INL/CON-23-75439-Revision-0

Failure Modes and Effects Analysis of Biorefinery Pathways

November 2023

Changing the World's Energy Future

Rachel M Emerson, Nepu Saha, Jordan Lee Klinger, Tiasha Bhattacharjee, Danny Carpenter, Steven Phillips, Lorenzo J Vega Montoto, Pralhad Hanumant Burli

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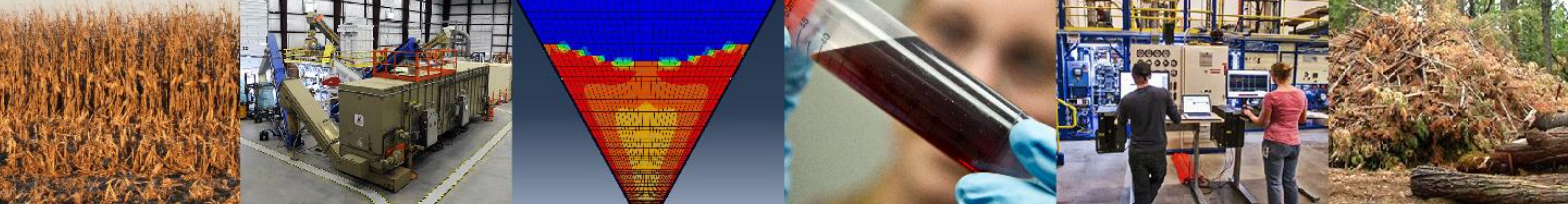

2023 AIChE Annual Meeting

Feedstock Conversion Interface Consortium: Understanding Feedstock Variability to Enable Next Generation Biorefineries

November 6, 2023

Failure Modes and Effects Analysis of Biorefinery Pathways

Rachel Emerson

FEEDSTOCK-CONVERSION INTERFACE CONSORTIUM

U.S. DEPARTMENT OF ENERGY

Acknowledgement

Co-Authors and Subject Matter Experts

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Danny Carpenter	National Renewable Energy Laboratory
Steven Phillips	Pacific Northwest National Laboratory
Lorenzo Vega-Montoto	Idaho National Laboratory
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Risk: Variability in Biomass Properties

Variability in biomass feedstock properties translates to **risk** for bio-projects

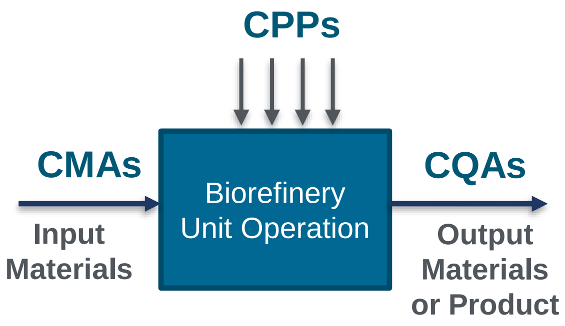
- **Shutting down of existing biorefineries**
- **High capital costs for emerging bio-projects**

Variability in **critical material attributes** › **Technical Risk** ›

- Equipment failure
- Inconsistent product quality
- Environmental consequences
- Safety

Quality by Design

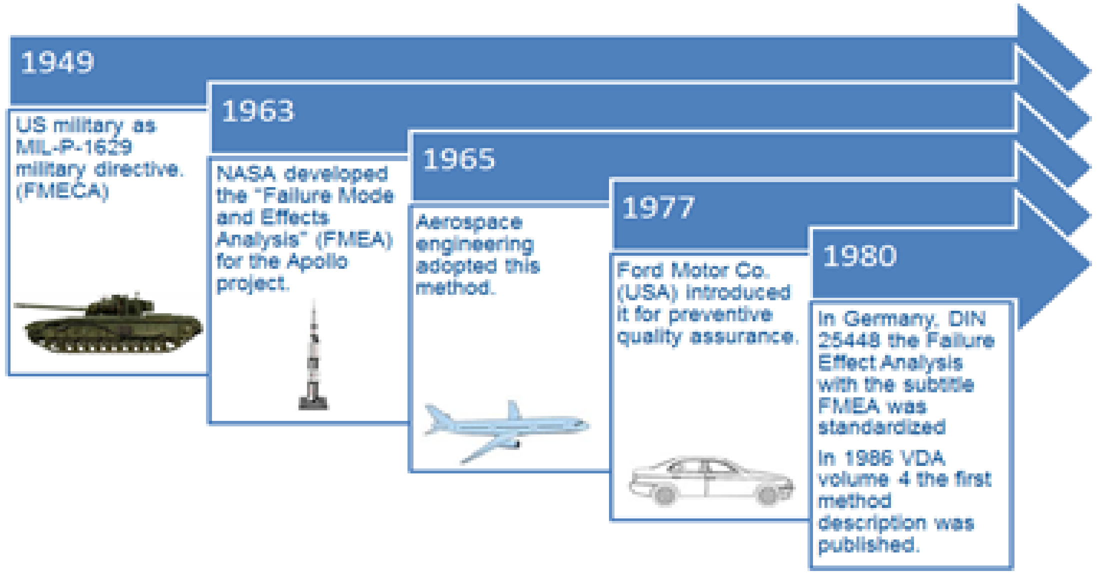
Emphasis on systematic understanding of processes and control



Example: Jet Fuel Production
CMA: lignin content, H_2 content
CPP: process design & operation
CQA: Aromatic content < 25%

› **Process Risk Assessment**

FMEA Background



Benefits Failure Mode and Effects Analysis (FMEA)

- Well-accepted risk assessment tool
- Combining qualitative and quantitative data
- Easily adaptable
- Couples well with Quality-by-Design approaches

Overview

- Extensive interviews with subject matter experts (SMEs)
- Systematic semi-quantitative analysis based on failure identification for a given operation or system of operations for a process
- Failure defined as "not performing or producing as intended".

Ranking of **Severity** (S), **Occurrence** (O) and **Detection** (D) by Subject Matter Experts to calculate **Risk Priority Number** (RPN).

RPN = S x O x D = Risk x D

Semi-quantitative criticality value for each identified CMA, CPP, CQA for given material/unit operation/system configuration

Systematic Data Collection

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FMEA Interview Form

Date:
Interviewee:
Interviewer:

Which unit operation should we focus on?

What is the primary purpose of this unit operation?

Should this be considered one unit operation?

Can you briefly describe how it works?

- Inputs
- parameters/process
- outputs

What scale is the target unit operation intended for

- lab - >0.5 DTPD
- pre pilot – 0.5 DTPD
- pilot – 1 DTPD
- demonstration – 50 DTPD
- commercial – >50DTPD

What scale do we usuall

How often are we runnir

Background	
Interviewee	
Interviewer	
Date	
Rev	
Unit Operation/Equipment	
Material	
Input format (approx)	
Output format (approx)	
System Design (Product)	
Nameplate Capacity	
TRL (A-C)	

Follow-up Questions:

Potentential

Process Step/Input	Potential Failure Mode	Potential Failure Effects	CQA	Layer	SEVERITY (1 - 10)	Potential Causes	CMA	CPP	OCCURRENCE (1 - 10)	Current Controls	DETECTION (1 - 10)	RPN
What is the process step, change or feature under investigation?	In what ways could the step, change or feature go wrong?	What is the impact on the customer if this failure is not prevented or corrected?	What CQAs are impacted directly or indirectly by this failure	Failure/CQA impacts: Process efficiency (Proc), Product quality (Prod), Economics (Eco), Sustainability (LCA)		What causes the step, change or feature to go wrong? (how could it occur?)	Identified CMA (and ranges if known) associated with failure and cause	Identified CPP associated with failure and cause		What controls exist that either prevent or detect the failure?		

Information Collected - Background

- Equipment scales
- Operation duration
- Level of expertise for combinations of equipment/material/product (system)
- Establish primary scope (e.g., material, system configuration)

Systematic Data Collection

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Information Collected - Failures

- Impacts (process, quality, cost, sustainability)
  - CQAs – Critical Quality Attributes
- Severity (1-10)
- Causes
  - CMAs – Critical material attributes
  - CPPs – Critical process parameters
- Occurrence (1-10)
- Detection and Controls
- Detection Rank (1-10)

Guidance Scales

Severity

Effect	Rank	Criteria
Minor	1	None to minor disruption to production line. A small portion (< 5%) of product may have to be reworked online.
Low	3	Low disruption to production line. A portion (< 15%) of product may have to be reworked online. Process up. Minor annoyance exists.
Moderate	6	Moderate disruption to production line. A small portion (>20%) of product may have to be reworked online. Process up. Some inconvenience exists.
High	8	High disruption to production line. A portion (>30%) of product may have to be scrapped. Process may be stopped. Customer dissatisfied.
Very high	10	Major disruption to production line. Close to 100% of product may have to be scrapped. Process unreliable. Failure occurs without warning. Customer very dissatisfied. May endanger operator and/or equipment.

Occurrence

Occurrence	Rank	Criteria
Remote	1	Failure is very unlikely. No failures associated with similar processes.
Low	3	Few failures. Isolated failures associated with similar processes.
Moderate	6	Occasional failures associated with similar processes.
High	8	Repeated failures. Similar processes have often failed
Very high	10	Process failure is almost inevitable.

Detection

Detection	Rank	Criteria
Almost certain	1	Process control will almost certainly detect or prevent the potential cause of subsequent failure mode.
High	3	High chance the process control will detect or prevent the potential cause of subsequent failure mode.
Moderate	6	Moderate chance the process control will detect or prevent the potential cause of subsequent failure mode.
Remote	8	Remote chance the process control will detect or prevent the potential cause of subsequent failure mode.
Very uncertain	10	There is no process control. Control will not or cannot detect the potential cause of subsequent failure mode.

Systematic Data Collection

fcic
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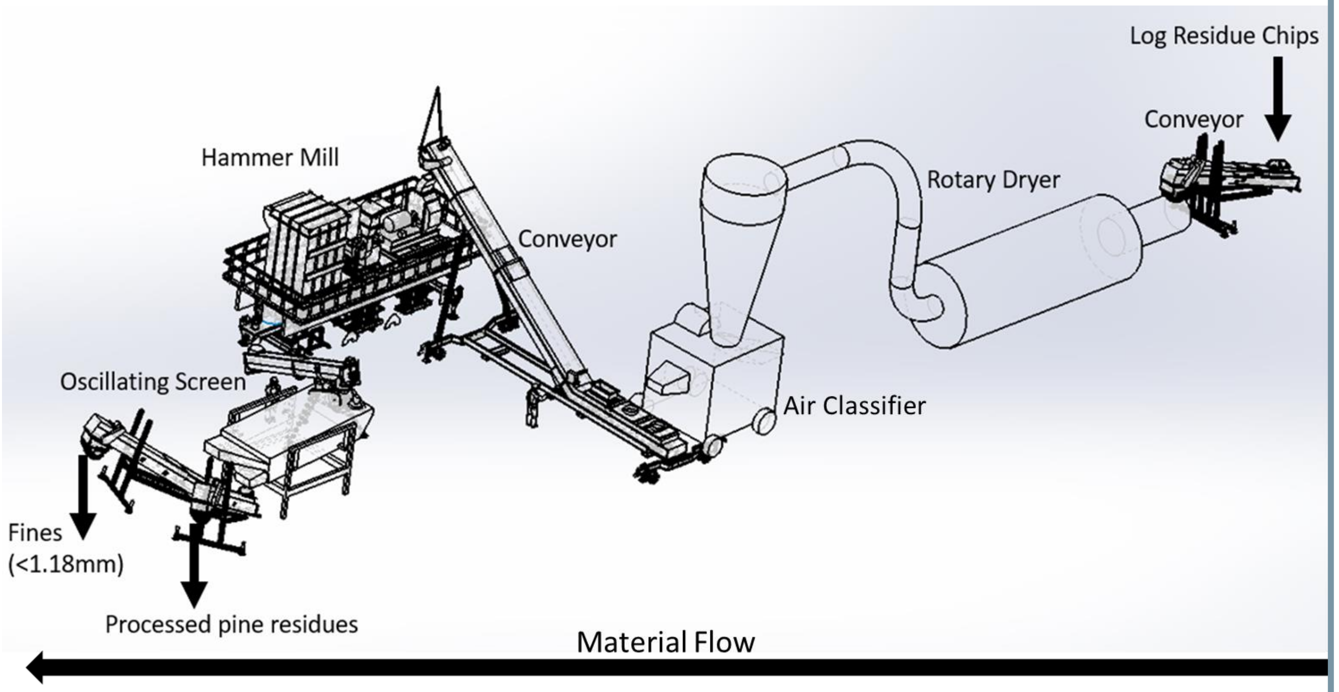
Information Collected - Mitigation

- What can be done to
  - Reduce severity
  - Decrease occurrence
  - Improve detection
- Categorize as
  - Idea
  - Proposed scope
  - In-Process
  - Implemented

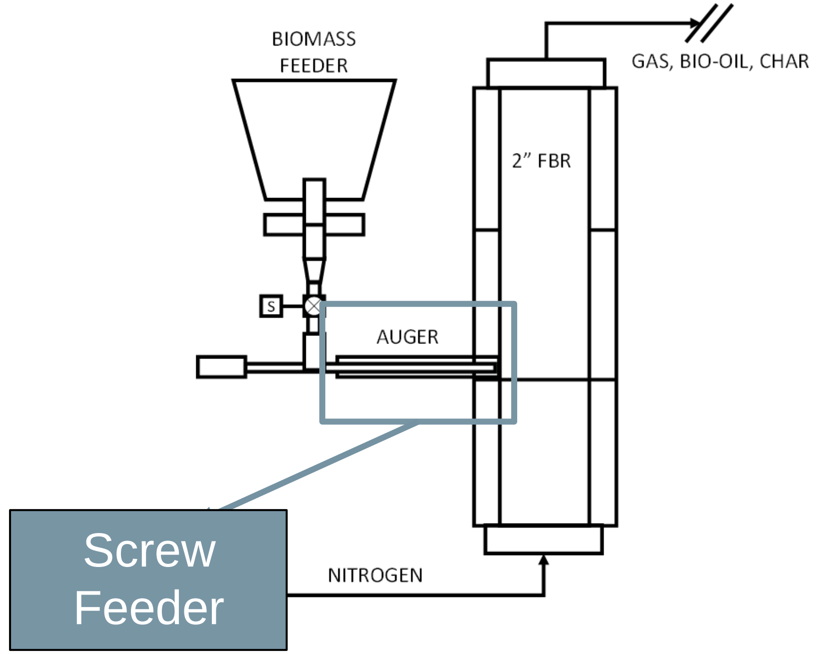
FMEA Implementation: Pyrolysis Conversion Pine Residues

Preprocessing System Configuration – Pine Residue



- FMEA performed on theoretical **system-wide**
- FMEA on each individual **unit operation**

Pyrolysis Conversion System



- FMEA performed on one problematic unit operation
- **Experimental results for identified failures**

Saha, N. et al. *Fuel Processing Technology* 245 (2023): 107725. https://doi.org/10.1016/j.fuproc.2023.107725

High Temperature Screw Feeder FMEA

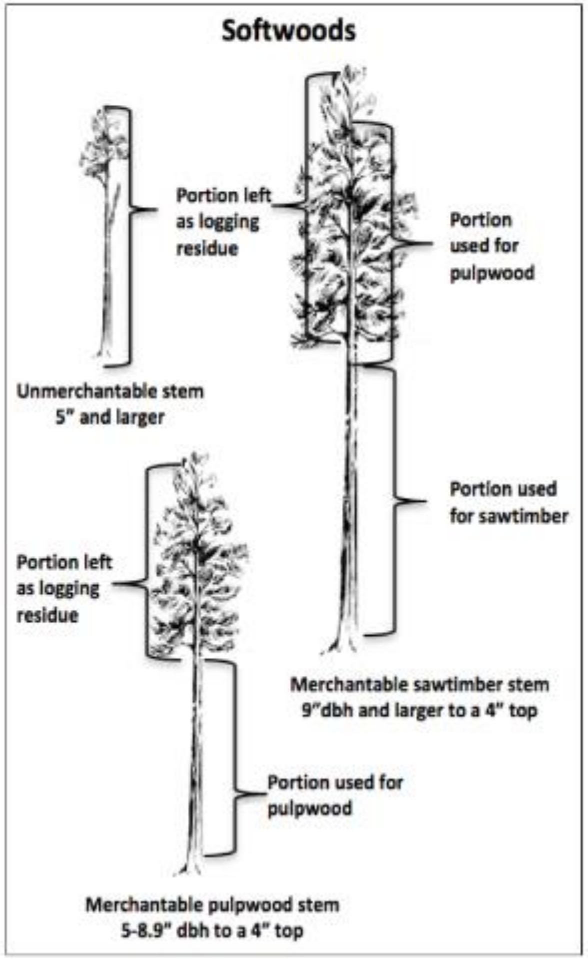
Failure	Impacts	CQAs	SEVERITY	Causes	CMAs	CPPs	OCCURRENCE	Detection methods	DETECTION	RPN
Feed system plug	• Complete Shutdown • Downtime • Potential equipment damage • Product quality	• Throughput • Biomass feedrate • Product quality	10	Sudden and severe build-up of material: • Particle agglomeration and compaction • In-feed and out-feed inconsistencies • Reactions between properties and heated auger • Auger properties	• Particle size and distributions • Moisture (<10%; >25-30%) • Particle surface • Compaction • Particle density	• Auger geometry • Temperature profile • Auger speed	1	Visual observations by trained operator of differential pressure and motor current	10	100
Char buildup on auger	• Reduction in throughput • Potential shutdown • Downtime • Product quality	• Biomass feedrate • Throughput • Particle size (fines) • Product quality	8	Particle agglomeration on auger: • Auger flight deformation • Reactions between properties and heated auger • Particle agglomeration through volatilization and recondensation.	• Particle size and distributions • Moisture (<10%; >25-30%) • Particle morphology • Particle surface • Particle density • Volatiles • Flow properties • Inorganics composition	• Auger geometry (screw pitch) • Auger metallurgy • Auger temperature profile • Auger cooling configuration • Auger speed • Auger surface finish • Auger fill volume • Sweep gas rate	8	• Scheduled maintenance burnouts • Observed increase in motor current, temperature fluctuation in reactor bed, and pyrolysis exit gas rates by trained operator.	3	192
Deviation from target particle size through agglomeration or attrition	<u>Attrition</u> • Reactor performance and yield efficiency • Further particle agglomeration and/or plugging • Increased wear rate • Material flowability <u>Agglomeration</u> • Decline in fluidized bed performance (incomplete conversion) • Plugging or buildup downstream • Product quality • Downtime based on burnout requirements	• Particle Size Distributions • Biomass Feedrate Consistency • Product Quality • Process Efficiency	6	<u>Attrition</u> Particles trapped in flights <u>Agglomeration</u> • Heat flux issue in augur • Heat transfer from auger to particles • Incoming particle properties causing cohesion. • Slower rotation speeds contributing to longer particle-auger contact time.	• Particle size distribution • Moisture • Particle morphology • Particle surface roughness • Volatile content	• Auger geometry • Temperature profile • Rotation speed • Compression forces	6	Observed increase in motor current and temperature fluctuation in reactor bed	6	216

High Temperature Screw Feeder FMEA

Failure	Impacts	CQAs	SEVERITY	Causes	CMAs	CPPs	OCCURRENCE	Detection methods	DETECTION	RPN
Feed system plug	• Complete Shutdown • Downtime • Potential equipment damage • Product quality	• **Throughput** • **Biomass feedrate** • Product quality	10	Sudden and severe build-up of material: • Particle agglomeration and compaction • In-feed and out-feed inconsistencies • Reactions between properties and heated auger • Auger properties	• **Particle size and distributions** • **Moisture (<10%; >25-30%)** • Particle surface • Compaction • Particle density	• Auger geometry • Temperature profile • **Auger speed**	1	Visual observations by trained operator of differential pressure and motor current	10	100

Flowability Biomass – Feed System Plugs

- Material Pine Residue Whole Chips
- Material Attributes:
  - Approximate Particle Size (2, 4, 6 mm)
  - Moisture Levels (Dry (less than 5%), 20% and 40%)
  - Anatomical Fractions (whole, stem, bark, needles)
- Process Parameters
  - Auger Rotational Speed (24, 36, 48 rpm)
- Parameters of interest
  - Flowrate
  - Power Consumption



Depiction of products produced from different fractions of Southeastern softwood trees (*Figure credit:* Bardon and Hazel, 2014).

Flowability Biomass – Feed System Plugs

Sample	Power x 10^3 (kW)			Flowrate (kg/hr)		
	24 RPM	36 RPM	48 RPM	24 RPM	36 RPM	48 RPM
2mm_Dry	8.1 ± 5.4	7.3 ± 6.7	4.1 ± 7.5	37.3 ± 1.2	58.3 ± 1.6	78.3 ± 2.1
4mm_Dry	37.6 ± 16.4	31.4 ± 22.0	24.8 ± 20.6	35.0 ± 1.6	55.5 ± 1.7	73.5 ± 2.8
6mm_Dry	85.3 ± 42.0	81.1 ± 59.6	25.0 ± 27.0	35.4 ± 1.8	56.0 ± 3.8	76.1 ± 5.34
2mm_20%MC	16.2 ± 10.5	14.2 ± 11.5	14.2 ± 12.7	38.0 ± 1.2	56.5 ± 1.8	73.9 ± 2.3
4mm_20%MC	77.8 ± 40.0	67.1 ± 56.0	61.0 ± 62.5	37.5 ± 1.6	56.0 ± 2.5	73.4 ± 3.2
6mm_20%MC	229.0 ± 122.2	171.0 ± 116.5	194.3 ± 167.0	35.9 ± 2.2	55.4 ± 2.9	74.9 ± 5.5
2mm_40%MC	22.9 ± 8.6	17.8 ± 8.4	13.0 ± 10.7	46.4 ± 1.5	68.4 ± 2.2	89.3 ± 2.5
4mm_40%MC	79.1 ± 36.0	90.9 ± 45.3	120.6 ± 40.0	53.6 ± 2.1	80.3 ± 2.6	106.6 ± 4.1
6mm_40%MC	143.2 ± 70.5	118.0 ± 71.9	106.2 ± 82.3	55.0 ± 2.9	82.2 ± 4.7	106.5 ± 5.0

Whole chip material

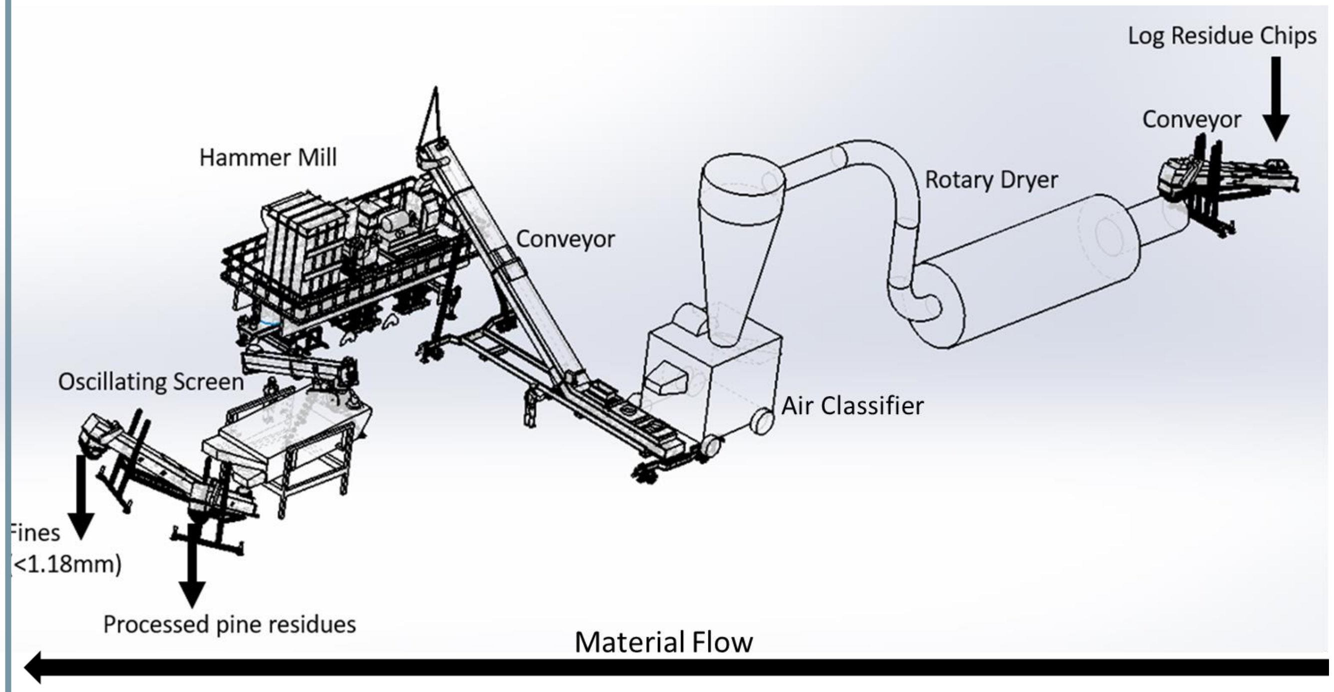
- Increases in rotational frequency resulted increases in flow rate and decrease in power consumption
- Increases in particle size increased power consumption
- Higher flow rates in general seen with increases in moisture

Plug Conditions – Higher Moistures

- Needle rich material
- 4 mm particle size
- **40% moisture**

FMEA Implementation:
Pyrolysis Conversion Pine Residues

Preprocessing System Configuration – Pine Residue



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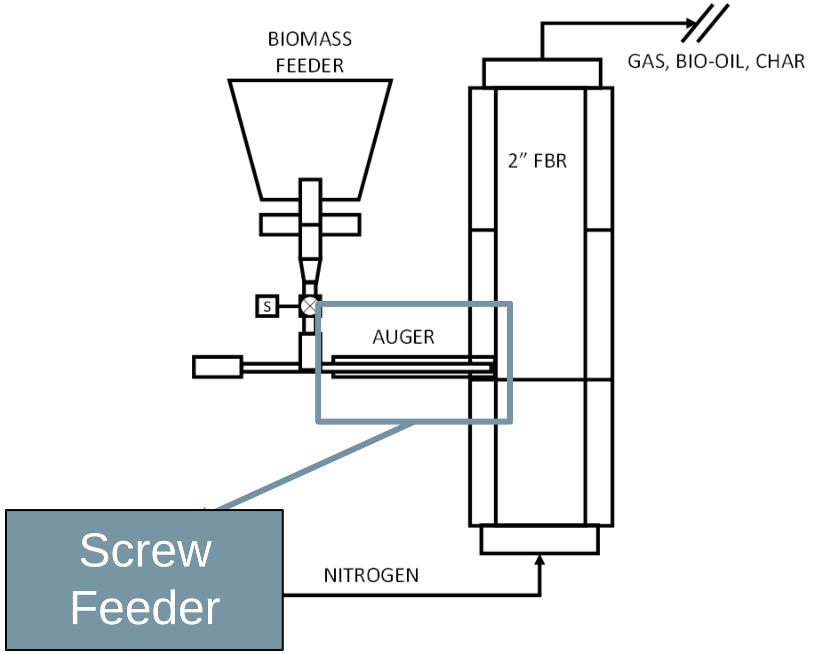
Pyrolysis Conversion System



- FMEA performed on one problematic unit operation
- **Experimental results for identified failures**

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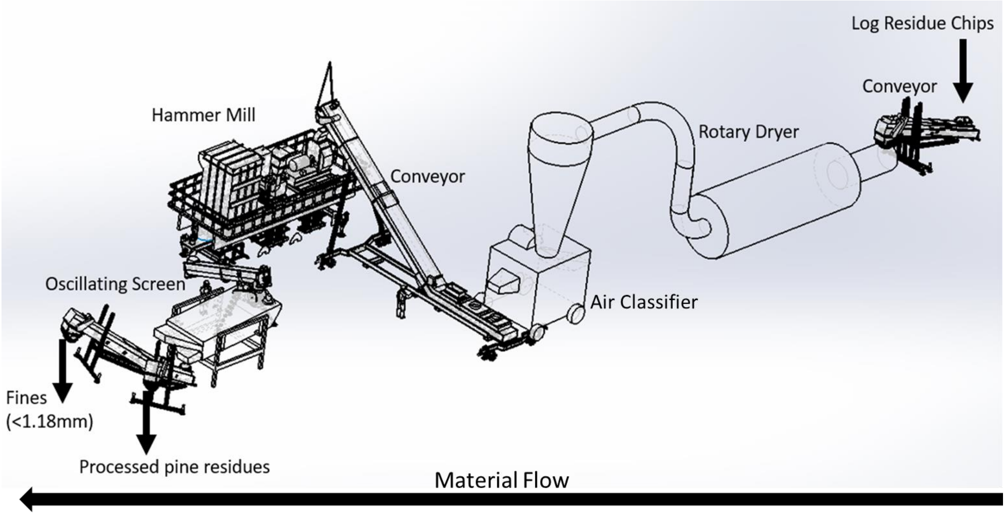
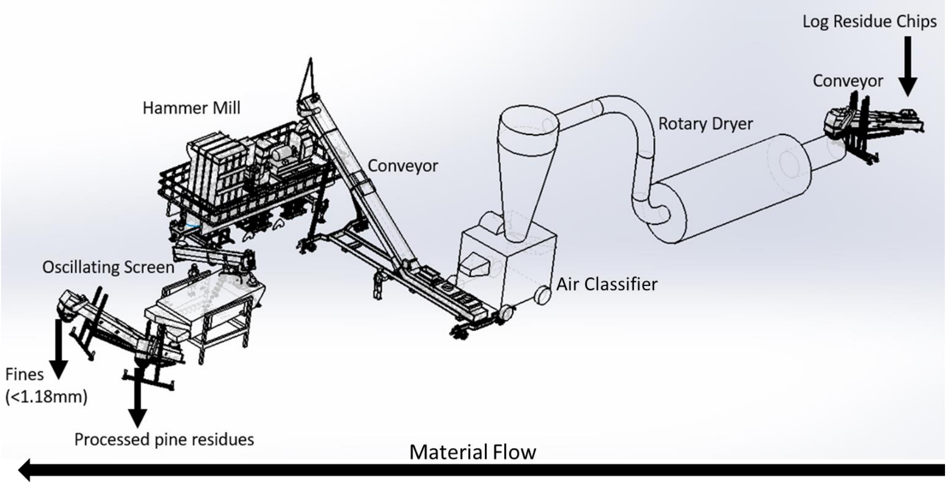
System Wide FMEA Results



- FMEA interviews on whole system
- FMEA interviews on each unit operation
- Target CQAs
  - Moisture (<10%)
  - Fixed Carbon (≥ 18%)
  - Particle Size (1.18–6mm)
  - Ash Content (≤ 1.75%)
  - Throughput

Unit Operation	System	Dryer (Rotary)	Air Classifier	Grinder (Hammer mill)	Oscillating Screen
Nameplate Capacity Throughput	1 tons/hr	5 tons/hr	1 tons/hr	5 tons/hr	5 tons/hr
Typical Throughput	1 ton/hr	1 ton/hr	1 tons/hr	5 tons/hr	3 ton/hr
Input Format	<2” chipped residues	<2” chipped residues	<2” chipped residues	<2” white wood rich	<½” white wood rich
Output Format	1.18mm > white wood rich material < 6mm	<2” chipped residues	Heavy stream: white wood rich; Light stream(s): bark, needle, fines rich	½” minus white wood rich material	1.18mm > white wood rich material < 6mm
Fixed process parameters	Screen sizes and mill speed on grinder and screen size on oscillating screen			Screen size: ½” Mill speed	Top screen: ¼” Bottom screen: 10 mesh

FMEA on Preprocessing



Highlights

- **Rotary dryer failures** resulted in **cascading failures** downstream due to increased moisture.
  - **Fire risk**
- **Best control** for **ash** content (lowest risk scores).
- **Fixed carbon** risk score based on **lack of** chemical specific **sensors.**

Critical Quality Attributes	Specification	Impacting Unit Operation(s)	Max RPN[a] (layer)
Moisture content	≤ 10%	Rotary Dryer	180 (Product Quality) 144 (Process Efficiency)
Fixed carbon	≥ 18%	Air Classifier	**192 (Product Quality)** 72 (Process Efficiency)
Particle size	1.18mm–6mm	Grinder, Oscillating Screen, Air Classifier	108 (Process Efficiency)
Ash content	≤ 1.75%	Air Classifier, Oscillating Screen	90 (Process Efficiency) 80 (Product Quality)
Throughput	Not defined	All equipment	180 (Product Quality) 54 (Process Efficiency)

[a]RPN=risk priority number; ranges from 1-1000 and is based on quantifying the severity, occurrence, and detection of a given risk

Mitigation

Use of visual AI to detect non-white wood concentrations
RPN 72

FEEDSTOCK-CONVERSION INTERFACE CONSORTIUM: Failure Mode and Effects Analysis Summary Report (FY22). United States (2022), doi:10.2172/1894327

Key Takeaways and Future Work

Outcomes

- Standardized framework to represent and semi-quantitatively rank CMAs, CPPs, and CQAs in the context of a ‘Failure’ across multiple unit operations.
- Help in identifying experimental needs.
- System-wide identification of pinch points
- Ability to quantify impacts of research driven improvements through mitigation.

Challenges

- Very dependent on SMEs expertise
- Unidentified critical properties
- Unidentified impacts (e.g., Economic)

- Multiple SMEs
- Use of literature or experimental results
- Input for techno-economic analyses

Questions

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