



# The Interaction of Material Properties and Design Factors in Reducing Mechanical Failures of Confectionery Machines

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**Abstract.** This article examines in detail the causes of equipment and production line failures in the confectionery industry, as well as ways to minimize such failures. Experience shows that mechanical breakdowns are not just random events, but the predictable result of the complex interaction of many factors. The reliability of equipment depends on the properties of the materials from which it is made, the design decisions of engineers, and operating conditions. One of the main factors is related to the choice of material. If the metal or coating is chosen incorrectly, the equipment will wear out faster. This includes corrosion of parts, fatigue cracking, etc. Therefore, at the design stage, it is important to consider the loads, temperature, humidity, and chemical aggressiveness of the environment. This is where the concept of “Design for Reliability” (DfR) plays a decisive role. Essentially, this means predicting in advance where a machine might fail and designing it so that this does not happen. However, good materials and the right design alone are not enough. The article takes a detailed look at the role of operating conditions. Temperature fluctuations, high humidity, abrasive particles, and installation errors accelerate wear and tear and increase the risk of accidents. The economic benefits are also clear, fewer accidents mean less unplanned downtime, less loss of raw materials, energy, and time. This directly affects production costs and profitability. The main idea of the article is that it is better to prevent breakdowns than to fix them. A proactive approach based on the right choice of materials, design, and regular maintenance increases equipment reliability and makes products safer. Compliance with strict sanitary requirements and maintaining consistent quality are especially important for the confectionery industry.

**Keywords:** Confectionary industry, Machinery, Mechanical failure, Material selection, Design considerations, Maintenance.

# **1. Introduction: The Criticality of Reliability in Confectionery Production**

## **1.1 Industry Context**

The confectionery industry operates in a high-volume, continuous production model, where the integrity and uninterrupted operation of machinery are essential for profitability. Any unplanned interruption in the production line, such as sudden machine stops, downtime, loose raw materials and spoilage of temperature-sensitive products such as chocolate, can have negative consequences, including significant financial losses. For products with strict temperature control requirements, the risk of spoilage increases the longer the food is out of the line, making rapid response to equipment failure a critical issue for both efficiency and food safety. Reliance on complex, interconnected systems means that failure in one component can bring the entire production line to a standstill, highlighting the need for a robust approach to equipment reliability.

## **1.2 Problem Statement**

Mechanical failures are a persistent problem in all industries, not just confectionery, but their causes are rarely simple. They arise from a complex interplay of factors, including hidden design flaws, poor material selection, and inadequate maintenance practices. A failure may appear to be a simple problem, such as a clogged conveyor belt or motor failure, but its true origin may often lie in a deeper, systemic weakness. For example, a part may fail not due to normal wear and tear, but because its material is poorly selected for the corrosive environment or because a design feature creates an excessive stress point. This article argues that a thorough understanding of these interrelated causal factors is essential for developing effective, long-term solutions that go beyond simply addressing the symptoms.

# **2 Basic Principles of Mechanical Failure in Confectionery Environments**

## **2.1 Common Mechanical Failure Modes**

Mechanical failures in confectionery machines manifest in various forms, each capable of disrupting production. The most common cause is the natural wear (such as abrasive, adhesive) and tear of critical components, resulting from regular use [1]. This degradation can lead to decline in equipment performance and efficiency, ultimately necessitating parts replacement or causing a breakdown. Specific mechanical issues frequently involve problems with bearings, gears and seals, which can disrupt normal machine operation.

Beyond physical wear, electrical and systemic failures also pose significant threats. These can include issues with a machine's wiring, fuses, or other electrical components, leading to sudden malfunctions. A machine's control panel, often referred to as its

"brain," can also display error messages that signal underlying problems or glitches that can be resolved by a simple reset.

Failures in the confectionery industry are often intrinsically linked to the product itself. For example, issues such as inconsistent tempering can lead to a dull appearance or blooming on chocolate products, a result of incorrect tempering temperatures or insufficient mixing. Blockages in piping or valves, caused by the hardening of chocolate mass, can lead to clogging and production downtime. Similarly, improper settings in the cooling tunnel can cause finished products to crack or melt during packaging.

## **2.2 The Unique Stresses of Food Processing Environment**

The environment of food processing facility is uniquely harsh, a factor that significantly accelerates equipment degradation and increases the risk of failure. Equipment in these settings must withstand a combination of environmental stressors not typically encountered in other manufacturing sectors.

A key risk factor is chemical exposure. Routine and rigorous cleaning and sanitation procedures often involve the use of highly corrosive agents, including alkaline, acidic, and oxidizing chemicals [2]. Many food products, such as sauces and citrus juices, are mild to severe corrosives that can further degrade equipment over time. Enzymes in foods can also cause corrosion, as can microbial contamination of surfaces. Unlike many other industries, the use of strong corrosion inhibitors is severely restricted in food processing for safety and health reasons, making material selection and protective coatings even more critical.

Humidity and moisture are general hazards. The use of high-pressure water and steam for cleaning, combined with ambient moisture, promotes the formation of rust and other corrosive compounds [3]. This wet environment also poses a slip and fall hazard for workers. In addition, the frequent and significant temperature changes, such as cooling and heating cycles required for processes such as chocolate tempering, cause thermal stress and fatigue in materials, increasing the risk of mechanical failure.

## **3 The Influence of Material Properties on Equipment Reliability**

The choice of materials is one of the most fundamental decisions in the design and construction of confectionery machinery, directly affecting its resistance to failure. The harsh, corrosive environment of food processing requires the use of special materials that can withstand humidity, chemical attack, and frequent cleaning cycles.

### **3.1 Metals: Stainless Steel Grades**

Stainless steel (SS) is a major force in the food processing industry due to its ease of cleaning and corrosion resistance. However, not all grades are created equal, and choosing between them represents critical engineering and financial decision.

**Composition and Properties.** SS 304 contains approximately 18-20% chromium and 8-10% nickel [4, 5]. It is a widely used and cost-effective choice that provides excellent corrosion resistance for general food and beverage applications. It is known for its formability and ease of manufacture, and is resistant to mild acids and alkalis. In contrast, SS 316 has a slightly different composition: 16-18% chromium, 10-14% nickel, and most importantly 2-3% molybdenum [6]. The addition of molybdenum is a key differentiator, as it significantly increases the material's resistance to pitting corrosion, which is common in environments with high exposure to salts, acids, or aggressive cleaning agents. This makes 316 an ideal choice for more challenging processing environments.

**Application and Cost-Benefit Analysis.** The choice between 304 and 316 grades is a long-term strategic and financial decision. Although SS 316 carries a higher initial cost, its superior corrosion resistance provides better long-term reliability and reduces the risk of premature equipment failure. This directly translates into lower maintenance and replacement costs over the life of the machine, thereby justifying the initial investment for applications involving harsh chemicals or extreme conditions. The decision to use 316 is a clear example of balancing the initial capital cost with the projected operating costs and risk of failure-related downtime, making it a case for reliability engineering rather than a simple material choice.

### 3.2 Engineering Plastics and Wear Resistance

In addition to metals, engineering plastics are essential components for various confectionery machinery, especially those requiring low friction, chemical resistance, and easy sanitation. These materials offer durability, wear resistance, and longevity that can surpass some metals.

**UHMW.** Ultra-High Molecular Weight Polyethylene is praised for its excellent abrasion resistance, low coefficient of friction and chemical resistance [7]. These properties make it ideal for use in conveyor belts and grooves, where it helps products move smoothly. Its non-porous nature also facilitates sanitization, which is a significant advantage in food-grade environments.

**PTFE (Teflon).** Polytetrafluoroethylene is known for its excellent non-stick properties, heat resistance and chemical resistance [8]. It is highly suitable for use as a non-stick coating for ovens and molds, where it prevents product sticking and facilitates easy cleaning.

**Polyurethane (PU).** Combining flexibility with strong wear and tear resistance, polyurethane belts can withstand repeated bending and stretching [9]. They also resist oil, grease, and many cleaning agents, making them a suitable choice for conveyor systems in wet environments.

**3.3 Environmental and Functional Issues**

The choice of plastic depends heavily on the characteristics of food and operating environment. For example, while polypropylene (PP) is a lightweight and cost-effective option suitable for dry goods and light-duty applications, it performs poorly at high temperatures and can warp or lose strength when exposed to heat. This highlights that material suitability is a function of the specific application, where environmental factors such as temperature, humidity and chemical exposure must be carefully weighed against the inherent properties of the material. Table 1 presents a brief comparative analysis of five materials frequently used in the design and manufacture of industrial equipment, especially in environments requiring strict hygiene and durability, such as food processing industry.

**Table 1.** Comparative analysis of materials for food and industrial processing equipment

Material	Key properties	Typical applications	Cost implications
SS 304	Good corrosion resistance; easy to clean and manufacture	General processing tanks, milk pipelines	Cost-effective option for many applications
SS 316	Superior corrosion resistance to pitting corrosion; high strength and heat resistance	Tanks for acidic/salty products, pharmaceutical equipment, high purity applications	High initial price justified by long-term durability and low maintenance
UHMW	Excellent abrasion and chemical resistance; low coefficient of friction; durable	Conveyor belts, cutting boards and blades	Generally durable and can provide partial longevity
PTFE (Teflon)	Outstanding non-stick properties; heat and chemical resistance	Non-stick coatings for molds/ovens	Excellent performance in high temperature or adhesive applications
Polyurethane (PU)	Flexible, excellent abrasion resistance; resistant to oils	Conveyor belts for tight turns or elevation changes; wet environments	Combines elasticity with strong abrasion resistance

**4 Engineering Design for Reliability (DfR)**

**4.1 Proactive Failure Prevention**

Design for Reliability (DfR) is a systematic and proactive engineering approach that integrates reliability principles into the design process from the beginning. Unlike a reactive model that fixes failures after they occur, DfR aims to predict and mitigate potential problems early in the product life cycle. The goal is to build reliability directly into the product by reducing risk and optimizing performance under real-world conditions.

A common result of poor design decisions, often driven by cost reduction or lack of experience, is the creation of system weaknesses known as “stress concentrations.” These are localized areas of high stress caused by geometric discontinuities such as sharp corners and holes. A seemingly small design flaw not only leads to a single failure, but also creates a predictable point of weakness that is susceptible to premature failure, especially under cyclic loading and fatigue. This creates a direct cause-and-effect chain: poorly designed geometry leads to stress concentrations, which in turn leads to the initiation of fatigue cracks and ultimately premature failure of the component. Analysis of repeated failures often points to these fundamental design flaws.

## 4.2 Mitigating Stress Concentration

The effects of stress concentrations can be reduced through several key design strategies.

**Geometric Optimization.** To distribute stress more evenly and reduce peak values, designs should avoid abrupt changes in geometry and favor gradual, circular transitions. For example, using a circular shape for a hole is a superior design choice over a diamond shape because it reduces peak stress and reduces material waste.

**Material Selection.** Choosing materials with high fracture toughness and fatigue resistance can help components withstand localized stress more effectively.

**Simulation and Analysis.** Modern engineering tools such as Finite Element Analysis (FEA) are essential for simulating the stress distribution within a component and identifying potential weaknesses before physical prototypes are built. This allows designers to make important changes at CAD stage to improve reliability and avoid costly physical testing later in development process.

## 4.3 Lubrication and Wear Management

Lubrication is fundamental to maintenance, necessary to reduce friction and wear on moving parts and prevent premature failure. Lack of proper lubrication is one of the main causes of equipment failure. However, in the food industry, lubrication is not just a mechanical task, but a critical issue of food safety and regulatory compliance. The need for food-safe lubricants means that standard approaches are not suitable. In addition, improperly applied lubricants can attract dirt and debris, which can be a source of contamination risk in food production environments. This unique challenge means that the solution to mechanical wear must also comply with specific, stringent food safety regulations. This added complexity highlights the need for specialized knowledge and materials in this sector.

## 5 Proactive Maintenance Strategies

### 5.1 Moving from Reactive to Proactive Maintenance

Historically, maintenance in many industries has been a reactive practice, with repairs being initiated only after an unexpected failure occurs [10]. This model is inherently inefficient, leading to costly downtime, wasted resources, and the potential for complete production shutdowns. Today, the industry is increasingly moving toward proactive, planned maintenance strategies that aim to anticipate and prevent potential failures before they occur.

### 5.2 Preventive Maintenance (PM): Foundational Approach

PM is a basic proactive strategy that involves series of regular, planned activities to maintain equipment and ensure production continuity. Implementing a systematic PM program requires multi-step process:

1. Asset inventory: Conduct a comprehensive inventory of all equipment and assets to create a clear roadmap for maintenance plan.
2. Criticality and risk assessment: Involves prioritizing equipment based on its criticality to production, food safety, and occupational hazards.
3. Identify failure modes: Using maintenance records and operator experience to identify specific failure modes that are likely to occur.
4. Schedule tasks and schedules: This involves developing a schedule of maintenance tasks, such as cleaning, lubrication, and inspections, that directly address the identified failure modes.

Key PM program activities include regular cleaning to prevent the buildup of debris that can cause corrosion on parts or cause mechanical problems, as well as regular inspections to check for wear and tear, loose parts, and also misalignments.

### 5.3 Predictive Maintenance (PdM): A data-driven evolution

The main challenge for implementing PdM in confectionery machines is the fundamental conflict between the adoption of new technology and the adherence to strict food hygiene regulations.

#### 1) Hygiene risk:

PdM sensors (for monitoring vibration, temperature, etc.) often require drilling holes or creating mounting points in the equipment [11]. These spots can create hidden gaps or crevices (called “hygienic dead spaces”). Since confectionery machines are often cleaned with high-pressure water and strong chemicals, these small gaps are difficult to clean properly and become potential spots for microbial contamination. This means that PdM technology itself can compromise food safety.

#### 2) Data reliability

Confectionery products such as chocolate or caramel are naturally viscous and temperature-sensitive [12]. Small, normal changes in the product (e.g. a slight thickening

of the batch or a change in flow rate) can cause false alarms in sensor data. Artificial intelligence can struggle to distinguish this common process noise from signs of real, impending machine failure.

3) Cost and benefit (low ROI on unique assets):

Many specialized confectionery machines (low-volume assets) require expensive, custom-designed, sanitary-grade sensors to ensure compliance. The high initial cost of this specialized equipment and effort to create customized predictive models often mean that the investment does not provide a sufficient Return on Investment (ROI) compared to standard factory machines.

#### 5.4 Root Cause Analysis (RCA): Learning from Failure

RCA is formal process for investigating a disruption or problem by tracing it back to the source with the goal of treating the underlying cause, not just the symptoms [13]. RCA is a powerful tool for preventing recurring problems and saving time (and also resources) spent on repetitive "symptomatic" fixes.

The RCA process involves several steps:

1. Defining the problem: This involves clearly and objectively stating the problem, moving beyond uncertain descriptions to specific, measurable statements.

2. Collecting data: Gathering information from various sources, including equipment records, production schedules, work orders, and direct billing from operators.

3. Identifying possible causes: At this stage, all potential contributing factors are considered, including human error, equipment problems, and environmental impacts.

4. Analyzing the root cause: This is about using tools like "5 Whys" and the "Fish-bone diagram" to move from symptoms to the real, root cause.

5. Developing and implementation solutions: This final stage involves creating corrective and preventive action plans, ensuring their implementation and monitoring.

RCA is not stand-alone process, but critical feedback mechanism for the entire maintenance program. The insights gained from RCA are valuable to both the PM and the PdM strategies, creating the closed-loop system of continuous improvement. For example, root cause analysis may reveal that a particular bearing is failing untimely due to stress and lack of proper lubrication. This insight can then be used to update PM schedule for that bearing to more frequent interval or configure the PdM system to monitor more closely, thus making entire system smarter and more resilient to future failures.

## 6 Conclusion

Mechanical failure in confectionery machinery is systemic problem, not a component-level one. Failures are predictable consequences of weaknesses built into the design phase, intensified by harsh and corrosive environments, and accelerated by inadequate maintenance practices. A reactive approach that only addresses the symptoms of failure is not financially and operationally sustainable in a high-volume, continuous production environment. The path to long-term reliability and operational excellence requires a

holistic, integrated approach that considers materials, design, also maintenance as interrelated and interdependent factors. Furthermore, future research could focus on the effective application of PdM-based maintenance methods for confectionery machinery.

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