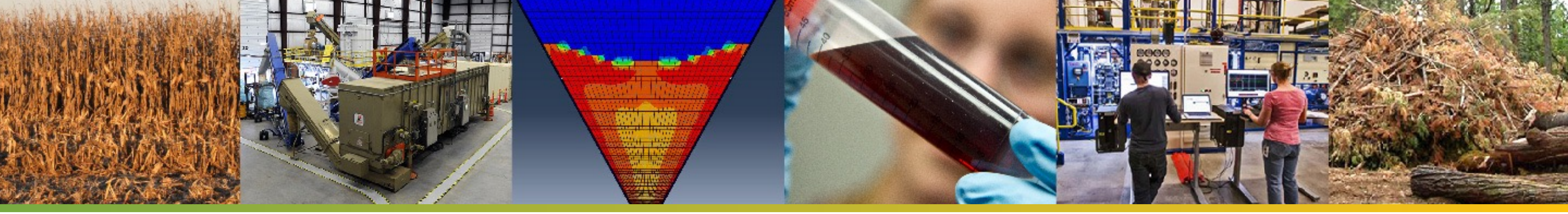


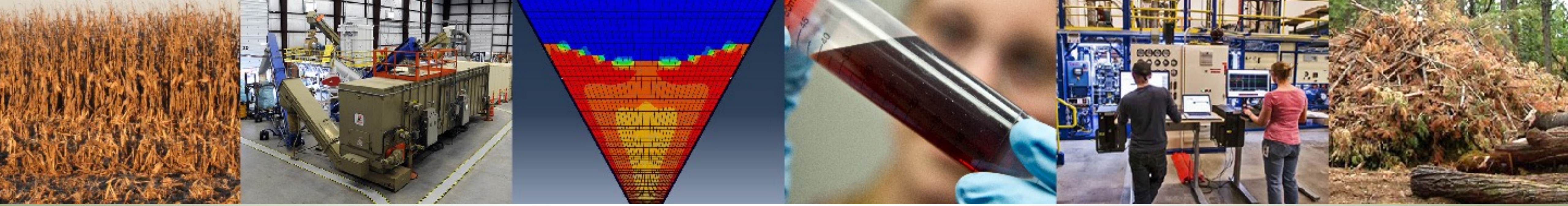
DOE Bioenergy Technologies Office (BETO) 2023 Project Peer Review

FCIC Task 9 – FMEA Criticality Assessment Tools

April 6, 2023
Feedstock-Conversion Interface Consortium (FCIC)

Rachel Emerson
Idaho National Laboratory

FCIC
FEEDSTOCK-CONVERSION INTERFACE CONSORTIUM
U.S. DEPARTMENT OF ENERGY



Project Overview

FCIC Task Organization

Feedstock | Preprocessing | Conversion

Task 2: Feedstock Variability

Task 5: Preprocessing

Task 6: High-Temperature Conversion

Task 1: Materials of Construction

Task 7: Low-Temperature Conversion

Task 3: Materials Handling

Enabling Tasks

Task X: Project Management

Task 4: Data Integration

Task 8: TEA/LCA
Task 9: FMEA

- **Task X: Project Management:** Provide scientific leadership and organizational project management
- **Task 1: Materials of Construction:** Specify materials that do not wear, or break at unacceptable rates
- **Task 2: Feedstock Variability:** Quantify & understand the sources of biomass resource and feedstock variability
- **Task 3: Materials Handling:** Develop tools that enable continuous, steady, trouble free feed into reactors
- **Task 4: Data Integration:** Ensure the data generated in the FCIC are curated and stored – FAIR guidelines
- **Task 5: Preprocessing:** Enable well-defined and homogeneous feedstock from variable biomass resources
- **Task 6 & 7: Conversion (High- & Low-Temp Pathways):** Produce intermediates for further processing
- **Task 8:Crosscutting Analyses TEA/LCA:** Valuation of intermediate streams & quantify variability impact
- **Task 9: Failure Mode & Effects Analysis (FMEA):** Standardized approach for assessing attribute criticality

FMEA Criticality Assessment Tools Task

Objective:

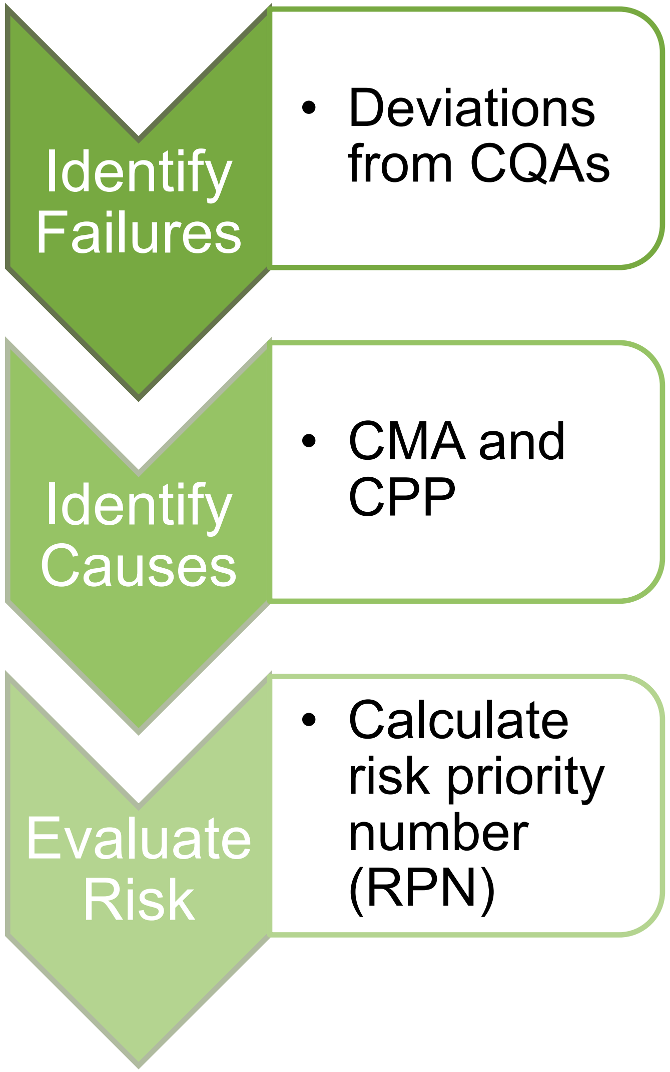
- Implement Quality by Design (QbD) by applying a systematic criticality assessment methodology to evaluate unit operations and systems.
- Develop framework to track and quantify the criticality of critical material attributes (CMAs), critical process parameters (CPPs), and critical quality attributes (CQAs).

Impact:

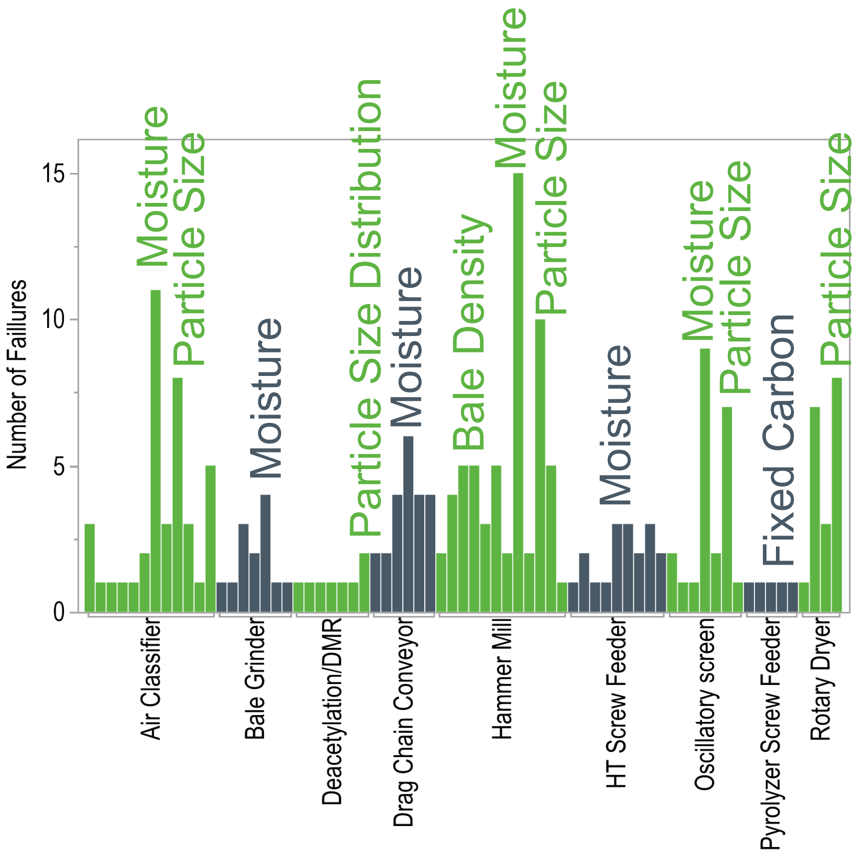
- Development of a systematic methodology for biorefinery risk assessment using a QbD approach.
- Generation of FMEA database for risk assessment of future simulated system configurations.

Outcome:

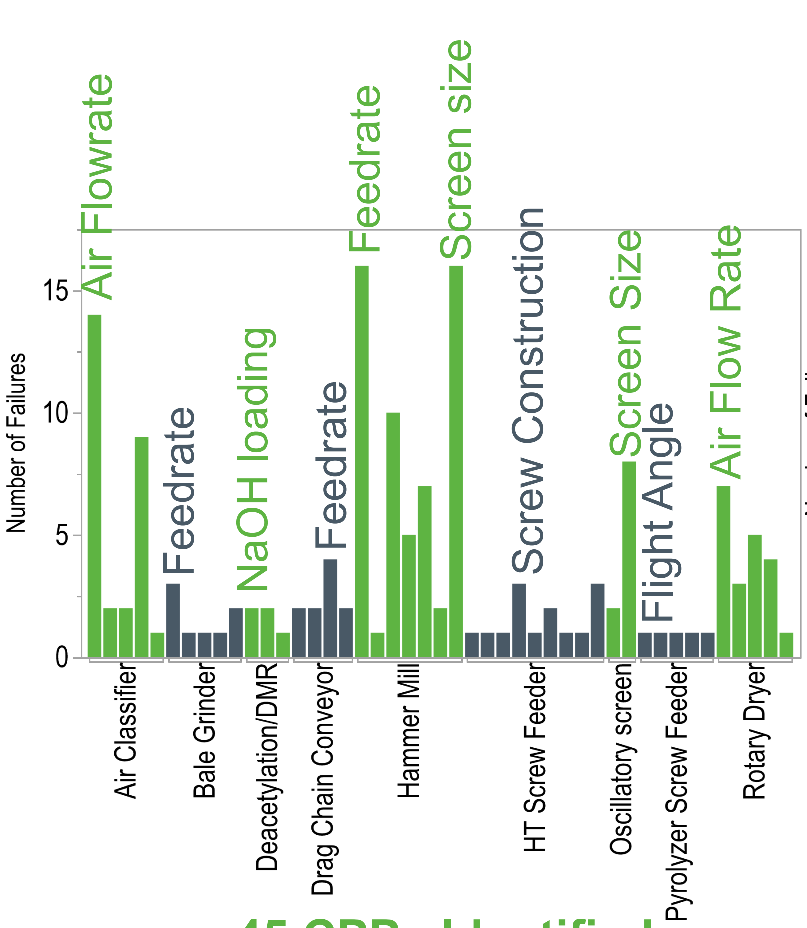
- Provides semi-quantitative criticality estimation for quality attributes (CMAs, CPPs, CQAs) for a given unit operation or system.



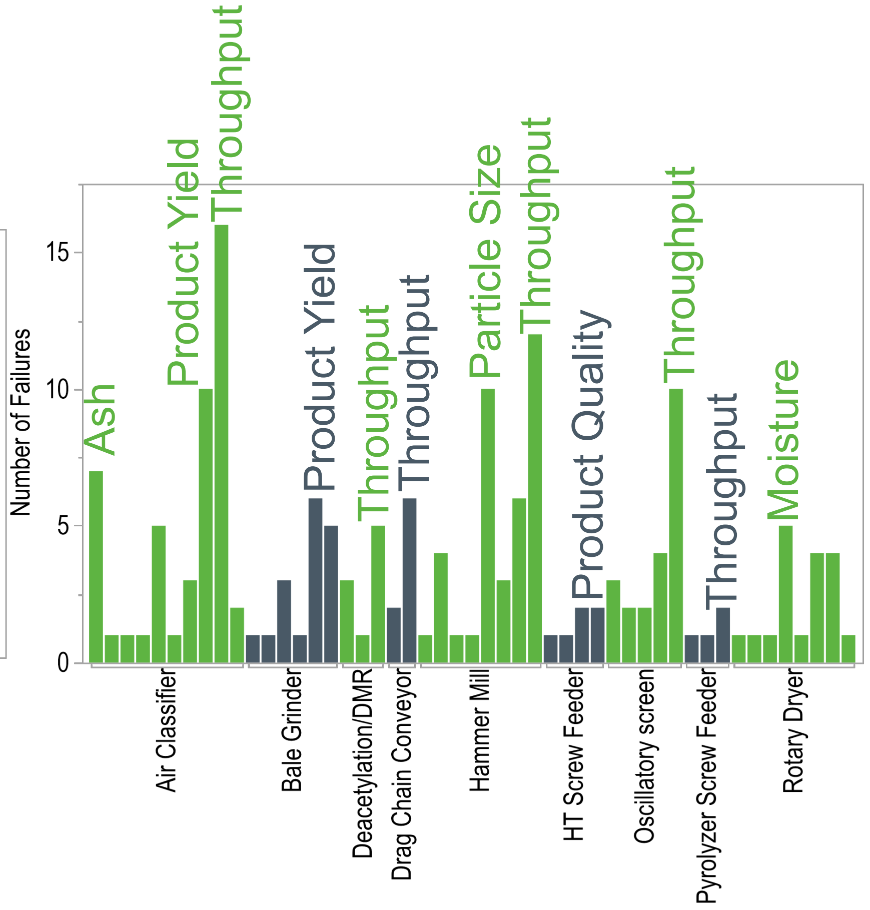
FMEA Criticality Assessment Tools QbD Summary



26 CMAs Identified



45 CPPs Identified



16 CQAs Identified

*Most frequent critical properties associated with failures for a given unit operation are called out in each figure. For example, moisture CMA is associated with 12 failures for the air classifier unit.

The Task 9 Team

Rachel Emerson

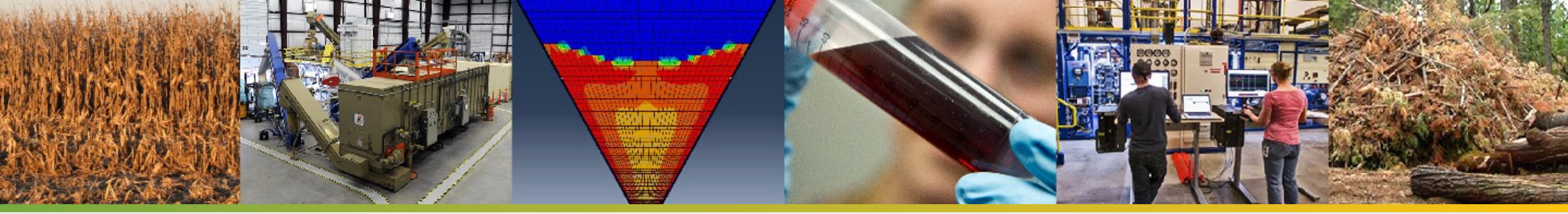
Lorenzo Vega-Montoto

Pralhad Burli

Tiasha Bhattacharjee

Subject Matter Experts

- Neal Yancey—INL
- Jeff Lacey—INL
- Jordan Klinger—INL
- Danny Carpenter—NREL
- Xiaowen Chen—NREL
- Steve Phillips—PNNL
- Corey Landon—INL
- Mark Small—INL
- Stephen Kanyid—INL
- Cody Scheer—INL
- Kristan Egan—INL
- Brad Kelley—GBB
- Sparta (Recycling equipment manufacturer)
- Pratt Recycling
- BHS (Recycling equipment manufacturer)
- Wasatch Integrated Waste



1 – Approach

1 – Approach

Failure Mode and Effects Analysis (FMEA)

- Well-accepted risk assessment tool
- Couples well with Quality-by-Design approaches

Necessary Components for Success

- Standardized approaches to data collection
- Quality of information and data provided through 1st person subject matter expert (SME) interviews

Challenges and Risks

- Bias and level expertise SMEs

Mitigation

- Using multiple SMEs for each piece of equipment
- Industry SME input

Unit Operation FMEA

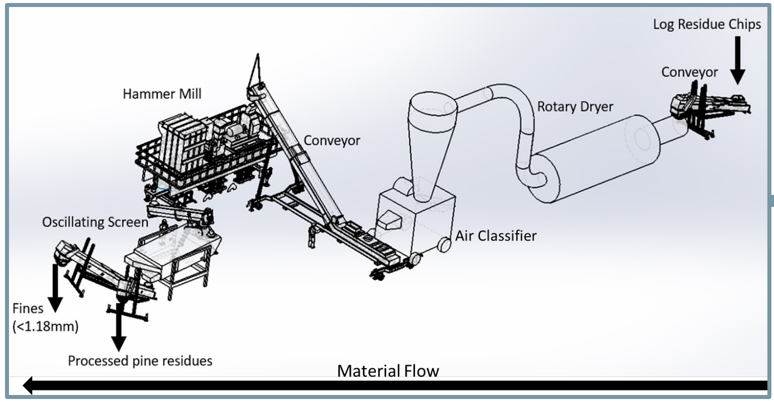
- Single unit operation
- Immediate upstream or downstream unit operations for QbD
- Mitigations focused on minimizing RPNs for failures associated with unit operation

System FMEA

- Focus on system as a whole
- CQAs based on next system or product
- Identification of point failures within system
- Mitigations include new system configurations

1 – Approach

FMEA Workflow



System Design Determination
Task 8

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

Interviews with Subject Matter Experts
Tasks 2, 3, 5, 6, 7, 8; Industry

Quantify* **Severity** (S), **Occurrence** (O) and **Detection** (D) to calculate **Risk Priority Number** (RPN).

RPN = S x O x D = Risk x D

FMEA Interview Results

Appendix D – Air Classifier (pine residues) FMEA

Failure	Impacts	CQAs	SEVERITY	Causes	CMAs
Inefficient Separation – Too much Bark in heavy fraction	• Product quality impacting HT conversion feedscrew equipment • Product quality impacting HT conversion reactor • Increased wear on downstream equipment	• Ash content (<1.0%) • Particle size • Tissue fraction ratios	10	• Increased moisture contents • Initial tissue ratios • Harvest method impacting chips size, tissue ratio, soil contaminants, moisture, etc. • Decreased mean particles size of chips	• Moisture • Particle s whole • Particle s tissue fra
Inefficient Separation – Too many needles in the medium fraction	• Reprocessing of portion or whole batch of material	• Ash content • Tissue fraction ratios • Throughput	6	• Increased moisture • Variability between batches • Shape and size of	• Particle s (needles • Particle s (needles

This database contains all of the FMEA results collected to date. To see details regarding the FMEA SME interview result the detailed FMEA interview summaries.

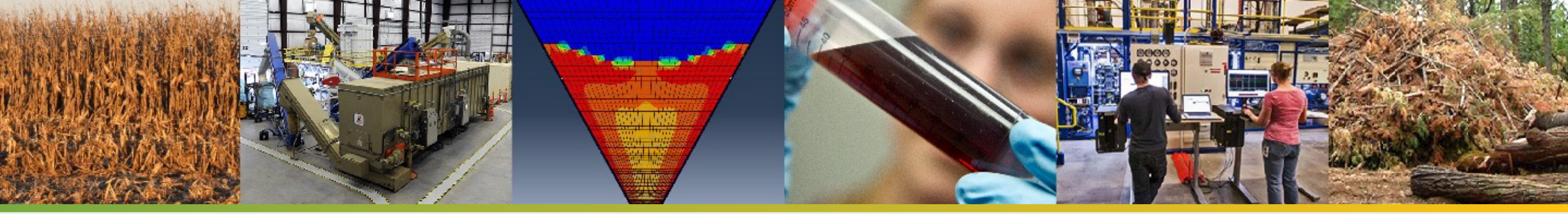
Design Delete All Rows

	Unit Operation	Equipment Type	Material Stream	Tech Pathway	Process Flow Diagram RT	Failure	TRL	Severity	Occurence	Detection	RPN	CQA Material	Units	CQA Pro
☐	FRACTIONATION_AIR_CLASSIFIER_03	Air Classifier	Pine Residue	FMEA_HT-P-1		Partially blocked screen_01	A	10	3	10	300	ASH_CONTENT_01	%	
☐	FRACTIONATION_AIR_CLASSIFIER_03	Air Classifier	Pine Residue	FMEA_HT-P-1		Partially blocked screen_01	A	10	3	10	300	PARTICLE_SIZE_01	mm	

Criticality Assessment

Results Harmonization
Task 4

*Guidance scale for quantifying **Severity**, **Occurrence**, and **Detection** provided in additional slides



2 – Progress and Outcomes

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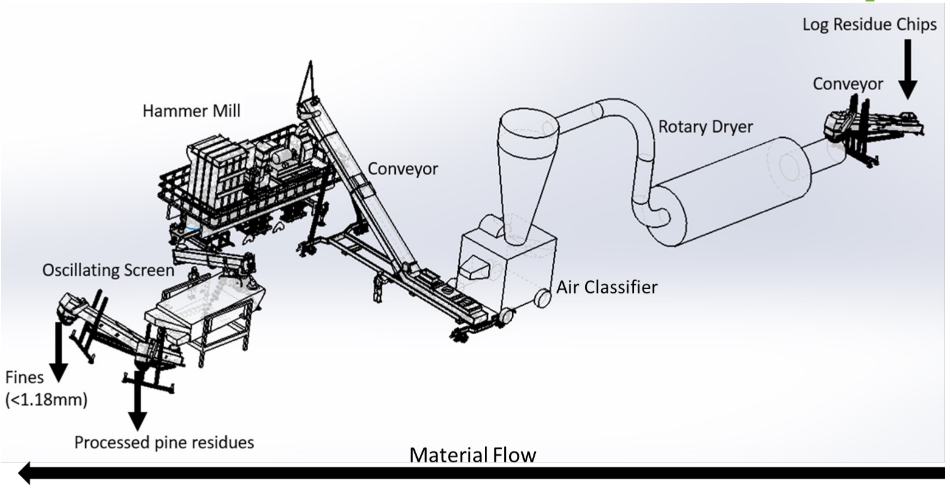
FMEA Results—Preprocessing system for Pine Residues



Highlights

- **Fixed carbon** risk score based on **lack of** chemical specific **sensors;** Detection = 8 (of 10).
  - **Visual detection (RGB)** for non-white wood **mitigation.**
- **Rotary dryer failures** resulted in **cascading failures** downstream due to **increased moisture.**
- **Best control** for **ash** content (lowest risk scores).

Critical Quality Attributes	Specification	Impacting Unit Operation(s)	Max RPN[a] (layer)	Mitigation RPN
Moisture content	≤ 10%	Rotary Dryer	180 (Product Quality) 144 (Process Efficiency)	90 72
Fixed carbon	≥ 18%; ≥ 21%	Air Classifier	**192 (Product Quality)** 72 (Process Efficiency)	**72** 54
Particle size	1.18mm–6mm	Grinder, Oscillating Screen, Air Classifier	108 (Process Efficiency)	54
Ash content	≤ 1.75%	Air Classifier, Oscillating Screen	90 (Process Efficiency) 80 (Product Quality)	18 48
Throughput	Not defined	All equipment	180 (Product Quality) 54 (Process Efficiency)	90 27

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

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

2 – Progress and Outcomes

4 Industry MSW interviews: 2D/3D Separation Equipment

- Sparta, BHS, Pratt Recycling, Wasatch Integrated Waste

Polishing Disc Screen

https://bulkhandlingsystems.com/equipment/polishing-screen/

Ballistic Separator

https://www.mswsorting.com/Waste-Sorting/Ballistic-Separator.html

Failure	CQAs	CMAs	CPPs
Separation Efficiency	• Throughput • Product Quality	• Moisture (high) • Particle size distribution (wide) • Bulk Volume (high) • 2D/3D Ratio	• Screen Angle • Feedrate • Shaft Speed (Disc Screen) • Fan Tail Angle (Disc Screen)

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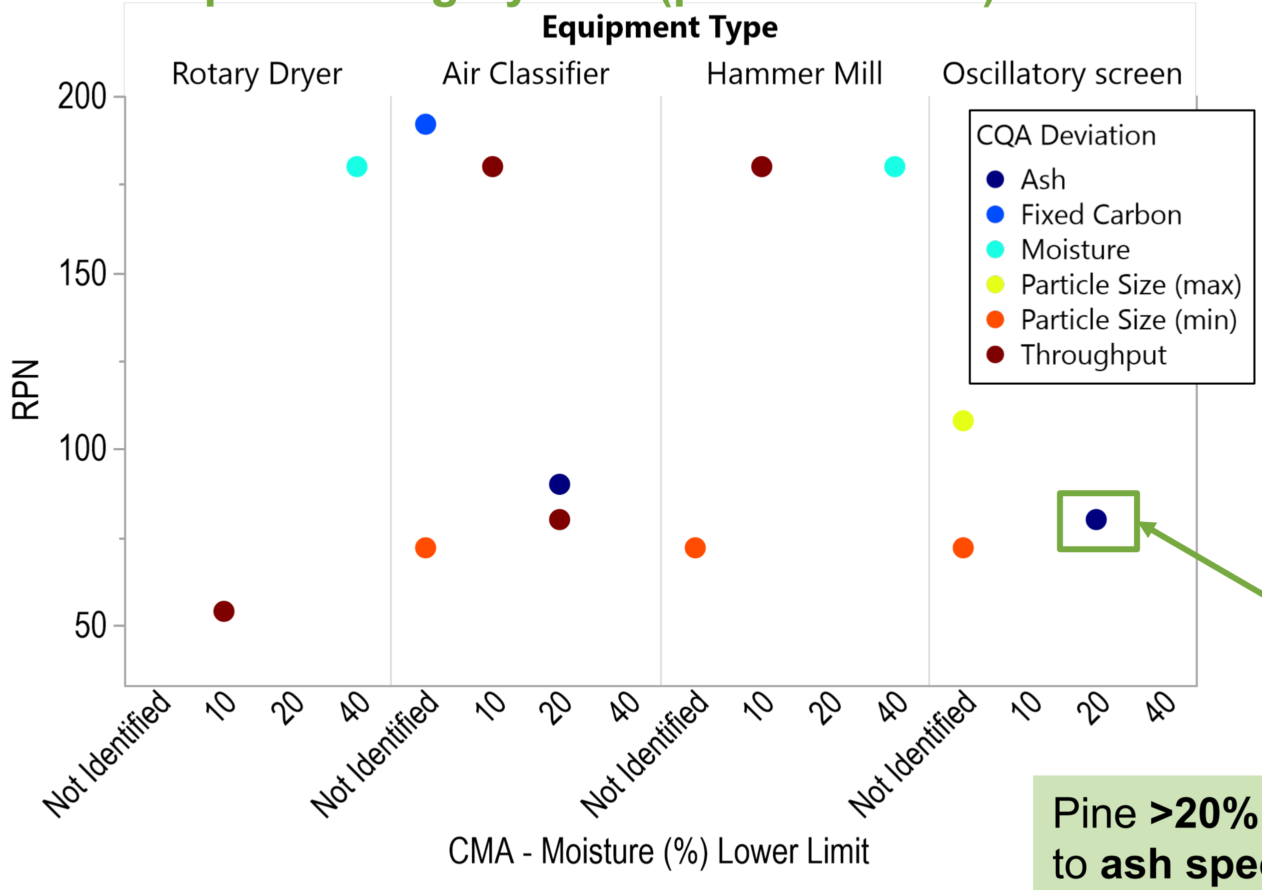
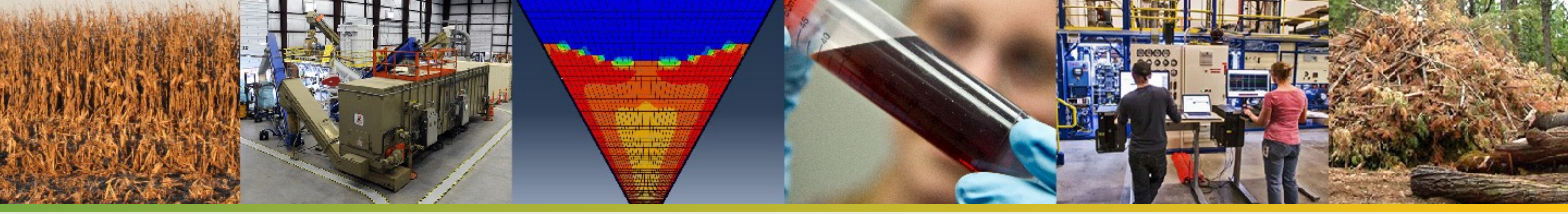
Standardized Data Collection - FMEA Database

HT Preprocessing System (pine residues)



- **Tracking moisture** (CMA) through pine preprocessing system.
- **Moisture levels** associated with the failure are **quantified.**

Pine **>20% moisture** for oscillatory screen contributes to **ash specification failures** (RPN = 80)



3 – Impact

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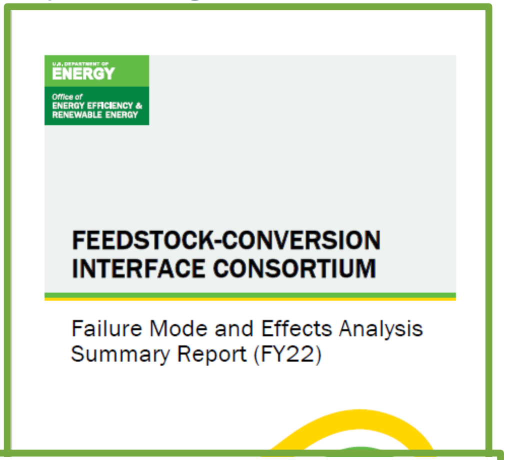
Project Impact

https://doi.org/10.2172/1894327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Failure Mode and Effects Analysis Summary Report (FY22)

- Development of a **systematic methodology** for biorefinery risk assessment using a QbD approach.
  - Ability to **quantify impacts** of research driven improvements
  - Provide evidence to help **prioritize experimental needs** for the consortium.
- Generation of FMEA database for risk assessment of **future simulated system configurations.**

Outreach

- Currently working with industry collaborators and Industry subject matter experts.
- Results dissemination through **Technical Summary Report.**
- Plans to attend industrial relevant conferences for dissemination before project end.

Failure	SEVERITY	OCCURRENCE	DETECTION	RPN	Mitigation(s)	SEVERITY	OCCURRENCE	DETECTION	RPN
Excessive overs production (> 6mm) Unit Operations: Mill, Oscillating screen	6	3	6	108	• **In-line particle size analyzer (in-process) – Selected** • Replace hammer mill with rotary shear mill; more experimental data to support optimal screen combination for meeting particle size specifications (Implemented).	6	3	3	108
Excessive fines production (< 1.18 mm) Unit Operations: Mill, Air classifier, oscillating screen	3	3	8	72	• System reconfiguration to move rotary dryer to after milling step. Would product more overs; less fines might be removed through air classification unit.	3	TBD	8	TBD
Deviation from fixed carbon specification (<18 or 21%) Unit Operations: Air classifier	8	3	8	192	• Moisture sensor for detecting materials higher than 10% moisture (In-process) • **Visual detection for identifying "non-white wood" (Idea) - Selected** • Carbon concentration sensor (idea)	8	3	3	72
	3	3	8	72	• Moisture sensor for detecting materials higher than 10% moisture (In-process) • **Visual detection for identifying "non-white wood" (Idea) – Selected** • Carbon concentration sensor (idea)	6	3	3	54

Table 10. FMEA mitigation strategies for HT system wide configuration.

Summary

Technical Approach

- **Implement Quality by Design (QbD)** by applying **Failure Mode and Effects Analysis (FMEA)** as a systematic criticality assessment methodology to evaluate unit operations and systems.

Impact

- Development of a **systematic methodology for biorefinery risk assessment** using a QbD approach.

Achievements

- Complete FMEA **system evaluation** for two **preprocessing system configurations.**
- **Industry** engagement through **MSW separation technology** focused FMEAs.
- Generation of **FMEA database** for risk assessment of **future simulated system configurations**.

Quad Chart Overview

Timeline
- *October 1, 2021*
- *September 30, 2024*

	FY22 Costed	Total Award
DOE Funding	*$153,640*	*$520,000*
Project Cost Share *	NA	NA

TRL at Project Start: 4
TRL at Project End: 6

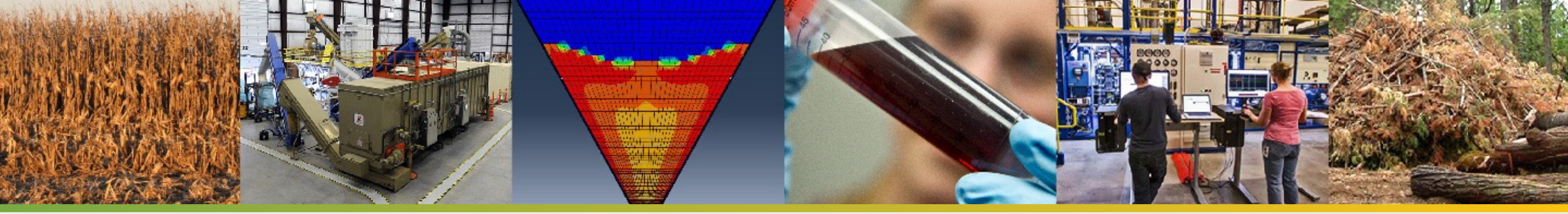
Project Goal
Implement Quality by Design (QbD) approaches to FCIC research by applying a systematic criticality assessment methodology using Failure Mode and Effect Analysis (FMEA), a robust and well-accepted quantitative risk analysis approach, to evaluate the FCIC processing and conversion unit operations in the context of a system.

End of Project Milestone
Complete FMEA on 90% of FCIC research relevant material/preprocessing unit operation combinations. Summary of FMEA results over the past 3 years will be captured in a final Technical Report.

Funding Mechanism
2021 Lab Call – FCIC Merit Review

Project Partners
- Gershman, Brickner & Bratton, Inc.

*Only fill out if applicable.



Additional Slides

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Responses to Previous Reviewers' Comments

Reviewers Comments from FY21 Peer Review WBS 1.2.2.2 - Standardized Risk Assessment and Critical Property Analytics" where the work in developing FMEA as a tool was jointly funded with FCIC.

Reviewers' Comments FY21:

- "Initial results indicate that the risk assessment provides a decision tool that may help in reducing perceived risk associated with bioenergy projects. The formed groups of subject area experts could contain bias which could limit the severity/occurrence/detection guidance tables."
- "FMEA is advancing the state of the art for determining risk associated with biomass quality. Interesting approach for sure. I am not sure how the CMA's and CPP's are to be derived but will need significant **industrial involvement**.... A sophisticated and logical approach."

Responses to Reviewers' Comments:

- "Our team agrees that this will always be a risk with this type of approach. The assembled **subject matter expert (SME)** teams include researchers with various experience levels, different backgrounds, and multiple researchers representing single unit operations. In addition to **industry SME** inputs."
- The FMEA approach requires interviews with Subject Matter Experts (SMEs) to gather the necessary data [for deriving CMA's and CPP's].

Publications, Patents, Presentations, Awards, and Commercialization

Publications

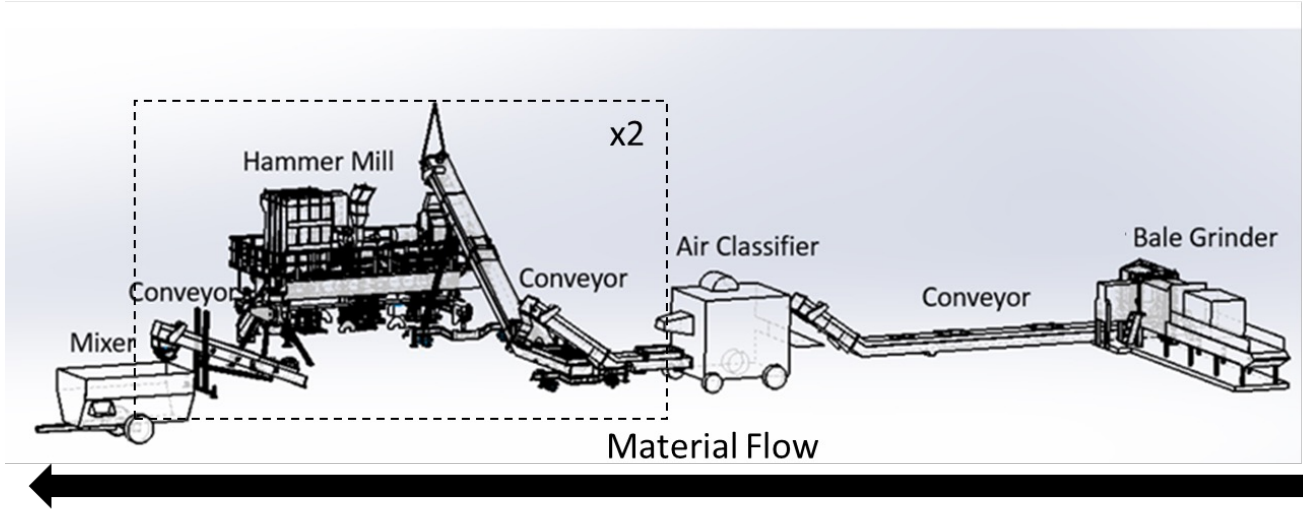
- FEEDSTOCK-CONVERSION INTERFACE CONSORTIUM: Failure Mode and Effects Analysis Summary Report (FY22). United States (2022), doi:10.2172/1894327

Presentations

- Emerson, R., Solomon, J., Lewandowski, M., Nair, S., Vega-Montoto, L., & Burli, P. (2021). Bio-Project ‘Derisking’ through Development of Systematic Methodologies and Frameworks for Risk Assessment. 2021 AIChE Annual Meeting, Boston MA, November 8.

Additional Project Achievements

FMEA Results—Preprocessing system for corn stover



Highlights

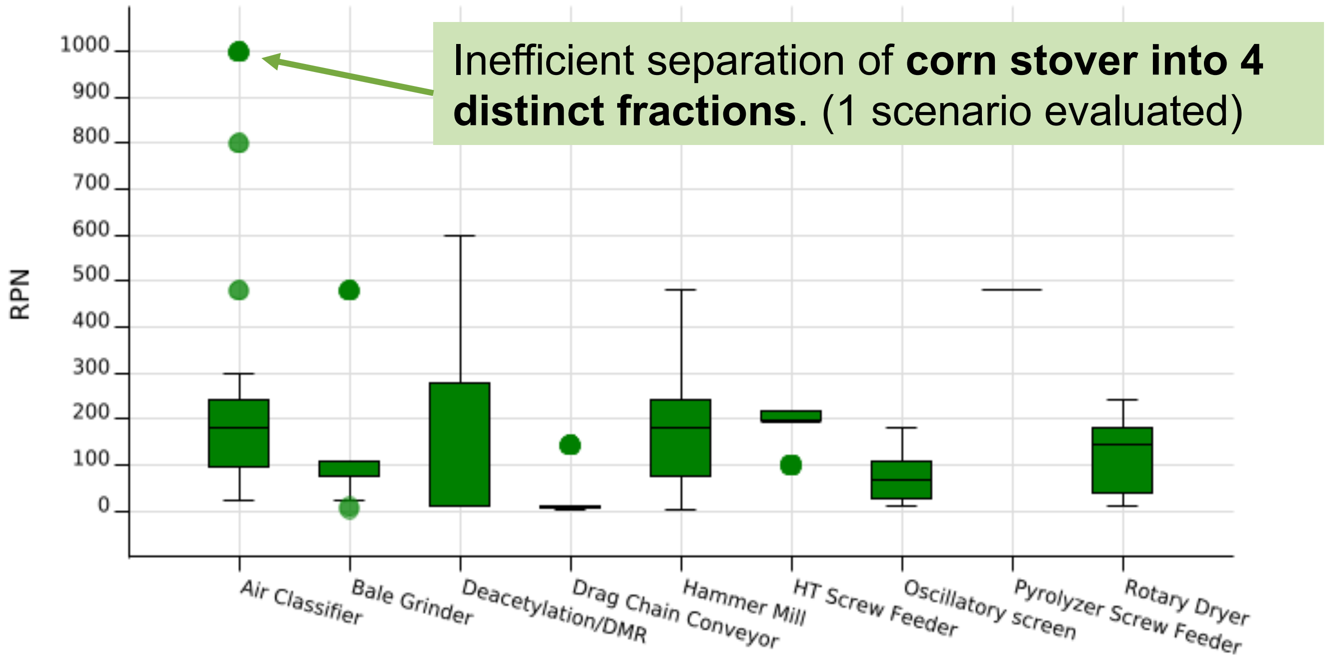
- System design **cannot control for moisture, carbohydrates, or ash** (high risk scores)
  - **40-60%** of bales **will not meet carbohydrate** specification.
  - **Ash** specification **rarely met** by single bale
- **Moisture (<20%)** and **fines (particle size)** identified to impacts downstream **conversion process efficiency.**

Critical Quality Attributes	Specification	Impacting Unit Operation(s)	Max RPN[a] (layer)
Moisture content	20%		60 (product quality) 240 (process efficiency)
Carbohydrate content	≥ 59%	Air Classifier (mitigation)	**800 (product quality)**
Ash content	≤ 4.93%	Air Classifier (mitigation)	**800 (process efficiency)**
Particle size	<1”	Bale Grinder, Hammer mill	480 (product quality)
Throughput	Not defined	All equipment	TBD (economics)

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

Standardized Data Collection - FMEA Database

- **Comparison of risk scores** across all equipment and systems configurations.
- Failure modes for **specific scenarios for air classifier** had the **highest RPN.**
  - Severity = 10 (of 10)
  - Occurrence = 10 (of 10)
  - Detection = 10 (of 10)



Guidance Scales

- **Severity (S)**—how serious the impact of the failure
- **Occurrence (O)**—the likelihood or frequency of the given failure
- **Detection (D)**—how effective are the methods for detecting and/or preventing the failure.

RPN = S x O x D = Risk x D

Severity Guidance Scale

Effect	Rank	Criteria
Minor	1	None to minor disruption to production line. A small portion (much <5%) of product may have to be reworked online.
Low	3	Low disruption to production line. A small portion (<15%) of product may have to be reworked online. Process up. Minor annoyance exist
Moderate	6	Moderate disruption to production line. A small portion (>20%) of product may have to be reworked online. Process up. Some inconvenience exist
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.

Guidance Scales (cont.)

Occurrence Guidance Scale

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 Guidance Scale

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.