	1232.9

Temperature Profiles for Full and Optimized Conditions at Reduced Production



The temperature profiles for the solids at full and optimized operating conditions for reduced production, Case 3, are similar. In that the residence time used in the model is independent of production rate, the time-temperature profile of the solids in the calcination zone should be the same for both cases. For this reason, it is expected the reactivity of the lime will be unchanged moving from full to the optimized conditions.

Firing Rate and CO₂ Emissions for Natural Gas and Wood



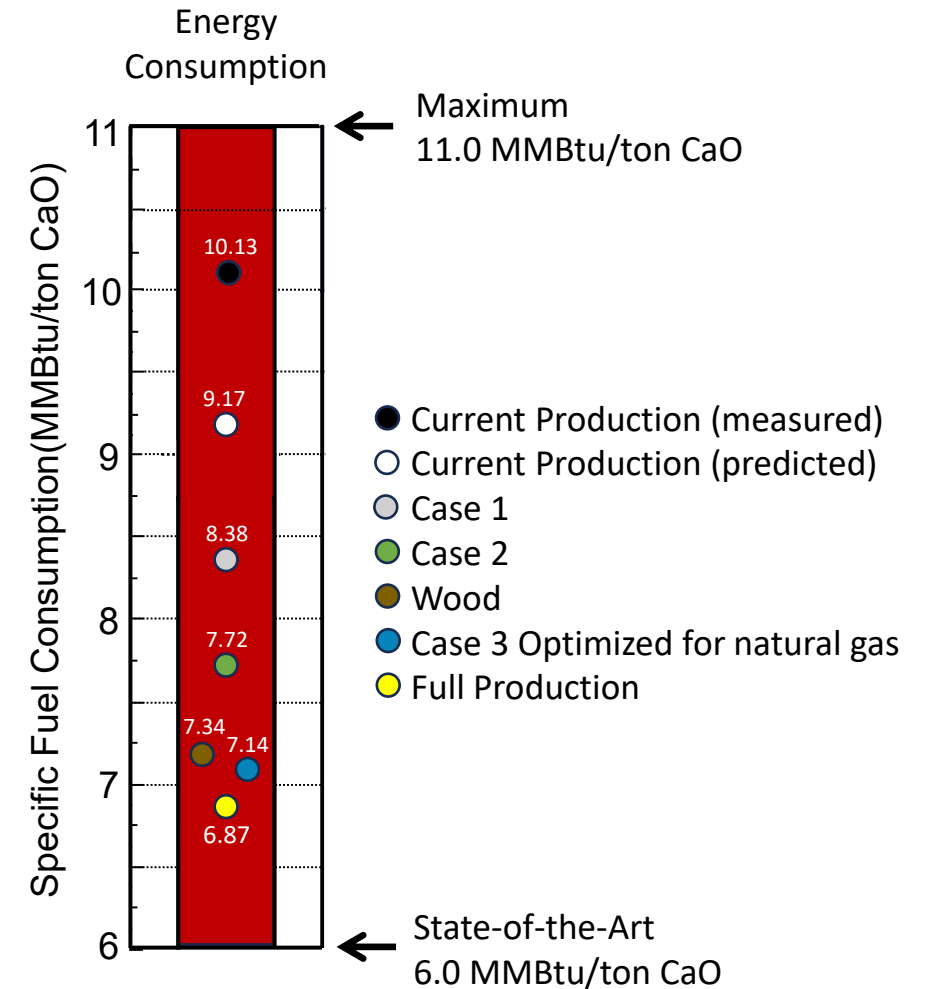
Replacing 100% of the natural gas with wood (5% moisture on WB) drops the fossil CO₂ to zero while increasing the specific fuel consumption from 7.14 to 7.34 MMBtu/ton CaO. An increase of 2.8%. Switching to alternative fuels, particularly lower-carbon options like biomass involves trade-offs, spanning environmental, economic, technical, and social considerations. Numerical tools can play a key role in determining the impacts of switching fuels.

Step 5: Results and Recommendations

Based on this study, the following changes are recommended for lowering fuel consumption that will compensate for the drop in production.

- Increase mud solids from 68% to 78% (the original value before dropping production).
- Decrease excess air from 30% to 20% of stoichiometric (optimum O₂ in the exit gas for combustion is 1.5-2%).
- Insulate first 160 ft. with 1.5" insulating molar brick (standard for the industry).
- Remove 50% of the existing chain to increase exit gas temperature to 339°F (avoid formation of TRS).

Making these changes drops the total specific fuel consumption for reduced production from 9.17 to 7.14 MMBtu/ton CaO bringing the energy consumption to within 3% of the that for full production. After making these changes the mill can consider alternate fuels. Switching from natural gas to wood eliminates fossil CO₂ while increasing fuel consumption by 6.4%. There are trade-offs that must be considered. Numerical tools provide insights to optimize both energy consumption and CO₂ emissions.



Next Steps to Speedup Modeling

Data Collection

The common problems with collecting data include:

1. missing data points
2. poor location of sensors
3. issues with sensor calibration or manual measurements
4. not collecting data in the designated period-of-time
5. failure to collect data during steady state operations

Develop improved methods to speed-up collection and reconciliation of operating data.

Automate Computer Simulations

Manually running the case studies is the bottleneck in terms of the time needed complete the project. The interdependency of the operating data along with the iterative process for running simulations increases the complexity. It may take 100s of simulations to connect the output from the model back to the original question that the model was intended to address.

While manual analysis of model predictions can take months. Develop AI tools to do the “heavy lifting” to shorten the work from months to weeks.

The remainder of this presentation will address data collection and automating the computer simulations.

Motivation to Improve Data Collection and Reconciliation

- **Manually** collect operating data
 - Isolated data sources (lab data, DCS/historian, shell scanner)
 - Collection (mismatched time, upset conditions, measurement location, etc.)
- **Manually** correct errors, discrepancies, or inconsistencies in the operating data

As the number of measurements increases, so does the complexity of correction!

Automation of Data Collection - Software

FPI Control platform

Register License Options

Time Kiln Reconciler

Variable parameters

Parameter name	Raw value	Epsilon	Corrected value
Kiln Diameter		0	
Kiln Length		0	
Wind Speed	5.6	0	5.6
Emissivity	0.9	0	0.9
Ambient Temperature	46	0	46
Exit Gas Temperature		0	
Bulk Discharge Temperature	1500	0	1500
Availability	0.9	0	0.9
DustLoss	0.1	0	0.1
Filtrate Loss	0.01	0	0.01
Mud Solids			
Slurry Flow Rate			
Specific Gravity Slurry	1.25	0	1.25
Back End O2 Content			
Feed Temperature			
Temperature Of Dust Recycle			
ESP Efficiency			
Residual Carbonate			
Solids Specific Gravity			
CaO Production Rate			
Dry Mud Feed Rate			
Mass Flow Fuel			

Shell elements

Element name	Raw value	Epsilon	Corrected value
Shell #1 Width	5	0	5
Shell #1 Temperature	186.62449	0	186.62449
Shell #2 Width	5	0	5
Shell #2 Temperature	224.681	0	224.681
Shell #3 Width	5	0	5
Shell #3 Temperature	212.42751	0	212.42751
Shell #4 Width	5	0	5
Shell #4 Temperature	197.897	0	197.897
Shell #5 Width	5	0	5
Shell #5 Temperature	200.4395	0	200.4395
Shell #6 Width	5	0	5
Shell #6 Temperature	201.866	0	201.866
Shell #7 Width	5	0	5
Shell #7 Temperature	195.61099	0	195.61099
Shell #8 Width	5	0	5
Shell #8 Temperature	202.19001	0	202.19001
Shell #9 Width	5	0	5
Shell #9 Temperature	203.0135	0	203.0135
Shell #10 Width	5	0	5
Shell #10 Temperature	208.35051	0	208.35051
Shell #11 Width	5	0	5
Shell #11 Temperature	221.9315	0	221.9315
Shell #12 Width	5	0	5

Watchdog In

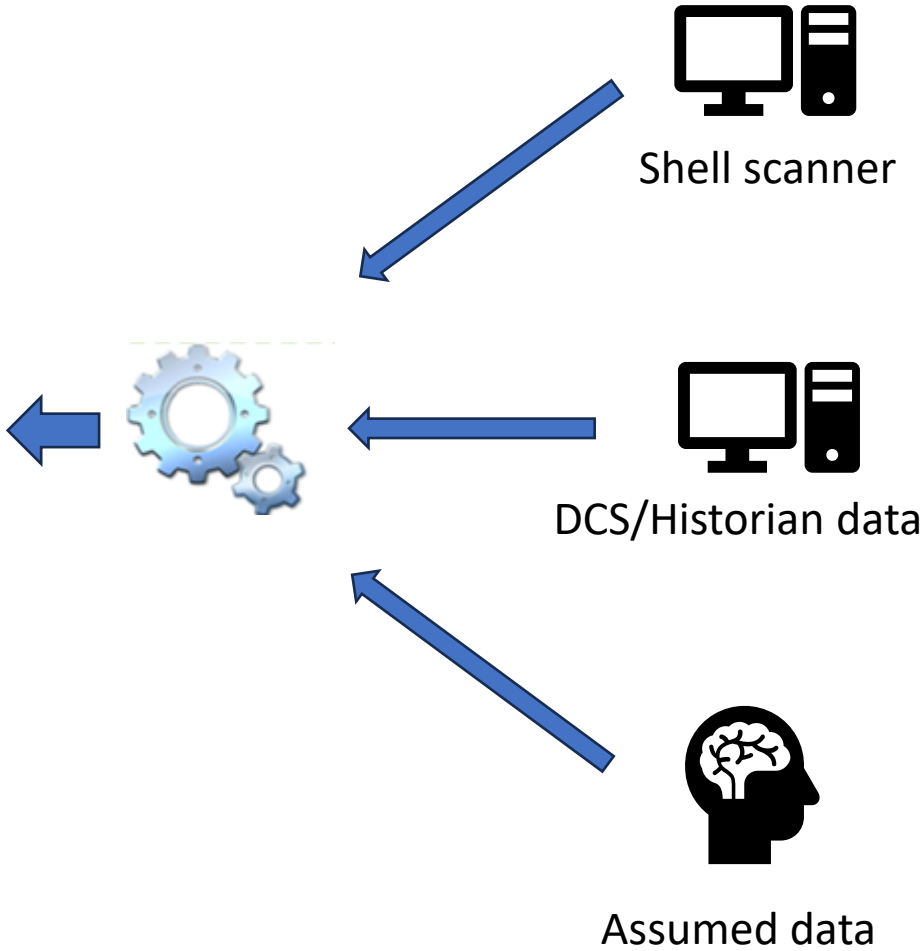
Watchdog Out

Running

Configure

Name	Read/Write	Target Update Rate (ms)	Mean Update Rate (ms)	Stdev Update Rate (ms)	Mean Idle Rate (ms)	Stdev Idle Rate (ms)	Mean Calc Rate (ms)	Stdev Calc Rate (ms)
OPCDA								
localhost_Matrikon.OPC.Simulation.1_10000_ReadGroup	Read	10000	10000.24	8.33	9984.59	7.42	15.65	3.77
ModbusEthernet								
Read Group: Device Id 1, Sample Rate 10000	Read	10000	9999.14	10	9965.55	9	33.59	4.36

Service Connected

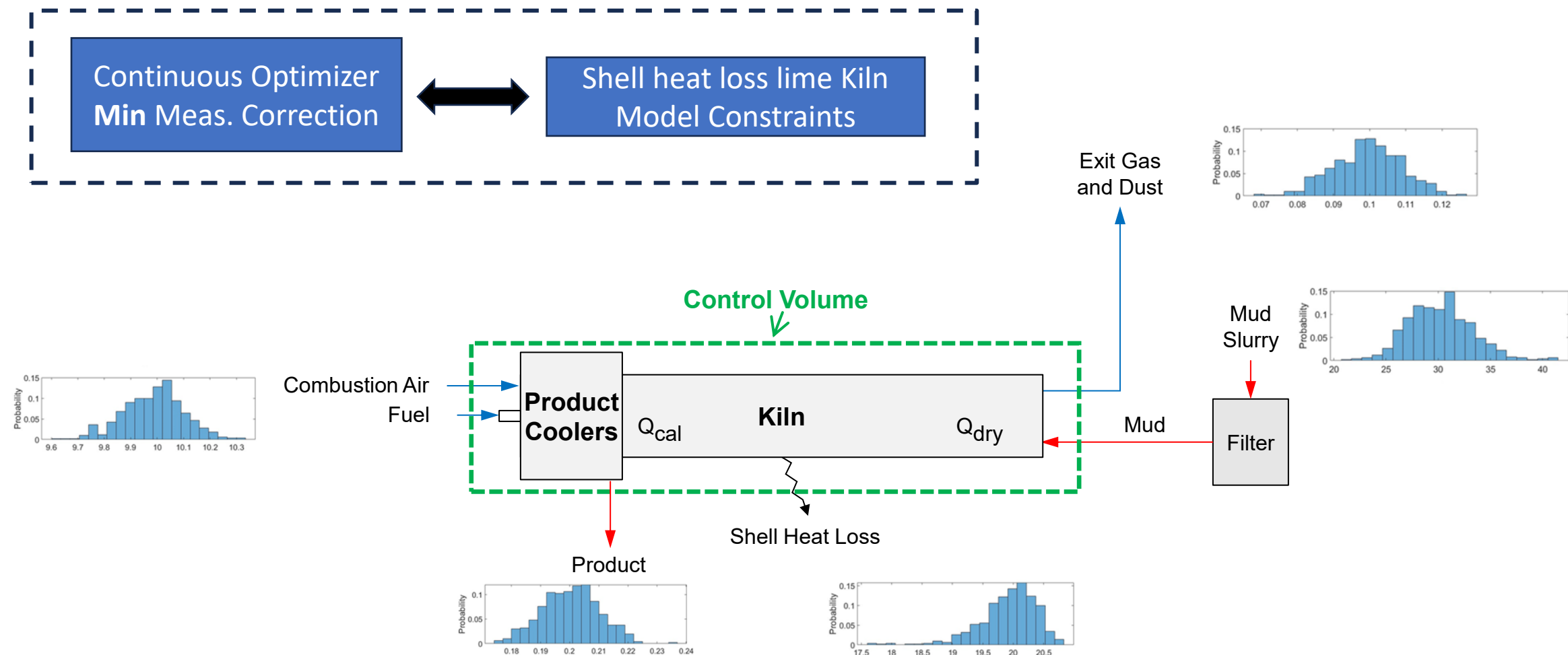


Automation of Data Reconciliation

- Objective:
 - Accept that measurements have associated errors and allow them to be corrected
 - Assign statistical confidence to each of the measurements
 - Minimize the amount of measurement correction based on confidence
- Constraints:
 - Shell heat loss mass/energy balance
 - Allowable measurement ranges

Numerical optimization!

Automation of Data Reconciliation



Automation of energy and carbon emission reduction calculations

- Goal is to **minimize** the energy consumption of an existing lime kiln
- There are discrete model elements to consider (i.e. type of bricks/chains, fuel, etc.)
- There are continuous inputs to the model (i.e. flow rates of fuel, air to fuel ratio, etc.)
- There are continuous outputs from the model (i.e. brick temperature, exit gas temperature, etc.)
- There are constraints
 - Limits (i.e. maximum temperatures, flow limits, product quality, etc.)
 - The physics (1D mass and energy balances)

Many discrete combinations and infinite continuous combinations need to be evaluated!

Automation of energy and carbon emission calculations

- Key words in the problem definition include “minimize an objective” and “constraints”
- This problem again falls into the domain of **numerical optimization**
- The combination of both discrete and continuous elements falls into the area of hybrid systems optimization
- Presence of the discrete element and spatial nature of the 1D model increases the complexity of the problem

The combinations are evaluated in a computationally efficient way!

Automation of energy and carbon emission calculations

- The 1-D continuity-based mass/energy equations are already developed and have been used extensively in the industry
- Redefine the model as for use in a hybrid system optimization problem
- Develop the optimization framework
 - What are the solution methodologies available in the literature?
 - Parallelization of computations for tractability
- Trial the concept and validation with the industry

Next Steps

- Develop tools for data collection. The data must be cleaned so that there are no contradictions or discrepancies between data points collected from the mill.
- Automate the process of modeling kiln performance. Develop software/computational tools to speed up the process and allow for more detailed analysis.
- The goal is to speed up the calculations from months to a few days. This would allow for benchmarking against a set of standard conditions to gather insights to drive improvements needed to minimize fuel consumption and CO₂ emissions.

ANY QUESTIONS?

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