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FEEDSTOCK-CONVERSION INTERFACE CONSORTIUM

Failure Mode and Effects Analysis Summary Report (FY22)

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Disclaimer

About the Feedstock-Conversion Interface Consortium

The Feedstock-Conversion Interface Consortium (FCIC) develops first-principles-based knowledge and tools to understand, quantify, and mitigate the effects of feedstock and process variability across the bioenergy value chain, from the field and forest through downstream conversion. The FCIC is a collaborative and coordinated effort involving researchers in many different disciplines. It is led by the U.S. Department of Energy's Bioenergy Technologies Office (BETO) and includes researchers from nine national laboratories: Argonne National Laboratory, Idaho National Laboratory, Lawrence Berkeley National Laboratory, Los Alamos National Laboratory, National Energy Technology Laboratory, National Renewable Energy Laboratory, Oak Ridge National Laboratory, Pacific Northwest National Laboratory, and Sandia National Laboratories.

Research within the FCIC focuses on two complementary conversion pathways: (1) the low-temperature conversion of corn stover to fuels and chemicals using deacetylation and mechanical refining, enzymatic hydrolysis, and biological upgrading of the sugar- and lignin-rich streams; and (2) the high-temperature conversion of pine residues to fuels using catalytic fast pyrolysis and hydrotreating. Each pathway covers three sequential process areas—biomass harvest and storage, preprocessing, and conversion.

The FCIC is organized into eight collaborative tasks working in each of these process areas. The Feedstock Variability task investigates biomass attribute variations that originate in the harvest and storage process area; the Preprocessing, Materials Handling, and Materials of Construction tasks investigate the effects of biomass variability in the preprocessing area; and the High-Temperature Conversion and Low-Temperature Conversion tasks investigate the effects of biomass variability in the conversion process area. Two supporting tasks (Crosscutting Analyses and Scientific Data Management) support all FCIC research.

The Feedstock-Conversion Interface Consortium uses first-principles-based science to de-risk biorefinery scale-up and deployment by understanding and mitigating the impacts of feedstock variability on bioenergy conversion processes.

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Availability

This report is available electronically at no cost from http://www.osti.gov.

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List of Acronyms

BETO	Bioenergy Technologies Office
CMA	Critical Material Attribute
CP	Critical Properties
CPP	Critical Process Parameter
CQA	Critical Quality Attribute
CQMA	Critical Quality Material Attribute
CQPA	Critical Quality Process Attribute
DES	Discrete Event Simulation
DMR	Disc Mechanical Refining
DOE	U.S. Department of Energy
FCIC	Feedstock Conversion Interface Consortium
FMEA	Failure Mode and Effects Analysis
FMECA	Failure Mode Effects and Criticality Analysis
HT	High-Temperature
LCA	Life Cycle Analysis
LT	Low-Temperature
PSD	Particle Size Distribution
QbD	Quality by Design
RPN	Risk Priority Number
SME	Subject Matter Expert

TEA	Techno Economic Analysis
TRL	Technology Readiness Level

Executive Summary

This report provides an overview of the development of failure modes and effects analysis (FMEA) and its implementation as a systematic criticality and risk assessment tool supporting a quality by design (QbD) approach for FCIC research. This report also provides a high-level overview of the results for the FMEA evaluation of two feedstock preprocessing system configurations: (1) generation of pine residue materials for high-temperature pyrolysis conversion and (2) generation of corn stover materials for low-temperature conversion using deacetylation and disc mechanical refining pretreatment for fermentation to hydrocarbons. For the results presented in this report, our FMEA interviews included two approaches. The first approach was to perform FMEA interviews for the entire system of unit operations giving a wholistic system level view. The second approach consisted of detailed interviews for each individual unit operation within the system allowing for a “deep dive” into the specific failures for the individual components within the configuration. These two approaches provide different resolutions of information. The FMEA results of this report were focused on failures associated with meeting critical quality attributes (CQAs) identified for the target conversion processes for each processed feedstock type. The information gathered through the FMEA interviews include estimations of risk scores for meeting each given CQA specification, identification of the impacts for not meeting a CQA specification, capturing causes associated with material attributes and process parameters for each failure, identification of current detection methods, and speculation of potential mitigation strategies for decreasing a failure’s risk score. The complete results of all FMEA interviews are provided in the Appendices of this report.

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Introduction

Quality by Design (QbD) is a systematic approach to product development that begins with predefined objectives and emphasizes product and process understanding and process control, based on sound science and quality risk management (Stamatis 2003). Several quality risk management tools have been proposed for industry and regulators such as basic risk management facilitation methods (i.e., flowcharts and check sheets), failure mode and effects analysis (FMEA), fault tree analysis, hazard analysis and critical control points, hazard operability analysis, and preliminary hazard analysis. FMEA is a risk management tool to systematically identify and assess the causes and effects of potential failures in a system, translating the anecdotal information provided by subject matter experts (SMEs) into a semi-quantitative risk priority number (Stamatis 2003). The FMEA approach was developed after failure mode effects and criticality analysis (FMECA) as a less data intensive risk management tool. FMECA was developed by the army in the 1940s and it was adopted by NASA in the 1950s. Ford Motor Company started using the more simplified FMEA in the 1970s, becoming an industry-wide tool by 1980s (Carlson 2012). Currently, FMEA is the preferred risk management tool employed by the pharmaceutical industry when QbD is implemented. FMEA and FMECA methodologies only differ in the way they assess the risk associated with the issues identified during the analysis and to prioritize corrective actions. FMECA employs Criticality Analysis and FMEA uses Risk Priority Numbers (RPNs).

A typical FMEA exercise is a continuous improvement method that it is performed by completing the following steps: selection of processes to be assessed, formation of a multidisciplinary team, i.e., SMEs, collection and classification of risk scores from each process based on identified process failures, risk analysis, and implementation of remedial actions and reanalysis to see if those actions are effective. The multidisciplinary team brainstorms to assign an RPN to each potential failure (Stamatis 2003). The RPN is the product of scores representing the three aspects of a failure: severity (i.e., how severe is the consequence if the process fails?), occurrence (i.e., how frequently can a process fail?), and detection (i.e., how easily can a failure be detected or prevented?). These failures are usually connected to departures from critical quality attributes (CQAs) and can be directly rooted to a set or combination of critical material attributes (CMAs) and critical process parameters (CPPs). This semi-quantitative risk analysis approach assesses and reduces risk of process failures while unveiling CQAs, CMAs and CPPs. Overall, this approach allows for the prioritization and the of design optimal experiments to fundamentally understand the process and its working space envelope.

There are multiple types of FMEAs focused on improving and understanding system design: System FMEAs, Design FMEAs, and Process FMEAs. For this work we focus on System FMEAs where the objective is to improve the design of the system (Carlson 2012). System FMEA is the highest-level analysis of an entire system that is made up of various subsystems. It is mostly employed to identify and assess system-related deficiencies, including system safety, system integration, and interfaces or interactions between subsystems or with other systems. This approach can also identify interactions with the surrounding environment, including human interactions. More specifically, System FMEA is a wholistic approach that focuses on the functions and relationships that are unique to the system as a whole. The System FMEA also includes failure modes associated with single-point failures (where a single component failure can result in complete failure of the entire system). Anecdotal accounts indicate that 50% or more of system problems occur at the interfaces between subsystems or components (Stamatis 2003). Therefore, understanding and addressing interfaces and integration is essential to achieving safe and reliable systems. A System FMEA also allows for evaluation of alternative designs that could reduce failure risk while improving reliability and cost. For these reasons the results provided in this report included two FMEA approaches. The first approach was to perform FMEA interviews for the entire system of preprocessing unit operations giving a wholistic system level view. The second approach consisted of detailed interviews for each individual unit operations within the system allowing for a "deep dive" into the specific failures for the individual components within the configuration. These two approaches provide different resolutions of information allowing for a fuller picture of the potential failures within the system.

Methods

FMEA Adaption Overview

For the purposes of the FCIC and other U.S. Department of Energy's BETO funded projects, the FMEA approach was adapted to meet the research needs of systematic QbD focused methodology for quantifying criticality of the proposed properties measured and evaluated across multiple unit operations within a system. Here we describe how FMEA has so far been implemented to meet these research needs.

The use of FMEA requires establishing guidance scales to apply numeric values to describe the severity—how serious the impact is of the failure mode, occurrence—the likelihood or frequency of the given failure, and detection—how effective current methods are for detecting and/or preventing the failure. When FMEA is utilized for a specific process design or system, some level of adaptation is required to meet the needs of the specific objective for using FMEA. For the case of the FCIC, FMEA is used to evaluate and rank critical properties (CPs) in the context of a specified "failure" for a combination of identified materials, process or unit operation, system configuration (actual or theoretical), and target product. The description for each of the guidance scale levels are intended to be generic enough to assist the SME in identifying how the failure mode in question should be ranked (Tables 1-3). In some cases, only portions of the criteria statements are applicable to a specific failure severity, occurrence, or detection. In these cases, the nuances of the SME's justifications for selecting a specific ranking are captured within the interview process.

Table 1. Severity guidance scale

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.

Table 2. 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.

Table 3. 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.

The generic function of process units (e.g., deconstruction) will theoretically exist in system, but in most cases are being researched as separate unit operations for the purposes of FCIC research. Additionally, because of this focus on independent disconnected unit operations and theoretical system designs, the various process units that are evaluated using the FMEA approach will have varying levels of data and 1st hand experience for specific material and product combinations. Because of these reasons, an additional layer of information is collected through the interviews for FMEA-specific assigned Technology Readiness Level (TRL) for our adapted implementation of FMEA (Table 4).

Table 4. FMEA TRL (A-C) definitions used to categorize each FMEA interview

FMEA TRL (A-C)	Description
A	Common combination of material and equipment. Well understood and 1st hand experimental data readily available.
B	Common combination of material and operation. Well understood; however, 1st hand experimental data is not readily available. OR Uncommon combination of material and equipment and 1st hand experimental data readily available
C	Equipment relevant and common for processing different feedstock than the target material and/or used in another industry. Little data currently available.

After the selection of SMEs for a targeted material, process or unit operation, system configuration, and product combinations, the FMEA facilitator team conducted interviews with 1-2 SMEs at a time. A general outline for these interviews is shown in Figure 1. For each interview, the base questions were designed to focus the FMEA discussion on a very specific piece of equipment and configuration under normal operating conditions. As the unit operations throughout the FCIC are used for research purposes, as opposed to an industry setting where the objective is to produce specific products meeting yield and quality expectations, it was important to focus the interview on operating conditions in a setting where steady operation for production was the goal as opposed to operational modes designed to answer specific research questions. This was one of the more challenging aspects of using the FMEA approach in a research setting. After establishing the operational and equipment bounds, the various failure modes were identified. Failure modes were defined as situations where the unit operation or process was not performing or producing as intended. For each failure mode, the impacts of the failure (Severity), the causes for the failure, the likelihood of the failure occurring (Occurrence), and the methods for detecting and/or preventing the failure (Detection) were identified. The complete list of base interview questions is included in Appendix A. It should be noted that the research operation modes, i.e., modes of operation outside of meeting a product with identified specifications, though not used to rank the severity, occurrence, and detection of a failure, were useful to consider and discuss during the interviews for identifying root causes of failures.

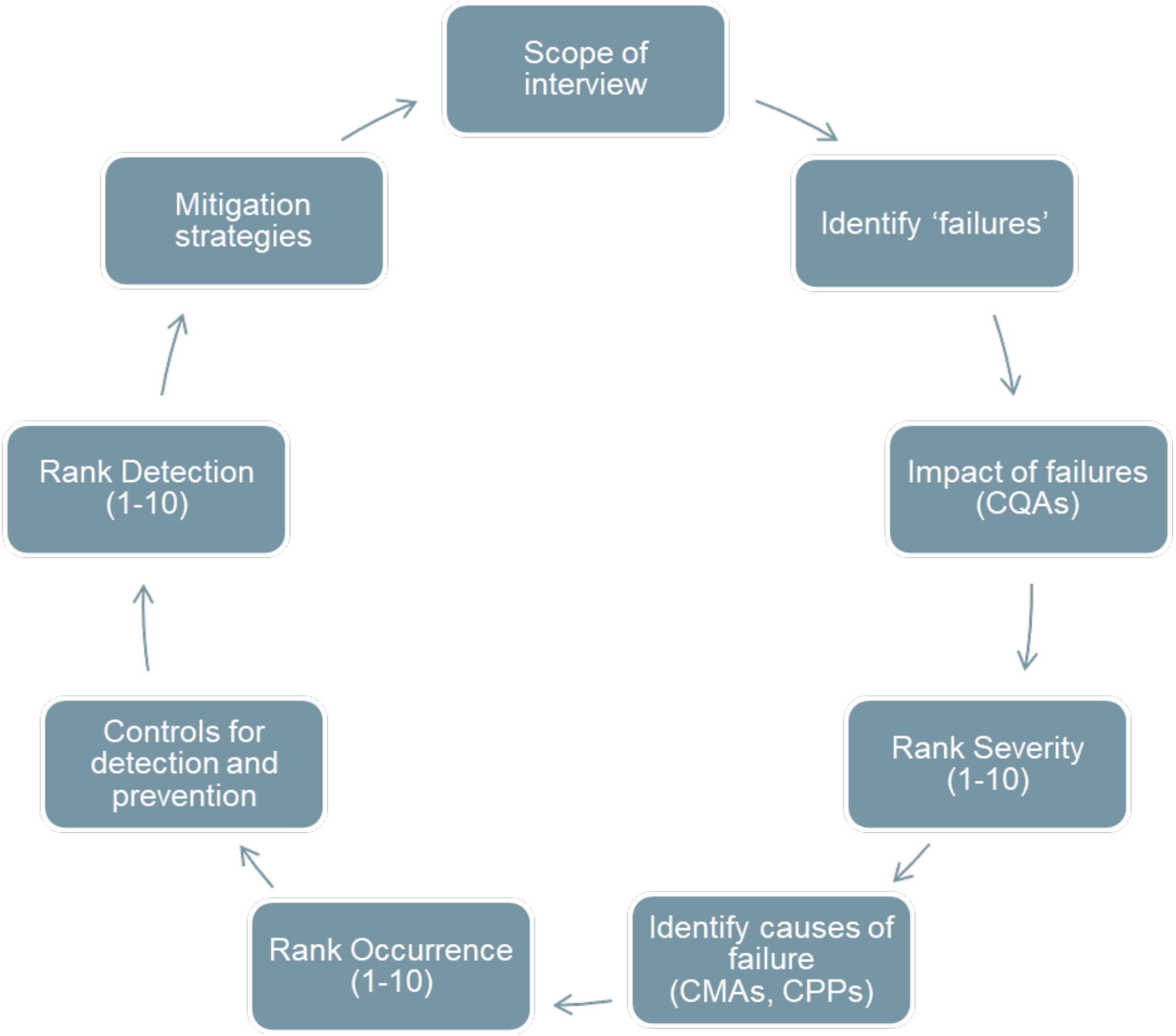

Figure 1. Failure Modes and Effects Analysis interview flowchart

Using the guidance scale tables to quantify levels of severity, occurrence, and detection, a risk priority number (RPN) was calculated for each failure mode within an operational parameter (Tables 1-3). During the interview the justifications for each of the guidance scale rankings was tracked for future reference. For the purposes of FCIC and supporting a QbD approach, along with each failure mode, the CQAs were identified as either the source of the failure itself (e.g., deviation from a particle size specification) or impacted by the failure (e.g., an equipment shutdown impacts the target throughput CQA specification). Along with identifying the impacts and CQAs for a failure these were also grouped into categories of 'Process Efficiency', 'Product Quality', 'Economics', and 'Sustainability' as most systems require optimizing or at least acknowledging these four categories. These categories became a useful tool for comparing the severity of a failure between two categories. This categorization of impacts was also useful for acknowledging gaps in information from the FMEA process based on these categories; for example, an SME might be able to identify the presence of an economic impact of a failure, but not be able to supply a ranked severity value for the impact.

Critical material attributes (CMAs) and critical process parameters (CPP) identified along with ranges or thresholds of the CMAs and CPPs, as available, by the SMEs were recorded as causes and/or potential contributing factors to the failures themselves. The results of the current FMEAs captured through this work essentially allow for each failure mode calculated RPN score to be associated with specific CQAs, CMAs, and CPPs providing semi-quantitative ranking of critical properties between failure modes for a single unit operation and/or process. In some cases, it was identified there was experimental data to support ranking the CMAs/CPPs within a specific failure mode providing more resolution of ranking within a single failure.

An additional step for the FMEA interview process is to identify actions and/or mitigation strategies for the failure modes. The RPN scores are recalculated based on the impacts that these actions have on reducing or potentially eliminating the impact and/or occurrence of a failure or improving the detection methods for prevention of the failure. In some cases, it was determined through the interviews that improvement efforts have already been identified and/or implemented for specific failure modes. An additional potential benefit for using an FMEA approach for FCIC research is the ability to quantify the impact that research implementations have on reducing risk for specific failure modes. Secondly, the FMEA approach also provides a framework to track proposed research that can be referenced for future research and experimental designs.

System Wide versus Single Unit Operations FMEA Approach

For the results presented in this report, the FMEA interviews included two approaches. The first approach was to perform FMEA interviews for an entire system of unit operations giving a wholistic system level view. The second approach consisted of detailed interviews for each individual unit operations within the system allowing for a “deep dive” into the specific failures for individual components within the system. These two approaches provide different resolutions of information. The system wide interviews focused on overall product and process specification failures (e.g., particle size and process throughput specifications). Within these system wide interviews, the SMEs helped to identify which pieces of equipment contributed most to these failures. Mitigation strategies included substituting specific pieces of equipment and system reconfigurations. These individual unit operation FMEA interviews focused in more detail on the single unit operation within both the context of the described system and considering broader parameters. This approach was intended to allow for unit operations to be independently evaluated outside of the confines of a single system design. For example, a specific unit operation might identify moisture at a specified level as a primary critical material attribute contributing to a specific failure. The system configuration might already have a drying step upstream to account for this unit operation failure. The system wide approach might not catch a failure with this unit operation associated with moisture; however, the individual unit operation interview increases the chances of capturing moisture as a cause of failure for the piece of equipment.

System Designs

For these results, two system configurations were evaluated: (1) generation of pine residue materials for high-temperature pyrolysis conversion and (2) generation of corn stover materials for low-temperature conversion using deacetylation and disc mechanical refining as the pretreatment step for fermentation to hydrocarbons. These system configurations were theoretical configurations as continuous processes have not be fully implemented for the research equipment being evaluated for the FMEA interviews. These system configurations closely mimicked previous system configurations used for techno economic analyses (TEAs) research under the FCIC. The results for these TEAs are planned to be published soon. As FMEA can also identify failures that would impact system economics, the results from the FMEA can be used in conjunction with TEA to obtain analytical insights and corroborate findings. Especially in the case of 1st-plant analyses, results from the TEA and FMEA can be compared to identify whether system-level pinch points identified from the stochastic analysis, for example discrete event simulation (DES), indicate similarities or differences from RPN-based metrics obtained through FMEA (Hartley et al. 2020). Together these two approaches can help construct a more complete analytical understanding of preprocessing systems, especially in cases where continuous processes have not been implemented at scale. FMEA interviews enable the gathering of valuable qualitative information in a structured manner and can be used as building blocks to inform modeling assumptions in TEAs. Furthermore, in cases where the guidance scales within the FMEA might fall short of arriving at a well-defined quantitative measure for the economic impact, the TEAs can provide quantitative estimates for the magnitude of economic implications for a specific failure.

Results and Discussion

High-temperature System Wide Overview

For the high-temperature processing system, pine residue chips were dried in a rotary dryer to 10-15% moisture, air classified to generate a white wood rich stream, ground to pass a ½” screen using a hammer mill, and fractionated into a final material with a particle size range between a bottom (1.18 mm) and top (6 mm) screen using an oscillating screen system (Figure 2, Table 5). For this system, FMEA interviews were conducted considering the whole system of equipment simultaneously, the rotary dryer, air classifier, oscillating screen, and conveyors.

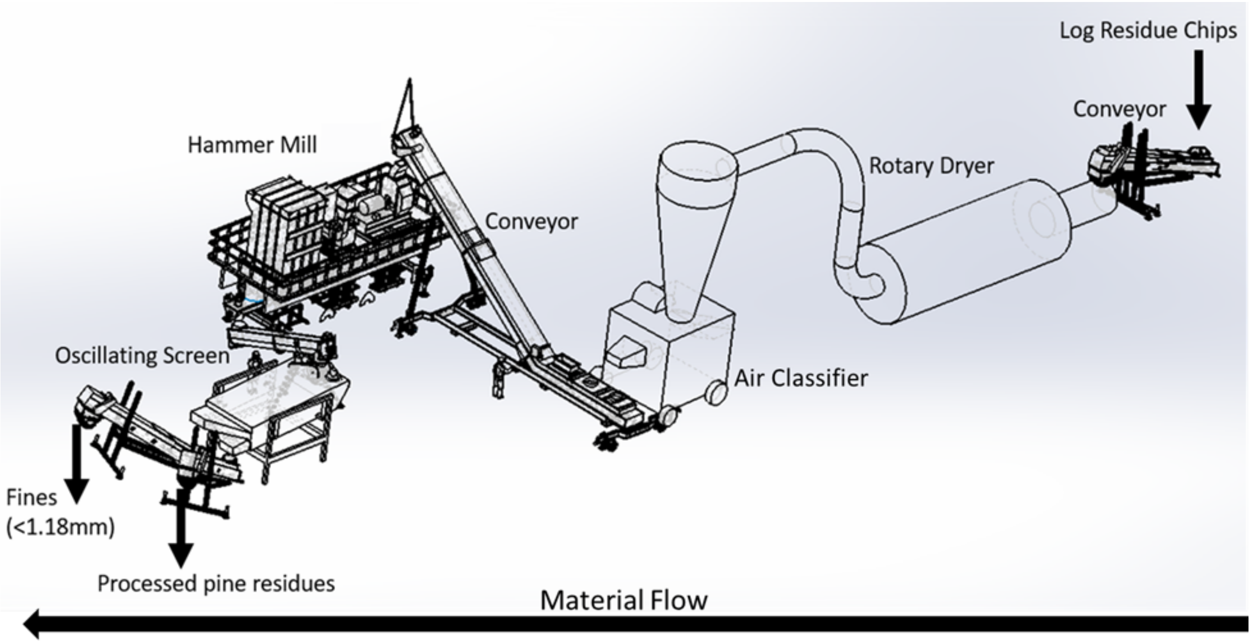

Figure 2. High-temperature preprocessing system configuration

Table 5. High-temperature system design unit operation parameters

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
FMEA TRL rating	B	A	B/C	B	A
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

For the system wide interview, the failures that were primarily focused on were associated with the defined CQAs for the final intermediate feedstock product intended for high-temperature conversion. These critical quality attributes and specifications included particle size ranges between 1.18 mm and 6 mm, fixed carbon contents above a set threshold (18% or 21%), moisture contents at or below 10%, and ash content less than or equal to 1.75%. The FMEA interviews also included discussion of impacts to throughput but did not define a specification for this research scale system (Table 6). Table 6 additionally provides an overview for each of the unit operations in the process design that had potential impacts to the identified system CQAs along with a max RPN associated with the failures in meeting a CQA specification for a given layer. For example, failures associated with meeting the final particle size specification were primarily associated with the grinder, oscillating screen, and air classifier. Failures associated with the fixed carbon specification had the highest RPN score (192) and were primarily associated with the air classification unit. The failures with the lowest risk scores are associated with meeting the ash content specification (RPN 80). The details of each of these failures for the system can be found in Appendix B, Table 9 and are discussed further in the following sections. The FMEA results from the individual unit operations processing pine residue materials—rotary dryer, air classifier, hammer mill, oscillating screen, conveyors, and high-temperature reactor feed screw system—were used to enhance and corroborate the findings of the system wide FMEA. The system wide interviews and individual unit operation interviews were also performed by different SMEs allowing for some level of replication and variability in the results. These interview results can be found in Appendices C-H, respectively. It should be noted that the impact "Layers" for the RPN represented in this Table 6 are focused primarily on product quality and process efficiency. Additional process CQAs, not originally listed, including product yield and energy consumption were also identified through the interviews.

Table 6. High-temperature system critical quality attribute risk summary

Critical Quality Attributes	Specification	Impacting Unit Operation(s)	Max RPN (layer)
Moisture content	≤ 10%	Rotary Dryer	180 (Product Quality) 144 (Process Efficiency)
Fixed carbon	≥ 18% or ≥ 21%	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)

Moisture Content CQA

Deviations from moisture content specification of >10% stemmed primarily from the rotary dryer unit operation, as would be expected. The impacts of this failure were evaluated both as impacting product quality but also process efficiency. As the rotary dryer is the first unit operation in the system, secondary cascading failures to downstream equipment were also captured by the FMEA interview process (Figure 2). For product quality, moistures above 10% had noted impacts on conversion efficiency based on increased moisture in the final product, but also through impacts to the fixed carbon contents and ash contents of the product as secondary impacts. The severity of these critical quality material attributes (CQMAs) was ranked as very high (10) based on the FMEA interviews associated with the high-temperature feed system where qualities such as higher ash content and lower white wood concentrations resulted in increased plugging and char buildup (Appendix H). These secondary impacts were based on the separation efficiency of the air classification unit in the system being impacted by unexpected increases in moisture. The separation efficiency risks for the air classification unit associated with moisture can be found in Appendix D where moisture, specifically variable moisture, contributes to increased bark content in the heavy (product) stream. The overall risk rating for product quality due to increased moisture in the in-process material stream and final product greater than 10% was 180; the second highest risk scores for the system.

For process efficiency, moisture above 10% also had impacts on the critical quality process attributes (CQPAs) of energy consumption and throughput. These were primarily based on the decreases in the hammermill performance as a cascading failure from increased moisture. It was noted that for every 10% increase in material moisture, the hammermill energy consumption doubles. The throughput of the hammer mill was also noted to be impacted the most compared to other equipment in the system. From the individual FMEA on the hammer mill, throughput decreases based on increased moisture levels were also observed from partial screen plugging failure events (Appendix E). The RPN for process efficiency was calculated slightly lower, at 144 compared to the RPN associated with product quality, primarily due to throughput and energy consumption severity being ranked as high (8) as opposed to very high (10). The oscillating screen also exhibited throughput impacted CQAs as a result of increased moisture content through screen plugging and motor failure modes (Appendix F).

Incoming moisture of the material (>30%) and particle size and shape, along with process parameters of the rotary dryer system including feed rate, outlet temperature, air flow, and the rotational speed (controlling the residence time) were the primary causes for failures in moisture contents. From the FMEA associated for the rotary dryer alone, it was noted that the highest risk failure for the rotary dryer was in meeting material moisture specifications (RPN 240) using a single pass through the system (Appendix C). This interview captured multiple scenarios of this specific failure. In the current configuration in the system where chipped material is the input format for the dryer, the dryer can sufficiently decrease the moisture by approximately 10 percentage points for a single pass through the dryer. Most woody material coming into the system is upwards of 30% requiring at least two passes through the system to reach moisture specifications of ~10%. If the number of recycling events is accounted for in the system so that throughput can be accurately estimated based on the initial moisture content of the incoming material, than the RPN for not reaching a specific moisture content reduces to 24 . To further decrease the risk of meeting moisture content specifications, additional in-line moisture sensors that can be used to optimize air flow and outlet temperature of the rotary dryer were the suggested mitigation strategies. These sensors are available and can be installed in the current system.

Fixed Carbon CQA

In the current system design the air classification unit allows for pine residue materials to be upgraded to higher quality feedstocks through the removal of dirt, needles, and bark fractions thereby increasing the concentration of white wood material and consequently fixed carbon content concentrations. It should be noted that though there is currently a quantitative fixed carbon specification(s), the system does not currently have a mechanism, sensor or otherwise, to reach these specification thresholds for a batch of material but rather maximize the white wood concentrations in the stream. All failures associated with the fixed carbon CQA of this system were evaluated based on removal of dirt, needles, and bark from the material stream. As air classification is the primary unit for achieving fixed carbon concentration, or white wood concentrations, most of the failures for this CQA are associated with the air classification unit.

As with failures associated with the moisture specification, failures associated with the fixed carbon specification were evaluated from both a product quality and process efficiency perspective. For product quality, the impacted CQAs were concentrations of fixed carbon and ash content as a result of inefficient bark removal from the air classification unit. As increased moisture content is one of the factors that impacts separation efficiency in the air classifier, this failure from the context of a cascading failure is associated with the rotary dryer as described previously. From the point of view of the air classification unit, the RPN score of meeting the fixed carbon specification is the highest for the system at 192. This increased score stems from the severity score of 8—that can be linked to failures in the high-temperature reactor feed screw associated with char build up resulting from increased ash content and other negative properties from bark materials (Appendix H)—and a detection score of 8 as the primary method for achieving specific proportions of anatomical fractions in the various streams relies on observations from trained operators (Appendix B).

For process efficiency missed fixed carbon specification failure impacts, the increase in inorganic (ash) content from bark and/or dirt leaving the air classifier could contribute to increased equipment wear for the hammer mill unit. This was ultimately associated with throughput due to increased time for replacing hammers potentially but could also be associated with changes to particle size distributions exiting the hammer mill if not addressed. This failure was identified in the hammer mill FMEA interviews associated with corn stover but could also be assumed to be associated with higher inorganic concentrations from pine materials (Appendix L). This process efficiency failure associated with fixed carbon was slightly lower than the product quality failure with a score of 72 based on the severity of the downtime associated with hammer mill maintenance being ranked as low (3).

The primary causes for deviation from the fixed carbon specification based on the air classification unit include moisture, as previously mentioned, along with particle size of the tissue fractions as seen in the FMEA from the air classification unit alone (Appendix D). If tissue fractions are close in size, smaller white wood pieces in relation to bark and needles, the less efficient the air classification unit is at separating these fractions from one another. Additionally, if variations in harvesting equipment dramatically changes the particle size distributions, optimizing the air speeds and feed rates can become more challenging.

The mitigation strategies for failures associated with fixed carbon concentrations focused on detection improvements. Moisture sensors could be used to automatically adjust air speeds in the event of a failure in the rotary dryer and visual detection methods for differentiating white wood and bark could also be implemented. It was estimated that a decrease in the RPN scores from 192 to 72 and 144 to 54 could be achieved for the product- and process-efficiency based failures, respectively, if these sensor-based strategies were included in the system. The moisture sensor was identified as an in-process addition (Appendix B, Table 10).

Particle Size CQA

Particle size failures were split into two separate failure groups: (1) generation of excessive overs—particles over the maximum specification of 6 mm, and (2) generation of excessive fines—defined as particles smaller than 1.18 mm for this system configuration (Appendix B, Table 9). For situations where excessive overs were produced, two pieces of equipment were associated with this failure; the hammer mill and the oscillating screen. The current system design using a ½” screen on the hammer mill assumes that particles greater than 6 mm from the hammer mill will be recycled and reprocessed. Excessive overs generation from the hammer mill was considered when more than 1/3 of the material was recycled at any given time. The primary

CQA impacted by increased recycling was throughput. The oscillating screen downstream from the hammer mill includes two sets of screens. The top screen, set at 6 mm for this configuration, catches most overs for recycling through the hammer mill. The bottom screen removes fines from the product. This design prevents overs from being included in the final product. The failures in the oscillating screen that impact particle size primarily contribute to increased generation of fines as opposed to overs. During the system wide interview, the increased recycling, based particles greater than 6 mm, was assigned a risk score of 108 with a severity of 6 (moderate) based on the impacts to the system throughput.

The generation of increased fines stemmed from multiple unit operations, the air classifier, the hammer mill, and the oscillating screen. Fines generation can impact both product yields when more material is discarded, along with product quality where fines materials is included in the final feedstock product. The high-temperature feed system can be impacted by larger particle size distributions and by the increased inorganic content that is often associated with the fines particle size fraction (Appendix H). The system wide interview primarily focused on the impacts based on product volumes and yield; however, a higher severity might be considered for the impacts to product quality. An RPN of 72 was assigned, lower than the production of overs. It was also noted that there is likely an economic impact for increased volumes of discarded materials that should be captured in a TEA of this system. This cost amount could not be captured quantitatively during the interview.

Increased fines from the air classifier would primarily be in the form of dirt. The air classifier separation efficiency is impacted by increases in moisture along with air speed that should be adjusted to account for moisture and format conditions of the incoming material. The hammer mill has been shown to plug with increased fines from materials like corn stover (Appendix L); however, in the interview for hammer mill focusing on pine residues, the material attributes contributing to screen plugging were stringy materials and moisture and not from fines (Appendix H).

For the hammer mill, increased fines generation was associated with increased moisture (>20%) and slower feed rates. Screen size also had a large impact on fines generation for the system. It was estimated that when ¼" screens are used, fines concentrations can be as high as 20%. When using ½" screens are used, as in this system configuration, fines generation is closer to 10-15%. Excessive fines generation likelihood with the current system configuration and parameters for the hammer mill was noted as being remote to low depending on the moisture contents of the materials. Though the risk score is relatively low (9), it should be noted that increases in fines can impact the drag chain conveyors (Appendix G). Fines material can get caught in and cause wear on moving parts within the conveyor leading to mechanical failures. More of these failures might be seen for conveyor systems after hammer mill operations where larger concentrations of fines would occur.

The oscillating bottom screen is intended to remove fines from the final product stream; however, multiple remote to low (1-3) occurring failures were identified that might result in fines accumulation in the final product (Appendix F). The bottom screen can plug with a combination of increased fines and moisture allowing fines in the final product. The likelihood of this occurring in material at 10% moisture was remote; however, in the event of a failure in the upstream rotary dryer the likelihood of this failure increased to low (3). This screen plugging failures was evaluated from both a process efficiency and product quality standpoint giving an RPN of 180 for impacts to product quality and 108 for impacts to process efficiency for a 30% moisture content scenario. An additional remote failure identified from the oscillating screen, that could result in both material loss and/or increased fines in the final product, was a plug in the top screen. This would not occur in a low moisture (10-15%) scenario. When the top screen of the oscillating screen system plugs, on-spec material is more likely to be recycled through the system and overprocessed for increased fines generation. It was noted in the interview that if the top screen was plugged it was likely that the bottom screen had already been plugged first.

The causes between generation of excessive overs versus excessive fine were often opposites of one another. For instance, the primary causes of overs generation in the hammer mill included the feed rate being too fast along with screen sizes much larger than maximum particle size specification; conversely, excessive fines were more likely to occur with slower feed rates and smaller hammer mill screen sizes (Appendix E). One recurring material attribute for both the generation of fines and overs was unexpected increases in moisture content. The hammer mill and air classifier can perform at increased moisture content but parameters such as feed rate and air speed must be adjusted accordingly to achieve optimized particle sizes and remove dirt. In-line moisture sensors again were identified as mitigation strategies for air classifier separation efficiencies and fines generation from the hammer mill (Appendix B, Table 10). For overs, two strategies for decreasing overs in the system were identified: (1) replacement of hammer mill with a rotary shear mill and (2) addition of in-line particle size sensors to automatically adjust hammer mill feed rate. For the rotary shear equipment, the throughputs of the system would need to be evaluated; however, the rotary shear does have more experimental data for optimizing screen sizes to achieve target particles size distributions and has been shown to be less impacted by moisture. For this analysis we evaluated the in-line particle sensor mitigation scenario. The reduction in the RPN for overs generation was estimated at 54, down from 108, with the implementation of the particle sensor to automatically adjust the feed rate for the hammer mill.

Ash Content CQA

Of the CQAs considered for the system, meeting ash content specifications had the lowest RPN scores at 90 for impacts to process efficiency and 80 for impacts to product quality (Table 6). The primary unit operations associated with meeting ash content specifications included the air classifier and the oscillating screen. For process efficiency, it was identified that inefficient separation of high inorganic content material from the air classifier, i.e., bark, needles, and soil, could result in increased wear on hammer mill hammers and eventual impacts on throughput based on hammer mill processing efficiency and potential unanticipated downtime to change out hammers. For product quality impacts that resulted in higher than specified ash contents in the final product, these were based on subsequent failures of separation inefficiencies in the air classifier to remove higher ash tissue fractions and the oscillating screen failures for removing fines, which are assumed to contain higher concentrations of inorganics. Overall, the occurrence of these failures was determined to be low (3) and remote (1) for impacts to process efficiency and product quality specific to processing pine residue materials in low moisture conditions. The air classifier interview identified failures associated with increased bark concentrations in the heavy (product) fraction (Appendix D). The instances of this failure were more likely in higher moisture conditions, as were captured in this interview, when particles sizes for white wood and bark were closer in range.

The true unknown failures associated with ash specifications are based on accurate measurement of product ash content. Visual inspection by a trained operator to detect the presence of bark in the product stream was assumed to be relatively high (3) for manual adjustment of air flow rates (Appendix D). For overall ash content, not just the presence of bark, the system wide detectability was ranked at very uncertain (10) based on the fact that there are currently no in-line sensors or systems in place for the preprocessing configuration, Figure 2, or the high-temperature conversion system for quantitatively evaluating ash content (Appendix B). Contributions of increased ash content based on oscillating screen failures are identical to those associated with meeting fines specifications discussed above.

In terms of mitigation strategies both in-line moisture and ash sensors would help decrease the occurrence and increase the detectability of failures associated with ash. RPN scores of 18 and 48 were estimated for ash failures associated with process efficiency and product quality respectively with the addition of these sensors (Appendix B, Table 10).

Throughput CQA

Deviations from throughput for this system have been identified as secondary failures impacts based on the CQAs previously discussed including increased moisture (failures from the rotary dryer), fixed carbon specifications (failures associated with air classifier separation impacting hammer mill performance with increased ash content in the stream), particle size specification (excessive overs requiring recycling and increased discarding of fines material ultimately impacting system throughput specifications), and ash specifications (again failures associated with air classifier separation impacting hammer mill throughput performance). Throughput failures can be dependent on meeting other CQA specifications as described above. In general, these other specifications take precedence in the research settings that much of the experimental data is generated from. In an industry setting and continuous system, throughput is likely more important. The system wide interview also captured some potential failures associated with throughput. Because throughput is primarily controlled through the feed rate of the system it is possible to view the system in terms of what secondary failures could occur when throughput specifications are the primary focus. It was determined that when throughput resulted in lower than optimal feed rates for the hammer mill than the potential for generation of additional fines was identified. As the air classifier, currently upstream of the hammer mill, does have a different throughput capacity, this could indicate that in a continuous system more fines generation (discussed in the particle size CQA section above) might occur. The throughput-based failure stemming from fines production from the hammermill was ranked at 180 for product quality. Conversely, the hammer mill FMEA interview identified that when feed rates were too high for the hammer mill, overs production increased. As already discussed, the increased in overs would ultimately have a negative impact on overall system throughput due to the increase in recycling.

One other throughput-based failure that was not captured directly from meeting the other CQAs was associated with the air classifier unit. The air classifier can have failures in separation efficiencies for removal of certain fractions, i.e., bark, needles, dirt, but can also have failures with removing too much white wood in the light and medium discard streams. This failure was seen in the individual air classifier unit operation FMEA and was identified as one of the highest risk failures for the unit (Appendix D). When chips are smaller or there are greater concentrations of branches and twigs coupled with air speeds that are too high, white wood concentrations can be lost in the discard fraction. This might require additional reprocessing or the material is lost; both of which are seen as impacts to system throughput.

As many of the throughput failures identified were secondary failures as a result of unexpected increases in moisture content, the primary mitigation strategy identified were in-line moisture sensors to support automated adjustments to temperatures and air flow in the rotary dryer, feed rates across the system, and air speed for the air classifier ultimately to decrease throughput failures to 27 and 90 for product quality and process efficiency impacts respectively (Appendix B, Table 10).

High-temperature System Wide Key Takeaways

- Failures to reach moisture specifications through the rotary dryer had potentially large cascading failures on multiple product quality CQMAs (moisture, fixed carbon, and ash) and process efficiency CQPAs (throughput and energy consumption), with RPN scores of 180 and 144, and impacted downstream equipment.

- Fixed carbon specification failures had the highest risk scores of 192 and 144 for product quality and process efficiency impacts associated with separation efficiencies to maximize white wood concentration using the air classification unit. These failure risk scores could be drastically reduced through in-line sensors implementation.

- The system design is well equipped to achieve particle size specifications in the final product; however, secondary failures associated with increased volumes of discarded fines and throughput failures associated with excessive overs production are necessary to account for with RPNs at 72 and 108 respectively.

- As with fixed carbon, ash specifications are assumed to be met by higher concentrations of white wood by removal of bark, needles, dirt, and fines through the air classification unit and oscillating screen. The detection ranking of ash specification is considered very uncertain currently (10). To consistently meet ash specifications the system would require the addition of in-line sensors.

- Throughput is a complicated failure that stems as a secondary, cascading failure based on the other failure modes associated with meeting moisture, fixed carbon, particle size, and/or ash specifications. As increased throughput can be inversely related to meeting product quality specifications, achieving throughput and CQMA specifications simultaneously will likely require system optimization or prioritization based on system economics.

Low-temperature System Wide Overview

For the low-temperature processing system, corn stover bales were deconstructed to approximately 3” particles, air classified to generate two streams including a cob and stalk rich stream and a leaf and husk rich stream. Each stream was then milled to pass a 1” screen using a hammer mill, in parallel operations shown in Figure 3 by the “x2” notation, and finally blended back together (Figure 3, Table 7). For this system, FMEA interviews were conducted for the whole system considering all unit operations simultaneously, the bale grinder (1st stage), air classifier, hammer mill (2nd stage), and conveyors. As with the high-temperature system design, the system is theoretical. The experimental equipment available are run at different throughput scales making integration difficult (Table 7). z

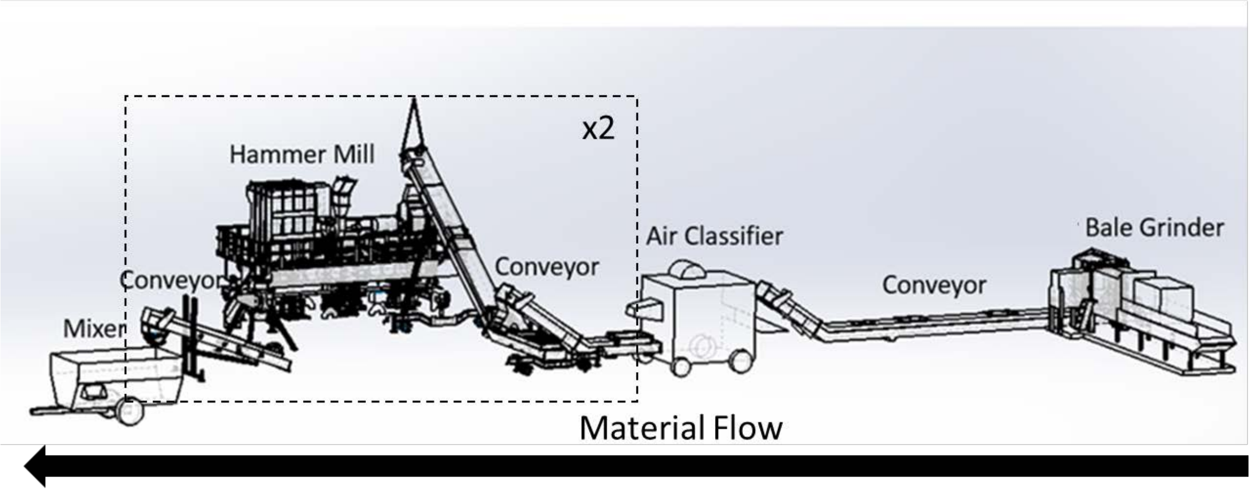

Figure 3. Low-temperature preprocessing system configuration

Table 7. Low-temperature system design unit operation parameters

Unit Operation	System	Bale Grinder	Air Classifier	Grinder (Hammer mill)
Nameplate Capacity Throughput	3 tons/hr	5 tons/hr	1 tons/hr	5 tons/hr
Typical Throughput	1 ton/hr	2-5 ton/hr	0.5-1 ton/hr	5 tons/hr
Input Format	Square bale	Square bale	<3” particles	2 streams (cob and stalk, husk and leaves)
Output Format	<1” particles	<3” particles	2 streams (cob and stalk, husk and leaves)	1” particle streams (blended in final step)
FMEA TRL rating	A	A	B	A
Fixed process parameters	Screen sizes and mill speed	Screen size: 3” Mill speed		Screen size: 1” Mill speed

As with the high-temperature for the system wide interview, the FMEA interviews primarily focused on failures that were associated with the defined CQAs for the final intermediate feedstock product intended for further low-temperature conversion processes. These critical quality attributes and specifications included moisture content at 20%, carbohydrate content ≥ 59%, ash content ≤ 4.93%, and particle size <1”. For the system wide interview, impacts to throughput were discussed but a quantitative specification was not defined for this research scale system (Table 8). Table 8 additionally provides an overview for each of the unit operations in the process design that had potential impacts to the identified system CQAs along with a max risk priority number associated with the failures in meeting a CQA specification for a given layer. For example, failures associated with meeting the final particle size specification were primarily associated with the grinder operations. Failures associated with the carbohydrate and ash specifications had the highest RPN scores (800) and were primarily associated with the air classification unit. The failures with the lowest risk scores were associated with meeting the moisture content specification (RPN 240). The details of each of these failures for the system can be found in Appendix I, Table 17 along with the FMEA results from the individual unit operations in Appendices G, J-M and are discussed further in the following sections. The FMEA results from the individual unit operations processing corn stover materials—bale grinder, air classifier, hammer mill, conveyors, and low-temperature DMR/deacetylation pretreatment system—were used to enhance and corroborate the findings of the system wide FMEA. The system wide interviews and individual unit operation interviews were also performed by different SMEs giving allowing for some level of replication and variability in the results. Like the high-temperature system results, most of the impact “layers” discussed during these interviews focused on product quality and process efficiency. Cost and sustainability impacts were identified but could not be quantified through the severity metrics by the SMEs. Additional process CQAs, including product yield and energy consumption, were also identified through the interviews. The low-temperature system wide interview focused on the system meeting the CQAs specifications rather than the impact of meeting those specifications throughout the system, as was done with the high-temperature system interview. Because of this, the individual unit operation interview results were important for filling in the gaps of impacts of the CQA specifications throughout the system.

Table 8. Low-temperature system critical quality attribute risk summary

Critical Quality Attributes	**Specification**	**Impacting Unit Operation(s)**	**Max RPN (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)

Moisture Content CQA

As the current system design does contain any unit operations to control moisture content, the moisture of the outgoing material is completely dependent on the moisture of the incoming material. Starting moisture of approximately 25% were identified as ideal for meeting a 20% outgoing moisture as there would be approximately a 5% loss in moisture through the system. It is estimated that approximately 49% of bales are between 15 and 25% moisture; indicating that the majority of bales will not meet this 25% initial moisture content. The impact of materials with too high or too low of moisture were captured as both economic, for discarding or rewetting batches with too little moisture or not processing materials with too high of moisture, and based on product quality (Appendix I, Table 17). It should be noted that this interview was based on considering the processing of a single bale units of material, whereas material to a reactor could be mixed to achieve an ideal mean moisture content (if not in a continuous system after preprocessing). The system severity, based on moisture contents less than 20%, was considered very high (10) due to overheating failures of the disc mechanical refining (DMR) step indicated by the DMR/deacetylation FMEA results (Appendix M). Overall, the failure RPN with meeting a moisture specification was relatively low (60) as the detection methods for identifying moisture contents of bales prior to processing is considered fairly robust and accurate. These detection methods could also be used to queue bales appropriately to reach on overall mean moisture for a batch of material.

As approximately 50% of materials coming into a facility are likely to be above 25% moisture, it is likely that higher moisture materials will need to be processed. The FMEA interviews for the individual operations captured some of these moisture-based failures. The process efficiency-based failures for moisture can have much higher risks. Running materials at higher moisture contents has the potential to cause issues within the preprocessing unit operations and secondary impacts to throughput and energy consumption CQAs. From the perspective of the bale grinder, higher moisture materials (>30%) leads to screen plugging and inconsistency in material volume. The risks scores for these failures were 72 and 108 respectively (Appendix J). Downstream from the bale grinder the hammer mill also had notable impacts associated with high moisture materials with 50% decreases in throughput for moistures 25-35% and an overall RPN of 192 (Appendix L). The hammer mill had screen plugging events that were contributed to higher moisture (>40%) and inconsistency in material volumes (as might be coming from the bale grinder). Ultimately, these grinder-based failures can impact the system throughput through decreases in feed rate to avoid the failure or shutdowns during a plugging event.

One of the objectives in the system design was to lower energy consumption of the hammer mill through the separation of corn stover stalk and cob from husk and leaves by air classification. Moisture was also noted to impact the separation efficiency for these fractions (Appendix K). Because there are currently no good detection methods for determining in-line separation efficiencies, the RPN of this failure was 90 with a very uncertain detection rating of 10.

The primary strategy, captured in the detection for the low-temperature system wide interview, for reducing moisture-based process efficiency failures is to avoid running bales that will cause a shutdown and to queue bales so that the system is not dealing with rapid changes in moisture levels and feed rates can be compensated appropriately (which will inevitably impact overall system throughput). This could be further improved by the addition of in-line moisture sensors to adjust based on within bale moisture variability.

Carbohydrate Content CQA

As with the moisture specification, the carbohydrate specification is completely dependent on the incoming material qualities. The current system design and configuration does not target to manipulate carbohydrate concentrations in the product stream. The estimate percent of material meeting these specifications is likely 40-60%. For this system design, the RPN for meeting this carbohydrate specification is one of the highest at 800. This is due to the fact that conversion yield is significantly impacted with an estimated severity of 10, the occurrence of not meeting the specification is high (8) as up to 60% of the material could potentially be discarded, and there are not current online methods for quantitatively detecting or preventing this failure resulting in a detection score of 10 (very uncertain). No process efficiency-based failures were identified associated with the carbohydrate specification.

One of the suggested strategies, not currently used but possible, with this system design would be to utilize the separate fractions from the two streams from the air classification unit operation for blending to increase carbohydrate concentrations. This would help decrease the occurrence of the failure for a potential risk score of 480 (Appendix I, Table 18). More data and system configurations are necessary to confirm this estimated risk reduction score.

Ash Content CQA

The ash content specification also had a very high-risk score of 800 for process efficiency. As with meeting carbohydrate and moisture specifications, the current system configuration does not control for ash and very few bales likely come into the system with ash concentrations of less than 4.93%. The severity (10) for process efficiency was identified through the DMR/deacetylation FMEA through failures with early wear on the DMR discs (Appendix M). There is likely a negative product quality impact for conversion not currently captured through the FMEA interviews at this time. The occurrence of product material having above 4.93% ash was estimated to be a 10, or inevitable, based on the current harvesting methods implemented in corn stover. It was also noted that increased ash also contributed to wear on the preprocessing equipment as well with a severity of 6 in the low-temperature system wide analysis (Appendix I). This severity is based on unanticipated maintenance time to change out worn hammers. These less-than-ideal ash contents are typically captured as dockage fees in TEAs.

The current detection methods for evaluating ash concentrations are based on visual inspection, which can likely only identify very “dirty” bales, and knowledge of general ash concentrations based on harvest methods and harvest conditions. Both methods required an experienced and trained operator resulting in an uncertain detection score of 8. One of the mitigation strategies included removing high ash tissues and/or fines using the air classification unit, already included in the system, or the addition of a disc screen prior to or after air classification. Leaves and husk, along with dirt and fines, which are higher in inorganics are currently being collected from the ‘light’ stream of the unit, ground, and blended back into the final product stream. This light stream could be further refined or discarded completely to decrease inorganic contents and likely increase carbohydrate contents. The estimated risk reduction from this strategy was 800 down to 240 based on decreasing the occurrence of the ash failure (Appendix I, Table 18).

Particle Size CQA

Currently the system design CQAs only specify a maximum particle size of 1”. Through the FMEA analysis it was identified that there should likely be specification for minimum particle size specification based on the DMR/deacetylation failures associated with fines (Appendix M). Incoming material with too many fines was associated with system shutdown due to plugging in the deacetylation reactor (RPN of 360). Increased concentrations of fines in the low-temperature system were also linked with higher concentrations of ash content which was previously discussed. Fines generated during the process were also shown to contribute to in-process failures. Excessive fines generation as a result of self-heating based on biological degradation has also been shown to heavily impact the 2nd stage hammer mill leading to plugged screens and ultimately impacting process throughput. The RPN for this plugged screen failure was estimated as a 480 due to the high severity (10), moderate occurrence (6), and uncertain detection methods (8) (Appendix L). As discussed with the high-temperature system FMEA analysis, increases in fines in the system can lead to potential failures with conveyors (Appendix G); though, these failures are considered infrequent and can typically be easily detected through routine maintenance procedures.

Increased generation of fines within the system was noted to occur in the bale grinder during screen and system plugs (Appendix J). These failures were driven by moisture levels and harvest methods. In the 2nd stage hammer mill both FMEA analysis of pine residues (Appendix E) and corn stover (Appendix L) identify that particle size, including fines production is impacted by feed rates (among other properties). In general, feed rates that are too fast for the given material properties can lead to more overs and feed rates too slow can produce more fines.

For the low-temperature system design the mitigation strategy proposed for reducing fines-based failures included removal of fines material prior to air classification using a disc screen. This would not address fines generated through the hammer mill, but it would prevent fines from entering additional processing steps and potentially remove higher inorganic material prior to grinding. The estimated risk score reduction was from 480 to 180 (Appendix I, Table 18). Additional mitigation strategies included using the air classifier in series to remove fines material or replacing the hammer mill with a knife mill which has been shown to generate less fines. These strategies can be evaluated in future FMEA evaluations.

For the particle size specification associated with particles over 1”, the risk score could not be accurately calculated as there were no risks identified with larger particles in the DMR/deacetylation FMEA in order to estimate a severity. It would be assumed that the risk score is likely low (10-30 range) based on the remote occurrence of excessive overs (>10%) with the current configuration and parameters (e.g., mill screen size of 1”). It was determined that the primary unit operation associated with the overs particle specification was the 2nd stage hammer mill.

Generation of overs were associated with feed rates that were too fast (Appendix I). The individual hammer mill FMEA also identified that overs occurred when hammer mill hammers were more worn by increased ash contents (Appendix L). This risk of overs based on early hammer wear was higher, at 384, compared to typical operation overs generation failures, with a risk score of 144, due to the lower detectability of the failure. The proposed removal of fines/high ash content material through screening methods addressed in meeting minimum particle size requirements along with ash content requirements, would have a cascading benefit for this overs-based failure.

Throughput CQA

Throughput for the system was identified as being most impacted by primarily the mills, both the bale grinder and hammer mill, and secondarily the air classifier. Additionally, the transition points between the mills and conveyors were also identified as having some impacts on system throughput. For the system wide analysis, the primary impact of not meeting throughput specifications was economic based and a severity for this economic impact could not be estimated. However, impacts to throughput and the severity of those based on equipment downtime were identified throughout both the system wide analysis and individual equipment interviews. The severity for these impacts and failures were quantified. In the hammer mill the plugged screen failures associated with self-heated bales generating large quantities of fines resulted in a complete equipment shutdown and was scored at 480. Moisture at various levels was also identified to quantitatively lower throughput for the hammer mill processing corn stover with RPNs ranging from 60-240 for increasing moisture contents (Appendix L). Screen plugged failures in the bale grinder could also be linked to decreased throughput (Appendix J). The inconsistent material volumes failure in the bale grinder, associated with decreased system throughput, was linked to increases in screen plugging for the downstream 2nd stage hammer mill. For the conveyor system, considering a closed drag chain conveyor, the highest risk failure was clogging. The primary impact of this failure was to the system throughput with a moderate severity (6) based on the time to clean out the system and an overall risk score of 144 (Appendix G).

In general, the higher severity events associated with throughput were downtime events caused by variable moisture and particle sizes. In-line moisture sensors were one of the primary mitigation strategies for better detection of these properties contributing to downtime events.

Low-temperature System Wide Key Takeaways

- The system configuration evaluated was not designed to manipulate material **moisture** to meet a moisture specification, and more than 50% of bales coming into process are estimated to not be in range for the moisture specification. Running materials at higher moistures (>25%) can have cascading failures for system shutdowns and decreases in throughput (max RPN of 192). Materials lower than 20% moisture specification had a very high severity impact of overheating in the disc mechanical refining pretreatment process for low-temperature conversion (RPN of 240).

- Like moisture content, the system configuration was not designed to manipulate **carbohydrates**, and it is estimate that 40-60% of materials might not meet this specification. An RPN of 800 was assigned to this failure. The air classification unit currently in the configuration could potentially be used for increasing the occurrence of achieving the carbohydrate specification potentially lowering the risk score to 480.
- As with moisture and carbohydrates, the system configuration currently cannot control for **ash** specifications. This ash specification failure was also assigned an RPN of 800. Ash has negative impacts on both product quality and process efficiency for the preprocessing equipment in the system having secondary impacts on other CQAs such as particle size and throughput. Ash removal through air classification or screening was estimated to lower the RPN to 240.
- Minimum **particle size** specifications were recommended to be added to the maximum particle size specification based on the impacts to the DMR/deacetylation process along with in-process failures associated with fines. The max RPN of 480 for excessive fines was estimated to be reduced to 180 through screening and/or air classification methods as suggested through the mitigation of ash related failures.
- Decreases and impacts to **throughput** could be seen throughout the system associated with many failures. Throughput failures associated with system shutdowns due to plugging in the mills had some of the highest risk scores (RPN 480). In-line moisture sensors were one of the primary mitigation strategies across many failures for the various interviews for better detection of these properties contributing to downtime events.

Conclusion and Next Steps

The FMEA approach was able to provide evaluations for the ability of two system design configurations to meet critical quality attribute specifications for each respective target conversion process. FMEA identified the risks associated with meeting CQA specifications along with the secondary impacts or failures that could also be linked to the CQA specification-based risks, providing a more complete picture of the system. Through the FMEA approach of performing interviews for both a system wide design along with interviews for each individual piece of equipment, additional failures not directly associated with the system CQA specifications were also captured. These are not discussed in detail in this report but can be found in the FMEA results in the report Appendices (C-H, J-M). These types of failures will likely be important when considering the unit operations included in this report for different system configurations.

A few limitations of the current FMEA approach were identified through the interview process. It was found that most of the FMEA SMEs interviewed were familiar with equipment operation could speak to impacts associated with products quality and process efficiency best. Economic and sustainability impacts were identified in some cases by these SMEs but not quantified based on the SME familiarity with these factors. It should also be noted that the current guidance scale for severity does not lend itself well to evaluating an economic and sustainability impacts of a failure. TEA and life cycle analyses (LCA) are likely better tools for quantifying these impacts as many of the product and process-based failures translate to economic and/or sustainable based risks.

The next steps for the development of the FMEA approach under the FCIC include comparison to related TEA and/or LCA results for similar system configuration designs. As the system designs evaluated through FMEA were based on systems previously evaluated TEA through FCIC economic 'Case Studies', the next step would be to thoroughly compare the results of the FMEA to the findings of these Case Studies. Additionally, many of the SME observations are very qualitative. For example, identification of throughput decreases in the presence of high moisture. A goal for FMEA interviews in the future would be to collect more quantitative relationships where possible, or at least identify data sources where those quantitative relationships could be found.

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Appendix A – FMEA Interview Template

FMEA Interview Form

Date:

Interviewee:

Interviewer:

Unit operation of focus
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 usually operate at?
How often are we running the unit operation (max continuous time on stream)?
Confirm selected FMEA experience level TRL?
What are the primary failure modes (i.e., not performing or producing as intended)?
Failure 1
What are the impacts of failure (to adjacent or further downstream processes)?

What CQAs directly/indirection does this include? Identify CQA categories (i.e., process efficiency, product quality, economics, sustainability)
(If Multiple Impacts) What impact is most critical?
What would you say is the severity of this impact (e.g., Low, Moderate, High)? (Refer to TRL based Severity Guidance Scales)
What are the potential causes?
What specific CMAs and CPPs are associated with these causes?
(If Multiple Causes) Is there a prevailing cause; suspected CMA/CPP?
How often does this failure occur (e.g., remote, moderate, high)? (Refer to TRL based Occurrence Guidance Scales)
Are there any controls to prevent and/or detect the failure?
How likely are these detection methods going to prevent and/or detect the failure before it occurs (e.g., certain, moderate, very uncertain)? (Refer to TRL based Detection Guidance Scales)
What experimental data is available?
What are the actions that could be taken to improve prevention of this failure?
What is the level of implementation of each strategy (idea, proposed future work, in-process, already implemented)
If implemented, what are the failure-based Severity, Occurrence, and Detection?
Repeat for additional failures

Appendix B – High-temperature System Wide FMEA

Table 9. Failure Mode and Effects Analysis for the high-temperature system wide configuration

Failure	Impacts	CQAs	SEVERITY	Causes	CMAs	CPPs	OCCURRENCE	Detection methods	DETECTION	RPN
Excessive overs production (> 6mm) Unit Operations: Mill, Oscillating screen	• Reprocess material through recycling	• Throughput (Proc) • Particle size (Prod)	6	• Higher moisture • Mill screen size	• Moisture	• Screen size (mill) • Mill speed (mill) • Feed rate (system)	3	• Energy consumption sensors (mill)	6	**108**
Excessive fines production (< 1.18 mm) Unit Operations: Mill, Air classifier, oscillating screen	• Material loss • Conversion efficiency	• Yield (Proc, Eco) • Particle Size (Prod)	3	• Mill screen size • Air classifier light fraction removal • Moisture impacting particle size in mill • Moisture impacting air classifier separation efficiency	• Moisture content	• Screen size (mill) • Mill speed (mill) • Feed rate (system)	3	• Current readings for automated and manual in-process adjustments to feed rate • Manual adjustment to pneumatic assist air flow	8	**72**
Deviation from fixed carbon specification (<18 or 21%) Unit Operations: Air classifier	Conversion efficiency impacted through high amounts of anatomical fractions with lower fixed carbon	• Fixed Carbon (Prod) • Ash Content (Prod)	8	Inefficient separation of bark, needles, dirt/fines from the white wood in air classifier	• Moisture content	• Air speed (air classifier) • system configuration (rotary dryer position)	3	Visual detection by trained observer – manual adjustment to air speed	8	**192**
	Increased inorganic material not removed through air classifier causing increased equipment wear	• Throughput (Proc)	3	Inefficient separation of bark, needles, dirt/fines from the white wood in air classifier	• Inorganic species	• Air speed (air classifier) • system configuration (rotary dryer position)	3	Visual by trained observer – manual adjustment to air speed	8	**72**

Deviation from moisture specification (>10%) Unit Operations: Rotary Dryer, Hammermill	• Impacts to HT conversion efficiency • Decrease/impact separation efficiency in air classification • Decrease separation efficiency in oscillating screen increasing fines in the final product • Indirectly higher moisture impacts the efficiency of air classification separation leading to high ash content and lower fixed carbon	• Moisture (Prod) • Fixed Carbon (Prod) • Ash Content (Prod)	10	• Initial moisture content of the material high (>40%) • Feed rate through rotary dryer too high • Chip size or grind size too large (>1") • Shredded material	• Moisture content (>40%) • Particle size (>1") • Particle Shape (non-chips)	• Feed rate (Dryer) • Outlet Temperature (Dryer) • Airflow (Dryer) • Rotational Speed (Dryer)	3	• Offline moisture measurement to set initial feed rate and temperature and recycle # • Observations by trained observer – manual adjust feed rate • Automated inlet temperature adjustments based on outlet temperature readings	6	**180**
	• Hammer mill energy increase (2X for every 10% increase in moisture) • Decrease in system throughput from most equipment	• Energy Consumption (Proc) • Throughput (Proc)	8	• Initial moisture content of the material high (>40%) • Feed rate through rotary dryer too high • Chip size or grind size too large (>1") • Shredded material	• Moisture content (>40%) • Particle size (>1") • Particle Shape (non-chips)	• Feed rate (Dryer) • Outlet Temperature (Dryer) • Airflow (Dryer) • Rotational Speed (Dryer)	3	• Offline moisture measurement to set initial feed rate and temperature and recycle # • Observations by trained observer – manual adjust feed rate • Automated inlet temperature adjustments based on outlet temperature readings	6	**144**
Deviation from ash content specification (>1.75%)	• Increased wear on equipment	• Throughput (Proc)	3	• Inefficient separation of bark, needles,	• Moisture content (>20%)	• Feed rate (Air Classifier)	3	• No in-line controls for meeting specific ash specifications	10	**90**

Unit Operations: Air classifier, Oscillating Screen	(hammer mill especially)			dirt/fines from the white wood in air classifier (moisture, physical properties of material) - Higher bark content	- Anatomical Fraction Ratio (higher bark contents)	- Air Speed (Air Classifier)				
	- Impact on conversion efficiency	- Ash Content (Prod)	8	- Inefficient separation of bark, needles, dirt/fines from the white wood in air classifier (moisture, physical properties of material) - Higher bark content - Failure with oscillating screen	- Moisture content (>20%) - Anatomical Fraction Ratio (higher bark contents)	- Feed rate (Air Classifier) - Air Speed (Air Classifier) - Screen size (oscillating screen)	1	- No in-line controls for meeting specific ash specifications	10	**80**
Throughput lower than target Unit Operations: Hammer mill, Air Classifier, Rotary Dryer	- Target material volume not achieved - Impacts on conversion process (in a continuous system)	- Throughput (Proc) - Yield (Proc)	3	- Initial moisture – longer drying times and/or more drying cycles. - Moisture (>10%) impacts hammer mill throughput. - Chip size and harvest method impact drying time - Ash (soil contamination) impact hammer mill mostly - Air classifier air speed too high removing too much material.	- Moisture - Particle size - Ash/soil	- Outlet temperature (Dryer) - Air Flow (Dryer) - Feed rate (System) - Air Speed (Air Classifier)	3	- Level sensors in system conveyors	6	**54**

	• Lower throughputs due to decreased feed rates can generate more fines through milling process • More material discarded	• Particle Size (Prod) • Particle Size Distribution (Prod) • Yield (Proc)	10	• Initial moisture – longer drying times and/or more drying cycles. • Moisture (>10%) impacts hammer mill throughput. • Chip size and harvest method impact drying time	• Moisture • Particle size • Ash/soil	• Outlet temperature (Dryer) • Air Flow (Dryer) • Feed rate (System) • Air Speed (Air Classifier)	3	• Level sensors in system conveyors • Energy consumption (Mill)	6	**180**

Table 10. Failure Mode and Effects Analysis mitigation strategies for the high-temperature system wide configuration

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
Deviation from moisture specification (>10%) Unit Operations: Rotary Dryer, Hammermill	10	3	6	180	• Replace hammer mill with rotary shear mill; impact of moisture not as significant - (implemented) • **After dryer in-line moisture sensor (in-process) – Selected**	10	3	3	90
	8	3	6	144	• Replace hammer mill with rotary shear mill; impact of moisture not as significant - (implemented) • **After dryer in-line moisture sensor (in-process) – Selected** • Tarping or covering material; rain prevention • Particle size sensor to also make adjustments to feed rate • Mass sensor	8	3	3	72
Deviation from ash content specification (>1.75%) Unit Operations: Air classifier, Oscillating Screen	3	3	10	90	**In-line moisture (and ash) sensors after dryer, air classifier unit and oscillating screen**	3	1	6	18
	8	1	10	80	**In-line moisture (and ash) sensors after dryer, air classifier unit and oscillating screen**	8	1	6	48

Throughput lower than target	3	3	6	**54**	**In-line moisture sensor.**	**3**	**3**	**3**	**27**
Unit Operations: Hammer mill, Air Classifier, Rotary Dryer	10	3	6	**180**	**In-line moisture sensor.**	**10**	**3**	**3**	**90**

Appendix C – Rotary Dryer (pine residues) FMEA

Table 11. Failure Mode and Effects Analysis for the rotary dryer processing pine residues chips to 10% moisture

Failure	Impacts	CQAs	SEVERITY	Causes	CMAs	CPPs	OCCURRENCE	Detection methods	DETECTION	RPN
Outcoming material greater than moisture specification (10%) after one pass through system (Scenario 1)	• Need to reprocess material through recycling • Conveying and flow issues • Air classification separation issues	• Moisture (Proc/Prod)	3	• Initial moisture higher than 20%; maximum decrease in moisture is approximately 10% for each pass though system • large particle size (chips); only surface moisture is impacted by system • Residence time too short • air speed too high • temperature too low	• Moisture • Particle size	• Outlet temperature • Rotation speed • Air flow	10	• Offline moisture analyzer for before and after moisture analysis • Trained observers monitoring material moistures before and after	8	**240**
Outcoming material greater than moisture specification after multiple passes through system (Scenario 2)	• Need to reprocess material through recycling • Conveying and flow issues • Air classification separation issues	• Moisture (Proc/Prod) • Throughput (Proc)	3	• Initial moisture high (>50%); maximum decrease in moisture is approximately 10% for each pass though system • large particle size (chips); only surface moisture is impacted by system • Residence time too short • air speed too high • temperature too low	• Moisture • Particle size	• Outlet temperature • Rotation speed • Air flow	1	• Offline moisture analyzer for before and after moisture analysis • Trained observers monitoring material moistures before and after	8	**24**

Plugging of cyclones before airlock	• Downtime (couple of hours) to clean out system • Material lost • Potential for leading to fire failure	• Throughput (Proc) • Yield (Proc)	6	• Too large of particle size (2" chips are the upper threshold) • Increased dirt with the 2" chips • Air flow too slow • Stringy materials (not as common for woody)	• Particle size (>2") • Particle shape (stringiness)	• Air Flow	1	visual detection by trained observer of material existing through stack instead of air lock	6	**36**
Fire within drum and/or stack	• System shutdown • Material loss • Quality of material if heated too high	• Throughput (Proc) • Yield (Proc) • Volatile emissions (LCA)	8	• Moisture content too low (<10%) • Plugging failure resulting in buildup of material in the drum • Stringy materials getting stuck in the drum • Forest residue needles bunching up and sticking in drum • Inlet temperature too high • Ground material >50% moisture sticking to inside of drum	• Moisture (>50%; <10%) • Particle size • Particle shape (stringiness)	• Temperature	3	visual observation of smoke	6	**144**
Material loss through stack	• Material loss and yields • Potential environmental consequences of particulates going out of stack	• Yields (Proc) • Particulate emissions (LCA)	3	• Cascading failure because of plugs and fires • Too low in moisture; fines can be lost more easily • Plugging can result in whole chips being lost through stack	• Moisture (<10%) • Particle size (fines)	• Air flow	1	visual observation of material loss to manually decrease air speed	3	9

Appendix D – Air Classifier (pine residues) FMEA

Table 12. Failure Mode and Effects Analysis for the air classifier separating anatomical fractions of pine residues chips

Failure	Impacts	CQAs	SEVERITY	Causes	CMAs	CPPs	OCCURRENCE	Detection methods	DETECTION	RPN
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 size – whole • Particle size – tissue fractions	• Air speed • Feed rate	6	Visual inspection by trained observer and adjustment to feed rate and/or air speed	3	**180**
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 needles	• Particle shape (needles) • Particle size (needles)	• Air speed • Feed rate	6	Visual inspection by trained observer and adjustment to feed rate and/or air speed	8	180
Inefficient Separation – Too much white wood in the light fraction(s)	• Product loss • Reprocessing of whole batch	• Yield • Throughput	10	• Initial tissue ratios of high needle and soil contaminants • Air speed too high • Particle size of wood chips small as results of chipper performance • Small white particles from branches and twigs	• Tissue fraction ratios • Particle size (white wood)	• Air speed	6	Visual inspection by trained observer and adjustment to air speed	6	360

Conveyor Jam	• System downtime • Equipment damage	• Throughput	10	• Tramp metal and rocks (contaminants) • Large wood chip pieces	• Particle size • Particle morphology		1	Visual inspection and removal beforehand by trained observer	3	30

Appendix E – Hammer Mill (pine residues) FMEA

Table 13. Failure Mode and Effects Analysis for hammer mill processing pine residues

Failure	Impacts	CQAs	SEVERITY	Causes	CMAs	CPPs	OCCURRENCE	Detection methods	DETECTION	RPN
Screen plugs (partial plugs)	• Overload on grinder motor • Shutdown of infeed upstream operations • Downtime to clean out screen and system (1-3 hours) • Reprocessing of material	• Throughput (Proc)	6	• Higher moisture materials (20-50%) • Stringy bark materials coupled with high moisture • Smaller screen sizes plug more easily • Infeed rate too high	• Moisture (20-50%) • Anatomical fraction ratios (higher bark concentrations)	• Screen size (smaller screens) • Feed rate	3	• Automatic feed rate adjustment based on motor current (this can also be controlled manually) • Offline moisture measurements to set appropriate feed rates	3	54
Too many particles over specification (>10% of product)	• Increased recycled of materials over >10% • Impact on downstream conversion if not addressed through recycling or screening	• Throughput (Proc) • Particle size (Prod)	3	• Screen size too big for material • Feed rate too fast • During system shutdown for plugged screen failure potential for unprocessed material to advance through system (very small amount)		• Screen size (larger screens) • Feed rate (too fast)	1	• Downstream oscillating screen address to ensure final product doesn't include overs. • Visual observation of increased overs in the recycle line	1	3
Too many particles under specification (fines)	• Downstream conversion process impacts with increased fines • Increased material loss (if oscillating screen used to	• Particle size (fines) (Prod) • Yield (Proc)	3	• Feed rate is too slow • Partial plug in screen results in over processing of materials • Higher moisture contributes to more plugging leading to	• Moisture (>20%)	• Feed rate (too slow) • Screen size (smaller screens)	1	Automatic feed rate adjustment based on motor current (this can also be controlled manually)	3	9

	remove/discard fines) • Increased generation of dust		🟩	more fines generation • Smaller screen sizes lead to increased fines			🟩		🟩	🟩

Appendix F – Oscillating Screen (pine residues) FMEA

Table 14. Failure Mode and Effects Analysis for the oscillating screen processing pine residues

Failure	Impacts	CQAs	SEVERITY	Causes	CMAs	CPPs	OCCURRENCE	Detection methods	DETECTION	RPN
Bottom (secondary) screen plugs – 10% moisture (scenario 1)	• Separation efficiency • Increase in fines in output material stream • Impacts to downstream conversion due to fines	• Particle Size Distributions (Prod) • Ash content (Prod)	10	• Increased moisture (>30%) • Increased fines or inorganics (coupled with moisture)	• Moisture content (>30%) • Particle size (fines)	• Screen size (<20 mesh—0.84 mm)	1	Trained observer monitoring fines generated in the output stream	6	60
	• Downtime to disassemble and clean out unit	• Throughput (Proc)	6	• Increased moisture (>30%) • Increased fines or inorganics (coupled with moisture)	• Moisture content (>30%) • Particle size (fines)	• Screen size (<20 mesh—0.84 mm)	1	Trained observer monitoring fines generated in the output stream	6	36
Bottom (secondary) screen plugs – 30% moisture (scenario 2)	• Separation efficiency • Increase in fines in output material stream • Impacts to downstream conversion due to fines	• Particle Size Distributions (Prod) • Ash content (Proc)	10	• Increase moisture (>30%) • Increased fines or inorganics (coupled with moisture)	• Moisture content (>30%) • Particle size (fines)	• Screen size (<20 mesh—0.84 mm)	3	Trained observer monitoring fines generated in the output stream	6	180
	• Downtime to disassemble and clean out unit	• Throughput (Proc)	6	• Increased moisture (>30%) • Increased fines or inorganics (coupled with moisture)	• Moisture content (>30%) • Particle size (fines)	• Screen size (<20 mesh—0.84 mm)	3	Trained observer monitoring fines generated in the output stream	6	108

Top (primary) screen plugs	• Lower material yields • More material recycling • Over grinding of recycled material leading to increased fines generation (bottom screen likely plugged prior to top screen plugging > cascading failure)	• Throughput (Proc) • Yield (Proc)	3	• Increased moisture • Particle shapes that plug holes (likely to only lead to partial plugging)	• Moisture content (>30%) • Particle size • Particle shape	• Screen size (<3/8")	1	Trained observer monitoring throughput of output material and recycling overs amounts	6	18
Screen tears - Bottom (secondary) screen	• On-spec material lost • Requires a shutdown to replace the screen	• Throughput (Proc) • Yield (Proc)	3	• Age of screen (usually requires replacement over time) • Metal contaminants causing damage • Increased wear due to high inorganics • Incorrect mounting of screen in the system. Too much tension causing strain on screen • Smaller screens tear more easily	• Contaminants (metals) • Ash content	• Screen size (smaller)	1	• Routine maintenance schedules to check screen quality • Visual observation of screens each day prior to running • Trained observer monitoring fines stream	8	24
Screen cracks - Top (primary) screen primarily	• Replacement of screen after normal operation • Potential of screen "snapping" if not replaced; this would lead to downtime to replace screen during normal operation (catastrophic failure)	• Throughput (Proc)	1	• Age of screen (metal fatigue over time) • Rocks or other contaminants causing uneven wear in screen • Sand or other abrasive inorganic species resulting in increased wear	• Contaminants (metals, rocks, sand) • Ash content		1	• Routine maintenance schedules to check screen quality • Visual observation of screens each day prior to running	10	10
Motor failures	• System shutdown • Replacement of motor	• Throughput (Proc)	6	• Power surges • Lack of maintenance	• Moisture (>30%) • Particle size	• Screen size	3	• Trained operator hearing the motor running "rougher"	6	108

				- If screens are plugged that could draw more current on the motor to increase likelihood of the failure	- Particle shape			or bearings making more noise - Trained operator observing increased heat generation from motor		
Belt breaking	- System shutdown to replace belt	- Throughput (Proc)	3	- Slipping if tension is not correct - If motor is drawing more energy, it can increase temperature on belt - Belt gets too worn			6	- Trained operator hearing the noises relating to belt or seeing wear and/or slipping - Maintenance schedule includes checking on belt wear and preemptively replacing during schedule maintenance	3	54
Sheet metal cracking on system	- In non-structural crack this can be repaired during scheduled maintenance - Structural cracks require shutdown and more than just a weld fix potentially	- Throughput	8	- Improper design or set-up - Operating incorrectly - Running in overload for long periods of time (motor would most likely fail before a crack though) - Equipment age (25+ years cracks would be more likely depending on environment)			1	- Visual inspection during routine scheduled maintenance - Non-structural cracks logged at the time they are observed to be repaired during routine maintenance	3	24
Bearings breaking/cracking	- System shutdown to replace bearings (catastrophic rare failure) - Potential damage to equipment due to sudden stoppage	- Throughput	6	- Improper or wrong lubrication (mixing of lubricant types) - Age of bearings - Poor construction of bearings	- Particle size (fines/dust)		3	- Visual inspection and lubrication during routine operation - Trained observer "hearing" operation	3	54

			🟩	• Dust or dirt around bearings (these are sealed but can still get dirty)			🟩	indicating bearing is going bad • Routine maintenance schedule to check and replace bearings • Increased current draw on motor (hard to see as this is gradual) • Power data changes	🟩	🟩

Appendix G – Drag Chain Conveyors FMEA

Table 15. Failure Mode and Effects Analysis for drag chain conveyors

Failure	Impacts	CQAs	SEVERITY	Causes	CMAs	CPPs	OCCURRENCE	Detection methods	DETECTION	RPN
Slipping off track	• Process shutdown to fix or change out conveyor • Replace equipment (belts and gears)	• Throughput (Proc)	3	• Improper maintenance and inspection processes • Feed rate too fast for conveyor • Interaction between material and moving parts • Interaction of material causing wear on moving parts (fines from pine residues causing wear) • Dryer materials have more potential of fines interacting with moving parts	• Particle size (fines) • Moisture (dry) • Particle shapes (stringy) • Material volume	• Feed rate	3	• Inspection by trained observer (check for gear wear and pulley tension) • Regular maintenance schedule	1	9
Overloading	• Process shutdown with stalled conveyor • Motor burnout (very unlikely)	• Throughput (Proc)	1	• Too much material on conveyor • Increased moisture adding additional mass • Higher density materials (smaller particle sizes; cohesive particles)	• Moisture • Particle size • Particle shape • Bulk density • Material volume	• Feed rate • Motor power level • Paddles geometry • Conveyor angle	1	• Trained observer monitoring feed rates and conveyor motor consumption. • Level sensors	3	3
Clogging (closed system conveyors)	• Process shutdown to clear clogged material • Potential damage to downstream equipment • Overload motor • Cause damage to conveyor itself if not addressed	• Throughput (Proc) • Product Quality (Prod)	6	• Feed rate too high for upstream/downstream equipment • Material builds up on itself (see this with MSW more)	• Particle cohesion • Moisture	• Feed rate	3	• Trained observer monitoring feed rates and conveyor motor consumption. • Level sensors • Energy consumption from adjacent systems	8	144

	• Compaction of material potentially impacting quality		🟩				🟩		🟩	🟩

Appendix H – High-temperature screw feeder (pine residues) FMEA

Table 16. Failure Mode and Effects Analysis for the pyrolysis reactor feedscrew system processing pine residues

Failure	Impacts	CQAs	SEVERITY	Causes	CMAs	CPPs	OCCURRENCE	Detection methods	DETECTION	RPN
Feed System Plug	• Complete Shutdown • Downtime • Potential equipment damage • Product quality impact	• Throughput (Proc) • Biomass feed rate consistency (Proc) • Product quality (Prod)	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 distributions • Moisture (<10%; >25-30%) • Particle surface • Compaction • Particle density	• Auger geometry • Temperature profile	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 feed rate consistency (Proc) • Throughput (Proc) • Particle size (fines) (Proc) • Product quality (Proc)	8	Particle agglomeration on auger: • Auger flight deformation • Reactions between properties and heated auger • Particle agglomeration through volatilization and recondensation.	• Particle size distributions • Moisture (<10%; >25-30%) • Particle morphology • Particle surface • Particle density • Volatiles • Flow properties • Inorgancics 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 reaction particle size through agglomeration or attrition	Attrition - Reactor performance and yield efficiency - Further particle agglomeration and/or plugging - Increased wear rate - Material flowability Agglomeration - Decline in fluidized bed performance (incomplete conversion) - Plugging or buildup downstream - Product quality - Downtime based on burnout requirements	- Particle Size Distributions (Prod) - Biomass Feed rate Consistency (Proc) - Product Quality (Proc) - Process Efficiency (Proc)	6	Attrition - Particles trapped in flights Agglomeration - 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

Appendix I – Low-temperature System Wide FMEA

Table 17. Failure Mode and Effects Analysis for the low-temperature system wide configuration

Failure	Impacts	CQAs	SEVERITY	Causes	CMAs	CPPs	OCCURRENCE	Detection methods	DETECTION	RPN
Deviation from particle size specification (fines) Hammer mill, Bale grinder	• Conversion efficiency • Increased system wear (with high inorganic concentrations)	• Particle size (fines) (Prod) • Particle size distribution (Prod)	6	• Dirt and fines in material • Over deconstruction from hammermill • biological degradation (self-heating)	• Inorganic contaminants • Degradation Level	• Screen size – grinder • Screen shape - grinder	8	• Visual inspection of bales for high soil - requires trained observer • a priori knowledge of harvest methods/conditions • Offline PSD analysis	10	**480**
Deviation from particle size specification (overs) Hammer mill	Downstream flow into conversion reactor	• Particle size (<1") (Prod) • Particle size distribution (Prod)	TBD	• Spearing pieces through grinder • Too fast of feed rates		• Screen size – grinder • Screen shape - grinder	1	• Visual inspection of bales for • Offline PSD analysis	10	**TBD**

Material over moisture specification	• Material discarded • Overheating in DMR if too low moisture	Moisture (20%) (Prod)	10	Incoming moisture (~50% bales have 15-25% moisture)	Moisture		6	• Bale probe sensors and in-line sensors • Queuing to avoid running bales with too high moisture	1	**60**
Material not meeting carbohydrate spec Unit Operation: Air Classifier (mitigation)	Material discarded	• Yield (Eco, Proc) • Carbohydrates (<59%) (Prod)	10	• Degraded material having lower initial carbohydrate. • Moisture impacting air classification separation • Incoming carbohydrate materials	• Carbohydrate • Anatomical fraction ratios • Degradation level			• Blending based on anatomical fractions • Offline analysis of carbohydrates		
High ash content Unit Operation: Air Classifier (mitigation)	• Significant failure for DMR when discs wear early	• Ash (>4.93%) (Prod) • Throughput (Proc)	10	• Harvest method • Harvest location • Initial ash content	Ash content		10	• Visual inspection of bales for high soil - requires trained observer • a priori knowledge of harvest methods/conditions	8	**800**

	- High ash contamination increases wear through the system (requiring increased maintenance)	Throughput (Proc)	6	- Harvest method - Harvest location - Initial ash content	Ash content		10	- Visual inspection of bales for high soil - requires trained observer - a priori knowledge of harvest methods/conditions	8	**480**
High Energy Consumption All Equipment	- Cost associated with unit operation energy - Overloading of equipment - Equipment shutdown	Energy consumption (Eco)	8	High moisture and material volumes causing plugging in mills, conveyor overloading, and plugging in air classifier and disc screens	- Moisture (high) - Material volume		3	- Bale probe sensors and in-line sensors for moisture detection - Energy consumption thresholds on equipment	1	**24**
Decreased throughput All Equipment	- Not meeting yield and throughput targets	- Throughput (Proc, Eco) - Yield (Proc, Eco)	TBD	- High moisture materials - Slugs or high volumes of materials - System shutdowns	- Moisture - Material volume - Particle size (fines) - Ash contents	- Feed rate (system) - Mill speeds (hammer mill) - Air speed (air classifier)	3	- System tracking for processing time for each bale - System feed rate known and adjusted	3	**TBD**

Table 18. Failure Mode and Effects Analysis mitigation strategies for the low-temperature system wide configuration

Failure	**SEVERITY**	**OCCURRENCE**	**DETECTION**	**RPN**	**Mitigation(s)**	**SEVERITY**	**OCCURRENCE**	**DETECTION**	**RPN**

Deviation from particle size specification (fines)	6	8	10	**480**	• **Inclusion of disc screen prior to air classification to remove dirt and fines. Both Light air classification streams become higher value. Remove materials that don't need to be further sized reduced. - Selected** • 3 stream air classifier unit • dual air classification (in-line) instead of disc screen. • Use knife mill instead (typically creates less fines) • Increase screen size in mill	**6**	**3**	**10**	**180**
Material not meeting carbohydrate specification (>59%)	10	8	10	**800**	• **Blending of fractions material from air classification streams (idea) - Selected** • Removal of dirt and soil (implemented)	**8**	**6**	**10**	**480**
Material not meeting ash content specification (<4.93%)	10	10	8	**800**	• **Use air classification or disc screens to remove ash (implemented)- Selected** • Inclusion of in-line detection for ash (in-process)	**10**	**3**	**8**	**240**

Appendix J – Bale Grinder (corn stover) FMEA

Table 19. Failure Mode and Effects Analysis for the bale grinder processing corn stover bales

Failure	Impacts	CQAs	SEVERITY	Causes	CMAs	CPPs	OCCURRENCE	Detection methods	DETECTION	RPN
Inconsistent material volumes	• Inconsistency in material • Hammer mill shut down (if too much material) • Plug up downstream conveyors and mills • Material is thrown out	• Particle size (Prod) • Throughput (Proc) • Yield (Proc, Eco)	6	• Bale construction • High moisture • Inconsistent pulling off of bales flakes • Degradation	• Moisture • Physical properties • Biological degradation (molded) • Biological degradation (Self-heated)	• Hammer rotation speed • Feed rate	6	• System design track surges bale grinder through energy to control conveyors and interlocks. • Feed rate set based on moisture	3	**108**
Screens plugs and system plugs	• System shut down • Material loss • Downtime impacts • Hammermill over processes • During partial plugging event (sub quality product potentially for particle size)	• Throughput (Proc) • Yield (Proc, Eco) • Particle size (Prod)	8	• Wet bale • Screen size - 6” leads to downstream plugs easier than a 3” • Fibrous stalks wrapping around the screen • Moldy/degraded bales sticking to the screen • Large flakes	• Moisture • Low cut (contributes more to screen plugging because of stalk length)	• Screen size • Feed rate	3	• Same controls as before • Don’t run bale if too wet • Set amperage at certain levels to slow the feed rate automatically • Visual detection of mold	3	**72**
Bale strings and twine making it into system	• Wrap around bale grinder shaft • 4-5 hours to remove all strings including safety processes • Eventually would prevent hammers from swinging	• Throughput (Proc)	3	• Twine is standard for harvest and storage methods • Not removed through manual bale preparation processes			1	• Visual inspection and manual removal • Detect string as soon as bale starts to deconstruct	1	**3**

	• Contamination of product. 100% of product would need to be scrapped depending on customer.	• Contaminants (Prod)	10	• Twine is standard for harvest and storage methods • Not removed through manual bale preparation processes			1	• Visual inspection and manual removal • Detect string as soon as bale starts to deconstruct	1	**10**

Appendix K – Air Classifier (corn stover) FMEA

Table 20. Failure Mode and Effects Analysis for the air classifier processing corn stover

Failure	Impacts	CQAs	SEVERITY	Causes	CMAs	CPPs	OCCURRENCE	Detection methods	DETECTION	RPN
Shut off	• Longer processing time • Machine starts slowing down	• Throughput (Proc)	3	• Outdated software • Unintended air speed		• Air speed outside efficiency range	10	• Energy consumption sensors (mill)	10	**240**
Inefficient separation – 3 fraction scenario (cobs (heavy), stalks (med), leaves + husk(light))	• Time and cost intensive • Bad product quality • Grinding energy	• Product quality (Prod) • Throughput (Proc)	3	• Unable to control air speed • Inaccurate separation • Humidity • Rock track fills up • Wet material • Drought samples • Harvest methods • Type of bale (round vs square) • Environmental conditions • Physical size • Major preprocessing • Incorrect feeding • Similar densities of fractions	• Moisture • Physical attributes	• Air speed • Belt speed • Frequency of cleaning out rock trap	3	• Visual inspection • Known parameters • Clean out rock trap • a priori knowledge of air speed relationship to moisture levels (all trained operator knowledge)	10	**90**

Inefficient separation – 4 fractions scenario (cobs, stalks, leaves and husk)	• Time and cost intensive • Bad product quality • Grinding energy	• Product quality (Prod) • Throughput (Proc)	10	• Unable to control air speed • Inaccurate separation • Humidity • Rock track fills up • Wet material • Drought samples • Harvest methods • Type of bale (round vs square) • Environmental conditions • Physical size • Major preprocessing • Incorrect feeding • Similar densities of fractions	• Moisture • Physical attributes	• Air speed • Belt speed • Frequency of cleaning out rock trap	10	• Visual inspection • Known parameters • Clean out rock trap • a priori knowledge of air speed relationship to moisture levels (all trained operator knowledge)	10	**1000**
Unintended material loss	• Material has to be recovered • Cost of material loss (Up to 7-10% potentially)	Product yield (Prod)	1	• Material gets stuck • Material is contaminated • Round vs square bale	• Physical properties (particles size - fines) • Brittleness (related to moisture content)	Air speed (too high)	10	Nothing in place	10	**100**
Rock trap fills up with husks	• Shut down • Lock out tag out • Impacts separation ability • Impacts air flow • Clean out	Throughput (Proc)	3	• Material gets stuck • Particle size changes			8	Visual control	10	**240**
Inconsistent feeding – Lower throughput (cause inconsistent feeding)	• Lower throughputs • Separation efficiencies	• Throughput (Proc) • Product quality (Prod)	8	• Volume of material doesn't align with set air speed • Upstream feeding • Improper material from bale grinder	• Material properties impacting bale grinder • Materials stuck together (compressed together)	Air speed	3	Visual detection of stream qualities	10	**240**

Appendix L – Hammer Mill (corn stover) FMEA

Table 21. Failure Mode and Effects Analysis for the hammer mill processing corn stover

Failure	Impacts	CQAs	SEVERITY	Causes	CMAs	CPPs	OCCURRENCE	Detection methods	DETECTION	RPN
Screen plugged	• Complete shutdown • Material lost	• Throughput (Proc) • Energy consumption (Proc)	10	• Buildup of material due to volume and material properties. • High moisture (>40% Fresh and stored) • Soil contamination • Harvest methods and bale construction	• Moisture content • Inorganic content • Physical strength (cut height) • Bale density	• Feed rate • Screen size	6	• Current readings for automated and manual in-process adjustments • Multiple moisture detectors • Material height sensors	1	**60**
			10	• Fines generated through self-heating • Soil contamination • Harvest methods and bale construction	• Particle size (fines) • Degradation • Inorganic content • Physical strength (cut height) • Bale density	• Feed rate • Screen size	6	• Current readings for automated and manual in-process adjustments to feed rate • Material height sensors • Visual bale inspection by trained observer	8	**480**
Process slowdown	>50% decrease in throughput	• Throughput (Proc)	10	• Decrease in feed rate because of partial screen plugging • High moisture contents (>35% fresh and stored) • Increased fines • Harvest methods and bale construction	• Moisture content • Particle size (fines) • Physical strength (cut height) • Bale density	• Feed rate • Screen size • Mill speed • Pneumatic assist air flow	8	• Current readings for automated and manual in-process adjustments to feed rate • Manual adjustment to pneumatic assist air flow	3	**240**

	~50% decrease in throughput	- Throughput (Proc)	8	- High moisture contents (25-35% fresh and stored) - Increased fines - Harvest methods and bale construction	- Moisture content - Particle size (fines) - Physical strength (cut height) - Bale density	- Feed rate - Screen size - Mill speed - Pneumatic assist air flow	8	Same as above	3	**192**
	~25% decrease in throughput	- Throughput (Proc)	6	- High moisture contents (15-25% fresh and stored) - Increased fines - Harvest methods and bale construction	- Moisture content - Particle size (fines) - Physical strength (cut height) - Bale density	- Feed rate - Screen size - Mill speed - Pneumatic assist air flow	8	Same as above	3	**144**
	Decrease in throughput	- Throughput (Proc)	1	- Overs from 1st stage bale grinder	- Particle size (overs)	- Feed rate - Screen size - Mill speed - Pneumatic assist air flow	6	Same as above	10	**60**
Overs production	Missed PSD specification	- Particle size (Prod)	8	- Moisture >15% (Fresh and stored)	- Moisture content	- Feed rate - Screen size - Mill speed - Pneumatic assist air flow	6	- Multiple moisture detectors - Visual by trained observer	3	**144**
		- Particle size (Prod)	8	- Early hammer wear	- Inorganic species	- Feed rate - Screen size - Mill speed - Pneumatic assist air flow - Hammer construction materials	6	- Visual by trained observer	8	**384**
Fines production	Missed PSD specification	- Particle size (Prod)	6	- Self-heated material (stored at high moisture) - High soil content	- Particle size (fines) - Moisture - Degradation	- Feed rate - Screen size - Mill speed - Pneumatic assist air flow	6	- Visual by trained observer	8	**288**

Appendix M – Deacetylation/DMR (corn stover) FMEA

Table 22. Failure Mode and Effects Analysis for the disc mechanical/deacetylation pretreatment of corn stover

Failure	Impacts	CQAs	SEVERITY	Causes	CMAs	CPPs	OCCURRENCE	Detection methods	DETECTION	RPN
Deacetylation – Plugging in reactor	• System shutdown • Material discarded • Material recovery through washing	• Throughput (Proc)	10	• Overfeeding biomass	• Particle size (Fines) • Mechanical strength • Aspect ratio	• Feed rate	1	• Trained observer monitoring sensors for system pressure and flowmeters • Visual detection through glass column	1	**10**
	• System shutdown • Excessive generation of fines	• Throughput (Proc) • Particle size (Prod)	10	• Overcooking		• NaOH loading • Residence time	1	• pH monitoring • controlling material residence time	1	**10**
	• System shutdown • Material discarded	• Throughput (Proc) • Particle size (Prod)	6	• Incoming material as too many fines	• Particle size distribution (Fines)		6	• No current detection method other than experimentally determining PSD of incoming material.	10	**360**
	• System shutdown • Material discarded	• Throughput (Proc)	6	• Incoming material is degraded (can contribute to fines generation)	• Degradation • Particle size distribution (Fines)	• NaOH loading	6	• pH monitoring can help detect degradation	1	**36**
Disc Refining – Wear in disc plates	• Frequent plate replacement • Impact material particle size • Reduction in EH digestibility • Reduce DMR performance	• Particle size (Prod) • Product yield (Proc)	6	• Soil contamination	• Inorganic species content		10	• No current detection method for inorganic species	10	**600**
Disc Refining - Overheating	• System shutdown • Equipment damage • Potential fire hazard	• Throughput (Proc)	10	• Material too dry • Material fed too quickly	• Moisture	• Feed rate	1	• Sensors to detect overheating, motor strain, or foreign objects • Disc spacing increased	1	**10**

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