



**5<sup>th</sup> International Conference of the International  
Commission of Agricultural and Biosystems Engineering  
(CIGR)**



Hosted by the Canadian Society for Bioengineering (CSBE/SCGAB)  
Virtually from Québec City, Canada – May 11-14, 2021

**CONCEPTUAL DESIGN OF COMPUTER-VISION BASED PLASTIC REMOVAL SYSTEM ON  
BEEF PRODUCTION LINES**

BERLAN, ANNE-CECILE<sup>1</sup>, CASTRO CHIARAVALLE, MATTHEW<sup>2</sup>, NIEMIEC, SEMARA,<sup>3</sup> SHU,  
XUHAN<sup>4</sup>, ANNAMALAI, MANICKAVASAGAN<sup>5</sup>, SUDARSAN, APARAJHITHA<sup>6</sup>, FOUNTAIN,  
JACQUELINE<sup>7</sup>

<sup>1</sup> Anne-Cecile Berlan, aberlan@uoguelph.ca

<sup>2</sup> Matthew Castro Chiaravalle

<sup>3</sup> Semara Niemiec

<sup>4</sup> Xuhan Shu

<sup>5</sup> Manickavasagan Annamalai

<sup>6</sup> Aparajhitha Sudarsan

<sup>7</sup> Jacqueline Fountain

**CSBE21310 - 5<sup>th</sup> International Conference of the International Commission of  
Agricultural and Biosystems Engineering (CIGR)**

**ABSTRACT** Plastic foreign bodies are common occurrence in the processing of beef products. Unidentified plastics might lead to severe food wastages, health hazards to consumers, food recalls or even larger product liability claims. Therefore, these plastics must be identified and removed at the early stages itself such as slaughter and butchery. The most common sources of plastic in the primary processing stage include nitrile gloves, vacuum seal bags, conveyer pieces and pins from carcass ID tags. In general, plastics are challenging to detect due to their varying densities, sizes and chemical compositions.

In this project, a conceptual design for computer vision based plastic removal system has been developed to identify and remove from the meat processing line. The detection mechanism consists of a vibrating conveyer belt, six RGB cameras, transparent conveyer belt and artificial intelligence-based detection algorithm. The removal mechanism contains an automated retractable conveyer and robotic arm to remove plastics of different sizes when signaled by the detection system.

The position of the RGB cameras has been arranged in such a way that the scans capture even micro size plastics at any location on the conveyer system. Plastics with surface areas smaller than 100cm<sup>2</sup> will trigger a retracting conveyer belt, allowing the affected meat to divert onto a reject line for manual inspection. Plastics with surface areas greater than 100cm<sup>2</sup> will signal a robotic arm for pick and place removal of the contaminant for immediate removal.

Given that the sorting arm technology has not been experimentally determined to be effective in removing small pieces of plastic from moist surfaces, the sorting arm will be utilized on pieces of plastic that are larger than 100cm<sup>2</sup>. This makes it possible for larger plastics, such as whole gloves, to be removed safely and effectively without deferring the removal for later manual inspection. This automated plastic detection and removal system is only a conceptual design and has yet to be evaluated in a beef processing plant setting.

**Keywords:** beef production, computer vision, RGB camera, quality control, plastic, contamination, automation

**INTRODUCTION** The meat industry is growing rapidly all over the world as the nutrition it provides offers a lot of benefits to the human body. Beef in particular is rich in protein, iron, zinc and selenium, which contribute to the production of hemoglobin, muscle growth and exercise performance. Beef production should be conducted in a careful, meticulous and efficient manner in order to ensure a final product that is free of health and safety hazards such as (a) chemical hazards, such as mycotoxins; (b) biological hazards, such as pathogens, viruses and bacteria; and (c) physical hazards, including glass, plastic and metal pieces. Foreign matter control programs from government agencies and individual companies aid in controlling conditions that pose risks of food product contamination, however they are not without flaw. The presence of these contaminants may cause harm to the consumer, leading to serious illness, injury or death. The latter consequence was observed in July 2013 when at least 23 students in the Saran district of India died as a result of eating a school meal contaminated with pesticide (Idrovo, 2014). More recently, in 2016, Mars Chocolates recalled chocolate bars and other products in 55 countries due to the discovery of plastic pieces in the final products (Reuters, 2016).

In regard to physical hazards, common contaminants include hair, plastic, metal and insects. Many of these foreign contaminants appear in facilities due to poor hygiene control, low security measures, jewelry worn by production employees and packaging (Aguiar, et al., 2018). These foreign materials are able to be detected by capacitive sensors, such as X-rays, capacitive sensors and metal detectors; this is common practice in large-scale food manufacturing facilities (Martini, Suzuki, & Hartel, 2008). Plastic, on the other hand, is much more difficult to detect and companies often rely on visual inspection by quality control staff to detect it. The human eye, however, is unreliable because of a combination of factors; experience of the inspector, accessibility of critical areas, time allocated to perform inspection activity and unreliability. Another common detection method is mechanical in nature, involving the use of mechanical sieving. This option proves to be non-viable regarding beef production due to the soft nature of the organic tissue. Given the rising demand of beef products, the integration of an automated quality control mechanism to detect and remove plastics in beef products is imperative to maximize food safety while meeting the world's nutrition needs.

**PROBLEM DESCRIPTION** Plastic foreign bodies are a high risk and common occurrence in the production of beef products. It must be detected in the primary stage of meat processing, which consists of slaughter and butchery, as detection in later stages can lead to food waste, large product liability claims, recalls and danger to the consumer. The most common sources of plastic in the primary processing stage include nitrile gloves, sample bags, plastic sleeves, liner bags, vacuum seal bags, conveyer pieces and pins from carcass ID tags. Some of these contaminants are due to malfunctioning of the product line while others are a result of human error and negligence during butchery, sampling, bagging and sorting. In fact, one case study conducted on the occurrences of indigestible foreign bodies in beef discovered that plastic was the most observed physical contaminant at 50.5% (Bwatota, Makungu, & Nonga, 2018). One of the biggest challenges with plastic contamination is that once it occurs, it is very difficult to find. Beef processing plants with inline metal detector units are not able to detect it unless it is mixed with metal. By the same token, conventional X-ray systems cannot adequately detect plastic due to its low relative density. In this project, our team will design an automated, integrated quality control mechanism for the detection and removal of plastic foreign bodies in a beef processing setting.

Beef trimmings, also commonly referred to as trim, is the industry term for pieces of meat remaining after primal cuts such as steaks, roasts and ribs are removed (Ferrier & Buzby, 2012). Trim is the main component in ground beef that is sold as-is or in burgers, sausages and meatballs (Ferrier & Buzby, 2012). It is collected from the portions of the carcass not further processed as whole cuts during butchery, often from the fat cover near the hide (Ferrier & Buzby, 2012). This process is shown in Figure 1. Following the butchery process, leftover trim is collected on a separate conveyer belt, where it is sorted into different combo bins based on fat content and type. Trim from several animals of the same quality grade is collected in combo bins, typically weighing 1 metric ton when filled (Ferrier & Buzby, 2012). A combo is shown in Figures 2, 3 and 4. Following the manual sorting of trim, combos are brought over to quality control staff where samples are collected using the N60 collection method, a current mandated HACCP testing protocol where 60 samples weighing a total of 375g are used to “clear” a lot of beef trim of E.Coli contamination subsequent to laboratory testing (Ferrier & Buzby, 2012). During N60 sampling, excision sampling is conducted using various tools such as scalpels, bone saws, electric knives or other sanitized knives, as seen in Figure 3. Thin slices of trim are collected into plastic sample bags for every combo in a lot. After sampling, trim is then grinded and blended into ground beef products.



Figure 1. Workers employed at Cargill beef processing plant cut excess fat and meat off primal cuts (i.e. ribs, tenderloin, etc.) in order to fit specification. The leftover trim is gathered on a separate conveyer belt. Employees wear plastic sleeves and gloves in order to minimize



Figure 2. Image of a corrugated cardboard combo bin, typically weighing 1 metric ton when full. Combos can also be solid metal or plastic.



Figure 3. Employee using scalpel for N60 sampling



Figure 4. Combo filled with trim, particularly smaller pieces and 65% lean

Issues arise when plastic pieces in beef trim destined for a ground beef final product make their way into the grinder. When this occurs, the grinder either automatically shuts off or the operator shuts it off for inspection. Any beef in the grinding batch contaminated with plastic must be discarded as there is no way to guarantee that all pieces of plastic have been removed. This results in big profit losses, time wasted and large quantities of food waste. For perspective, if ground beef retails for \$11/kg, a wasted 1 metric ton combo contaminated with plastic could cost the company \$11,000 CAD in profit.

Sources of plastic contamination along the production line include lost or sliced nitril gloves, plastic sleeves or plastic aprons during the butchery of primal cuts as seen in Figures 1, 3 and 5A. Another common source of plastic contamination arises during the N60 sampling procedure, as it is common to accidentally slice off a piece of nitril glove, sampling bag or plastic combo liner, as depicted in Figure 3. Moreover, plastic bags used for vacuum sealing of primal cuts also wind up on the trim conveyer. Examples of plastic sample bags used for the sampling of every trim combo are shown in Figure 5B and 5C. Carcass ID pins, which are used to secure a piece of paper with a carcass' weight, grade and variety information, are attached to every carcass and are to be removed before butchery. Due to human and machine error, carcass ID pins are either forgotten to be removed or misplaced and wind up in trim combos, resulting in another source of plastic contamination. A plastic carcass ID pin is visible in Figure 5D. Another source of plastic contamination are conveyer belt pieces that break off of the conveyer due to wear, damage or other factors. Similar to the carcass ID pins, conveyer belt pieces are composed of a denser, harder plastic and can be observed intact in Figure 5E.

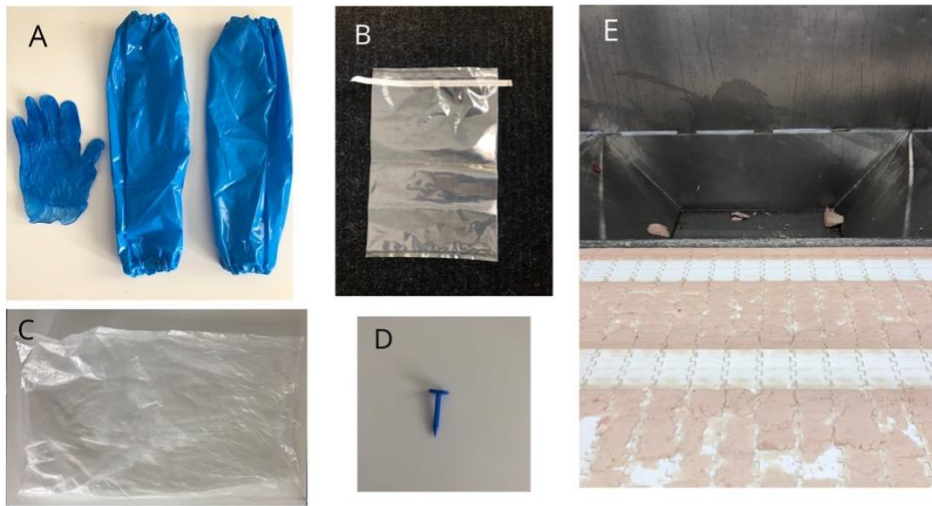


Figure 5. Common plastic contaminants in beef processing plants; A. Nitril gloves and plastic sleeves; B. Sealable sample bag; C. Sample bag; D. Carcass ID pin E. Conveyer belt for beef

## LITERATURE REVIEW

**Foreign Material Contamination Risk: Physical Contaminants** Any occurrence of foreign material in a product can harm the consumer, undermine confidence in the product and create negative brand publicity. Contamination during food processing is classified into three areas: biological, chemical, and physical (Burd, 2007). This project is focused only on plastic as a physical contaminant. A physical contaminant is dangerous if it is sharp, rough, or capable of creating a choking hazard. From the viewpoint of quality assurance, however, any foreign material introduced during the production process must be removed (Burd, 2007).

Process controls in the food industry are critical. The presence of physical contaminants in products would initiate a food recall. Such an event would bring on higher expenses but also hurt the brand value of a food processor. On January 28, 2020 Chicago-based food manufacturing giant Amity Packaging Company Inc. reported that they were voluntarily recalling at least 2,020 pounds of raw ground beef products over the presence of clear plastic says the U.S Department of Agriculture's Food Safety and Inspection Service (FSIS) (Gold, 2020). While this isn't the first time that raw ground beef has been recalled due to plastic being identified, it's not unusual. In November 2019, the USDA FSIS recalled approximately 130,000 pounds of raw ground beef products from Rick Rastelli Foods Group due to potential foreign matter contamination (Lee, 2020). After that, the USDA released another food recall the following month. Around that time, it was discovered that Advance Pierre Foods had shipped approximately 15,739 pounds of their ready-to-eat beef patty items, which included thin, green, soft plastic (Lee, 2020).

**RGB/Colour Imaging** Machine vision via colour detection has been previously explored for aspects of food processing including sorting, quality control and defect identification due to its ease of image analysis and low cost (Teena, Manickavasagan, Al-Sadi, Al-Yahyai,

& Deadman, 2016). This non-destructive imaging technique has been used to identify evident flaws in food products, such as size and shape of dates to certain quality defects such as bruises and flabbiness (Al-Rahbi, Manickavasagan, Al-Yahyai, Khrijji, & Alahakoon, 2013). In one study examining the range of capability for RGB quality control purposes, dates were categorized based on their skin delamination, where different levels of moisture produce a gradient in colour (Guo, Zhang, Lee, & Simons, 2020). Using a Cameleon-3 USB colour camera, Nvidia TX1 module (where complex computing, user interface and file system are housed) and Arduino microcontroller encased in a IP-64 enclosure, skin delamination was able to be determined with an average accuracy of 95% (Guo, Zhang, Lee, & Simons, 2020). This surpassed the average human grader's accuracy via visual inspection of 75%~85% (Guo, Zhang, Lee, & Simons, 2020). Of particular interest in this study is the usage of a simple, easy to configure and fast visual inspection algorithm called evolutionary constructed features (ECO-Feature) algorithm (Guo, Zhang, Lee, & Simons, 2020). Differing from sophisticated and powerful machine learning techniques such as convolutional neural networks (CNN) and K-nearest neighbor (KNN), the ECO-Feature algorithm is simpler, doesn't necessitate extensive training for configuration and is easier to change the algorithm to tailor to varying products (Guo, Zhang, Lee, & Simons, 2020). The ECO-Feature algorithm in this article is based off of a more simple one developed for binary decisions for object detection; the updated one uses an evolutionary learning method to achieve multi-class image classification and is capable of handling minor image distortions and geometric transformations well (Guo, Zhang, Lee, & Simons, 2020). Other software features that contributed to a user-friendly experience allowing the user to easily configure the camera settings, saving settings for future use, loading trained models, receiving signals from the conveyer belt, classifying objects as they pass the camera and allowing the user to calibrate the sorting outputs (Guo, Zhang, Lee, & Simons, 2020).

The ability to identify foreign plastic contamination in beef trim may avoid the waste of an entire lot in a simple, cost-effective and accurate manner. When using RGB detection, necessary equipment includes a camera, a lighting mechanism, image or remote shooting software and a monitor. Generally, colour imaging is a low-cost and simplistic process monitoring method. The colour of the contaminant is an important consideration in regard to foreign matter detection as it enables the use of camera technology and is used to establish a reference colour network for detection. Common plastic contaminants in beef processing are either clear, white or blue, as depicted in Figure 4. This creates a strong contrast when present on the surface of beef pieces, generally of a dark or bright red colouring. This is an optimal scenario as the evidently contrasting colours should produce accurate detection.

**Effect of Meat Colouring and Texture** The colour and appearance of meat is influenced by many factors and is a critical parameter when assessing any form of contamination. The final appearance varies by differing species, breeds, and handling before and after slaughter (Trinderup, 2015). The prominent red colour in beef products is dependent on the myoglobin present, so a darker purplish-red meat contains the most myoglobin, whereas a bright red meat contains its oxidized state, oxymyoglobin, and a brown meat contains an even more oxidized state, metmyoglobin (Trinderup, 2015). Since the colour

of meat depends on the myoglobin and oxidative states, it will also influence the absorption and scattering properties of meat seen in the image analysis stage. The surface of the meat sample contains the most oxygen and thus containing the most oxymyoglobin (around 5 mm), whereas the area underneath the surface contains the least oxygen and thus myoglobin itself will be present (Trinderup, 2015). RGB technology uses light that can scatter deep into the meat sample, penetrating through the initial 5 mm and reflecting light from the darker myoglobin layers. Myoglobin found on meat samples reflect rays at wavelengths corresponding to yellow or red light (ranging from 570-700 nm), and absorbs rays corresponding to green light (around 510 nm) (Trinderup, 2015).

Texture can also be characterized based on speckle size and patterns. Speckle patterns can be seen when the surface is rough at the scale of the wavelength of the illumination. The resulting images contain a granular-like pattern that can be used to characterize physical properties of the meat sample, depending on the average speckle size (Trinderup, 2015).

**Plastic Removal Methods** In the event of plastic contamination, the four proposed removal methods are stopping the conveyor belt, implementing a push-on-detect system, implementing a robotic sorting system or using the existing retractable conveyor belt ejection system.

With respect to the first alternative, when the conveyor belt is stopped, an employee within the proximity would ensure the removal of the plastic and restart the conveyor belt. The advantage of stopping the line would be that no detected plastic would be moving further towards the combo bins. Also, the plastic would be removed every time by the employee without the removal of the product or having to inspect ejected pieces once production is over. The disadvantages include slower production efficiency and the requirement of a paid employee to sort through the rejected product as opposed to a fully automated solution.

With respect to the second alternative, a push-on-detect system would be placed alongside the conveyor belt and connected to the selected detection method. Similar to common contamination removal mechanisms, once plastic is detected the section remover would be triggered by the detection method to push the contents within a 40 cm range off the conveyor belt into a collection bin (Conveying With Metal Detection, 2010). The advantage would be increased process efficiency through automated removal, particularly without the need of a paid employee's efforts. Also, all plastic would be removed whether it is on the surface, between pieces of meat or under the meat. The disadvantage of this alternative is both the product and plastic are removed, requiring manual sorting of the collection bin. There is also a risk that when the push-on-detect mechanism is used for plastic found under pieces of meat, the pusher may push the meat off the conveyor but leave behind the plastic due to adherence to the conveyor belt as a result of fatty buildup throughout production. Quantifying this risk would require in-situ experimentation as literature citing this occurrence was not found.

With respect to the third alternative, a robotic sorting arm would be placed alongside the conveyer belt and connected to the detection method. The detection method would signal and activate the robot arm to locate and remove the plastic (Stier, 2020). The robotic arm can be programmed to remove the plastic through colour variation to eliminate defects and contaminants (Stier, 2020). The advantages of this alternative include increased process efficiency through automated removal as well as the removal of plastic on its own (Stier, 2020). However, the robotic sorter is limited to the removal of surface visible plastic. Meaning if plastic is located under the product, it will not be able to locate it; this is unless the arm is also capable of removing the obstructing meat to access the plastic. Also, a robotic sorter has a high initial capital requirement and more complex maintenance and calibration requirements than previously cited methods.

The last removal option for the removal of plastic contaminants in beef is to use the existing retracting conveyer belt paired with the Mettler Toledo metal detector conveyer system (Mettler Toledo, 2020). In this already existing quality control point, the conveyer belt further up from the conveyer belt retracts when metal is detected, dropping its contents along with the metal onto a lower conveyer belt where it ends up in a collection bin for later inspection. If implemented, this ejection would also extend to plastic-contaminated product. A disadvantage of this removal method is the need for a paid employee to sort through rejected product once production is complete.

**Image Processing** A computer vision system, in general, senses the colour of an object at each pixel using three colour sensors (or one sensor with three alternate filters). The RGB model is the standard colour model, which collects information in the red (R), green (G) or blue (B) range, respectively (Di Wu, 2013). However, the RGB model varies from the Commission Internationale de l'éclairage (CIE) colour scheme in application characteristics, making correct colours difficult to obtain. sRGB is a device-independent colour model whose tristimulus values (sR, sG, sB) replicate the same colour on different devices and represent linear variations of the CIE colour space (Di Wu, 2013). It is intended for specifying maps between RGB and a device-independent model like CIE XYZ from a compatible rendering system. The rendition depends on the unit, so the parameters for the display systems have varying colour ranges. The sRGB values are often converted into other colour spaces such as  $L^*a^*b^*$  (Di Wu, 2013). The RGB to  $L^*a^*b^*$  conversion cannot be performed explicitly using a regular equation. However, the RGB transformation to  $L^*a^*b^*$  can be carried out using five models, including the gamma, linear, quadratic and neural network for converting the values delivered by the model as similarly as possible to those given by a colourimeter over the homogeneous surfaces (Di Wu, 2013). For the quadratic and neural network model, the best outcomes with low error (close to 1 percent) have been obtained (Di Wu, 2013). While this approach is universal, it should be noted that results derived from it are valid only for one system.

Digital image quality is primarily determined by its reproducibility and accuracy (Sun & Brosnan, 2004). If colour and geometric properties cannot be calculated correctly, any measuring results are ambiguous. To reduce the potential effects of illuminants and camera settings, calibration is necessary prior to creating photo images in food processing (Sun & Brosnan, 2004). There are several ways of describing different colour calibration

algorithms for cameras; the relationship between the input space and the sRGB space being one of these (Sun & Brosnan, 2004). Some applications are available to carry out colour profile assignment based on the system (e.g., ProfileMaker, (Di Wu, 2013), Monaco (Di Wu, 2013)) however, their results are insufficient for technological or scientific use. Consequently, polynomial algorithms, neural networks, and their combinations are needed for colour calibration (Sun & Brosnan, 2004).

**SCOPE AND OBJECTIVES** The scope of this project lies within primary beef processing facilities who do not conduct further processing such as cooking, grinding and smoking; primary operations encompass slaughtering and butchering. More specifically, the plastic detection solution must be installed on the production line somewhere between post-butchery and pre-sampling or post-sampling. The automated removal mechanisms will follow immediately after the detection system.

The objective of this design project is to create an accessible solution to detect and remove plastic contamination during food processing. This will be accomplished by analyzing the current industry standard method of plastic detection and researching current research articles and technological advances to determine the optimal solution. The same will be done for removal technologies.

The target client of the final design will be primary beef production facilities having a high daily processing rate using production lines. Plastic contamination in high volume food processing facilities is inevitable due to equipment malfunctioning, leading to broken conveyer pieces, or human error during butchery, packaging, and sampling. It is important to remove any plastic before it goes into further processing, where it could harm consumers and the company's bottom line. Though there are a lot of current technologies and methods with potential to detect plastic in beef production, the industry standard remains static in its use of optical detection and removal by quality staff. This method leaves a lot of room for error and results in ineffective removal of contaminants.

Our goal is to design a plastic detector using new technologies in order to increase detection efficiency and achieve higher beef quality and safety. The product should meet current food processing equipment standards and regulations, with high accuracy, efficiency, and sensitivity. The device should be easily installed and assembled on the existing production line somewhere along post-butchery and pre-sampling or post-sampling stage. Moreover, a removal mechanism will be implemented to decontaminate beef trim products in an automated manner.

### **Constraints and Criteria**

Detection System Key challenges that are to be considered in the design of a plastic detection system for beef production are: methods of detection, sensitivity, specificity and accuracy of the method, investigation and removal strategies, production line speeds, colour and density of plastic, location of the plastic either under the meat or on the surface and operational temperature (Burd, 2007). Line speed and room temperature

were obtained from a large-scale beef processing facility where a team member is currently employed.

Constraints:

- Must be operational at a line speed 0.43 m/s
- Must be operational at production temperature of 40°F/4.44°C
- Must identify plastic with a thickness as low as 2 mm
- Must adhere to ISO 9001: 2015 standards
- Must adhere to established HACCP system
- Must have an accuracy of 100%
- Must automatically identify plastic contaminants

Criteria:

- Minimize false positives
- Minimize changes to the production line
- Maximize the detectable size, type, colour and density range of the contaminant
- Minimize the time from detection to removal

### Removal System

Constraints:

- Must be operational at a line speed of 0.43 m/s
- Must be operational at production temperature of 40°F/4.44°C
- Must remove plastic with a thickness as low as 2 mm
- Must adhere to ISO 9001: 2015 standards
- Must adhere to established HACCP system
- Must have removal accuracy of 100%

Criteria:

- Minimize changes to the production line
- Minimize removal time
- Maximize automation factor

## **DESIGN INFORMATION**

**Design Approach** The chosen food processing challenge was inspired by a team member's employment experience at a large industrial beef processing plant where the issue of plastic contamination is a common and problematic occurrence. Given the realistic and authentic nature of the problem, a practical, economical and accurate solution is sought out, keeping in mind the typical order of process operations and the environment of the commonplace meat plant. First, a quality assurance manager with 30 years of experience at the beef plant was consulted in order to identify key challenges regarding in either the beef processing or quality control domain. Plastic contamination was selected as the topic

of interest due to its prevalence across the beef industry and its lack of efficient, standardized solutions. After this, background research was conducted using the University of Guelph library website on data regarding its pervasiveness, consequences and current technologies that may potentially resolve the issue. Cost, accuracy, energy consumption and practicality were principal factors in deeming recent technologies suitable for the challenge. A decision matrix with specifically chosen criteria was used to determine the optimal design solution. Following this proposal, a detailed design of the final plastic detection system will be presented along with energy calculations, dimensions, positioning within already existing equipment and other relevant information. Tools and programs such as SolidWorks and Excel were utilized to render calculations and visuals pertaining to the design.

To stay on track, the team holds weekly meetings to discuss progress updates and next steps in the development of the design solution. Communication between the team is frequent and ongoing via instant chat to answer questions quickly and discuss any upcoming deliverables. Microsoft Teams is continuously updated with relevant articles, scheduled meetings, and deliverable due dates in order to remain up to date. Weekly meetings with the Food Processing Design professor are conducted to stay on track and receive advice on designing, optimizing, and reporting on the final design solution. The student employed at a beef processing facility updates the team on process layout, contaminant specifications and typical operation procedures to create the most realistic and practical solution possible.

## **Design Solutions**

### Detection Methods

Dual Energy X-Ray Imaging: Dual-energy imaging has made advancements in product inspection through detection of a wide range of dense foreign bodies. A dual-energy imaging system is an enhanced form of X-ray imaging that can detect materials previously unseen by X-ray or other conventional inspection technologies, such as low-density plastic. Akin to standard X-ray systems, dual-energy imaging projects an X-ray beam through a product and onto a detector (R. Haff, 2008). However, two energy spectrums are used to discriminate between high and low channel X-rays, as well as a dual-layer detector (H. Watabiki, 2013). This system only allows the high-energy X-rays to pass through to the high energy detector and is largely based on the material's chemical composition rather than just density variation like standard X-ray technology. The system produces two images by the two spectra of energy and measures the ratio of X-ray

energies that pass through a food product to differentiate between organic and inorganic materials (H. Watabiki, 2013).

Dual-energy X-ray imaging technology is effective at detecting very small X-ray absorption variations by removing the effect of product thickness, producing an image that shows density difference based on chemical composition. The contaminated material will have a denser contrast in the X-ray image, indicating a removal method is necessary (H. Watabiki, 2013). Therefore, many foreign bodies that are not detected by standard X-ray systems, may be detected with this technology. However, due to the system's high energy, the detection efficiency can be limited by cost considerations (Fu, 2010).

Multi-Modal X-Ray Imaging: New imaging techniques such as phase contrast and dark field contrast have been developed using grating-based interferometry. These X-ray methods have proven to be more effective in diagnostic capability than the traditional X-ray techniques (Einarsdottir, et al., 2016). The grating-based approach allows for the collection of three distinct forms of images simultaneously. The imaging techniques include traditional X-ray, phase contrast and dark field. In the study by Einarsdottir and colleagues, a novel identification scheme is built based on mathematical analysis techniques and image recognition. (Einarsdottir, et al., 2016). First, the algorithm computes texture features of the imaging techniques (Einarsdottir, et al., 2016). Next, a representation of each of the food products is created by fitting a Gaussian mixture model to either the picture intensities alone, or by including the texture features (Einarsdottir, et al., 2016). Images with foreign bodies are analyzed by measuring the Mahalanobis distance to the food models using all image pixels (Einarsdottir, et al., 2016). Optimal threshold values for foreign objects are then used to optimize identification and eliminate false positives (Einarsdottir, et al., 2016). To assess if the benefit of using grating-based imaging is greater than that of traditional absorption radiography, the rates of foreign objects detected versus false positives were compared. This was achieved by examining both pixel-wise and on an object count basis. The findings from both pixel-wise and object-based research highlight the benefits of using the grating-based X-ray technique over conventional absorption X-ray (Einarsdottir, et al., 2016). To improve the feasibility of the X-ray grating technique for line inspection of items, some obstacles need to be overcome. The technique only produces a limited field of view because of the gratings utilized to scan it (Einarsdottir, et al., 2016). Additionally, when rump steak was subjected to multi-modal X-rays, hard plastics of sizes 3mm and 2mm had 7.6% and 3.2% respective detection accuracies (Einarsdottir, et al., 2016). This indicates that for a meat-specific application this detection method yields inadequate results (Einarsdottir, et al., 2016). Moreover, X-rays are costly in capital cost and operation. In addition, methods for scanning conveyor belts should be developed which will allow for improved image acquisition at high speeds (Einarsdottir, et al., 2016). Here several attempts have been made (Kottler, Pfeiffer, Bunk, Grünzweig, & David, 2007) (Momose, Yashiro, Maikusa, & Takeda, 2009).

RGB Camera: The advantages of an RGB camera are similar to those of SWIR and NIR imaging in that they are non-destructive, cost-efficient and easy to install. RGB cameras are also incapable of penetrating surfaces. However, they are already an industry-standard technology used for other aspects of quality control such as colour inspection, colour sorting and colour matching in applications ranging from food processing to cosmetics production (JAI, 2020).

### Detection Method Determination

Table 1. Decision matrix for selecting between different types of physical contaminant detection systems, with 5 being highest weighted or most important, and 1 being lowest weight or least important parameter. Each alternative is ranked with respect to the design criteria from 1 to 4, with 1 being the lowest and 4 the highest.

Design Criteria	Weight	RGB Camera	X-Ray Detection	Thermal Detection	Hyperspectral Imaging
Scalability	4	$4 \times 4 = 16$	$4 \times 1 = 4$	$4 \times 2 = 8$	$4 \times 2 = 8$
Cost	2	$2 \times 4 = 8$	$2 \times 1 = 2$	$2 \times 4 = 8$	$2 \times 3 = 6$
Operational and Maintenance Feasibility	2	$2 \times 4 = 8$	$2 \times 2 = 4$	$2 \times 3 = 6$	$2 \times 2 = 4$
Efficiency of Detection	4	$4 \times 3 = 12$	$4 \times 1 = 4$	$4 \times 1 = 4$	$4 \times 3 = 12$
Energy Consumption	1	$1 \times 4 = 4$	$1 \times 1 = 1$	$1 \times 4 = 4$	$1 \times 3 = 3$
Least Disruptive to Current Process	3	$3 \times 2 = 6$	$3 \times 1 = 3$	$3 \times 2 = 6$	$3 \times 2 = 6$
	5	$5 \times 3 = 15$	$5 \times 4 = 20$	$5 \times 1 = 5$	$5 \times 2 = 10$

Accuracy of Detection					
Detection Penetration	2	$2 \times 1 = 2$	$2 \times 4 = 8$	$2 \times 2 = 4$	$2 \times 3 = 6$
Total		71	46	45	55

The scalability of the detection systems is a highly important consideration, as it must remain effective in the fast paced, high volume environment of an industrial beef processing facility. Some technologies may only be efficacious in detecting contaminants in very small batches, rendering the process highly impractical. The detection system to be implemented must be able to provide accurate results when scanning and removing plastic from 500,000 pounds of trim per day. A low cost of the detection system is another important factor in increasing accessibility and potential implementation by beef processing entities. The operational and maintenance feasibility of a detection system refers to its ease of use and the learning curve associated with the technology. It may be more appealing and cheaper for a company to implement a detection system able to be used by an employee with no post-secondary education as opposed to hiring a full-time engineer or biotechnologist to operate the technology. Efficacy of detection refers to the system's ability to detect the foreign contaminant of concern in this circumstance, which consists mainly of thin-film plastic. The disruption that the implementation of the detection system causes is another design consideration. A lengthy installation time or physically large machinery associated with the system may result in long down-times, lost profits and the modification of the existing process layout on the production floor. Lastly, the chosen detection system must be accurate and minimize false negatives to ensure uncompromised food safety for consumers.

Due to the complex amalgam and exigency of the design criteria, it was concluded that additional design features would be necessary to ensure accuracy and reliability. RGB camera technology was chosen as the optimal plastic detection method, primarily due to its ease of installation, use, surface detection accuracy, low cost and ability to efficiently use multiple cameras. This detection method, however, does not allow for detection of plastics under and between pieces of meat on the conveyer. Therefore, additional design features are to be paired with the RGB cameras in order to ensure total vision for accurate detection. One such feature is the implementation of a transparent conveyer belt at the location where plastic detection will be taking place. More precisely, a fluoroscopic-capable, transparent conveyer with low thickness will be required. Another added design element is a food processing shaker, such as a vibratory in-feed shaker, which would be placed prior to the RGB cameras. The purpose of the vibratory conveyer would be to separate pieces of meat that are stuck to each other while having secondary purpose of dewatering the antimicrobial agent sprayed on the meat and distributing the product flow as it enters the frame of the cameras. Separating joint meat pieces is crucial to ensuring a

clear line of site from the camera lens to plastic contamination that may be located between pieces. Its strategic placement subsequent to the existing metal detector would have the added benefit of separating joined pieces prior to passing through the metal detector to allow for improved metal detection conditions. The third design feature would be the addition of an RGB camera underneath the conveyor belt in order to detect pieces of plastic located underneath pieces of meat. The plastic detection system will be located between the existing metal detector and the final trim sorting line. A transparent conveyor belt is necessary at the RGB camera stage in order to view pieces of meat from the underside of the conveyor belt. It is imperative to factor in the existing capacity requirements in regard to how much trim is produced per day as the selected pieces of equipment must be able to sustain 12 hour run times while processing 500,000lb of trim per day, around 41,700lbs per hour (18.9 tonnes per hour).

Removal Methods Although simple in design and low in capital requirement, the method of stopping the conveyor belt upon detection of plastic poses many challenges. Stopping a mainline conveyor belt multiple times per hour during production will lead to delays in production, incurred overtime wages and scheduling difficulties. The push-on-detect removal technology boasts a higher automation factor which would negate any production delays, however given its high capital cost and the uncertainty surrounding its ability to remove plastic adhered to the conveyor belt, it may not be the most suitable solution to contaminants removal in this context. The existing ejection system linked to the metal detector combines the advantage of automation to prevent line stoppage while ensuring the complete removal plastic contaminants, even those located under pieces of meat, through the use of an already installed retracting conveyor belt mechanism. The principal detraction factor of utilizing the retracting conveyor is that the plastic-contaminated trim pieces that are separated onto the separate belt must be sorted through manually at a later time, requiring the use of a paid employee. To mitigate this occurrence and further increase the automation component of the system, a robotic sorting arm will be used for larger pieces of plastic that are easy to capture. Given that the sorting arm technology has not been experimentally determined to be effective in removing small pieces of plastic from moist surfaces such as meat, especially in a scenario where rapid displacement on a conveyor belt is involved, the sorting arm will be utilized on pieces of plastic that are larger (surface area >100cm<sup>2</sup>). This makes it possible for larger plastics, such as whole gloves or vacuum seal bags, to be removed safely and effectively without deferring the removal for later manual inspection. This also creates an opportunity for increased process automation in the future as advances in calibration, software and robot dynamics down the line may allow for the removal system to be executed completely by the robotic arm. The combination of the exiting retracting conveyor belt and a robotic sorting arm has thus been chosen as the final plastic removal system.

Table 2. Decision matrix for selecting between different types of removal methods, with 5 being highest weighted or most important, and 1 being lowest weight or least important parameter. Each alternative is ranked with respect to the design criteria from 1 to 4, with 1 being the worst and 4 the best.

Design Criteria	Weight	Stopping Conveyor Belt	Push-On-Detect	Retracting Conveyor Belt	Robotic Arm
Cost	1	1 x 4 = 6	1 x 2 = 9	3 x 3 = 9	1 x 1 = 3
Minimal Operational Requirement	4	4 x 1 = 2	4 x 2 = 8	4 x 4 = 16	4 x 3 = 12
Efficiency of Removal	4	4 x 1 = 4	4 x 2 = 8	4 x 3 = 12	4 x 4 = 16
Least Disruptive to Current Process	3	3 x 4 = 12	3 x 1 = 3	3 x 3 = 9	3 x 1 = 3
Accuracy of Removal	5	5 x 2 = 10	5 x 1 = 5	5 x 4 = 20	5 x 3 = 15
<b>Total</b>		<b>34</b>	<b>33</b>	<b>66</b>	<b>49</b>

### Detailed Final Design

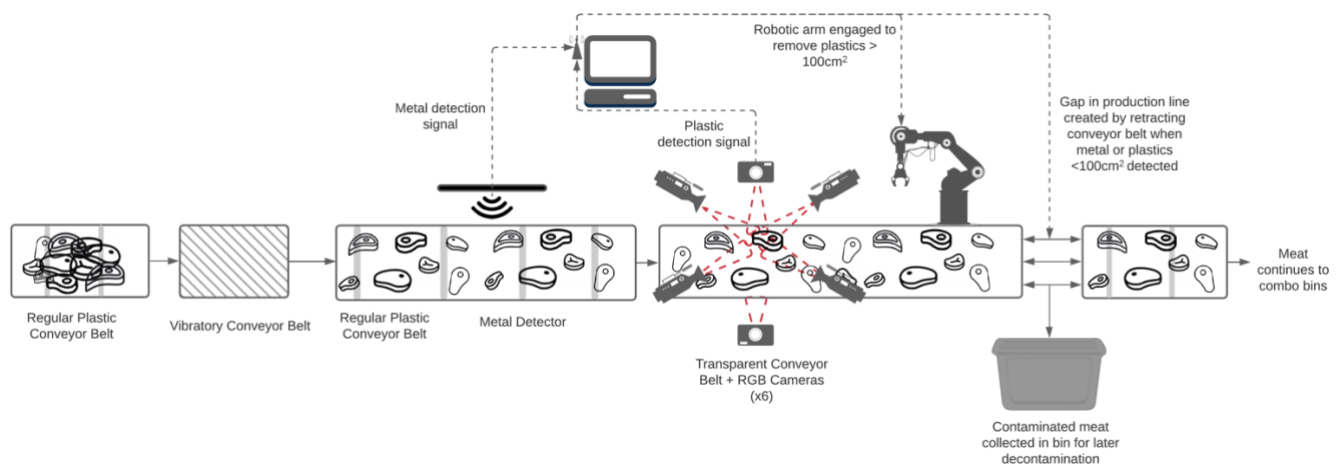


Figure 6. Plastic detection and removal from beef trim process

Vibratory Conveyor Belt Parameters The first element of the detection system is a food-grade vibratory conveyor belt. This kind of conveyor belt consists of a flat-bottomed metal bed which would be used to transport the bulk trim pieces through controlled vibrations at a relatively high frequency and low amplitude (Obi-Njoku, 2012). Having the dual purpose of separating and dewatering in this application, the vibratory conveyor belt is generally cleaner and more reliable than most other conveyor belt types (Obi-Njoku, 2012). A stainless-steel construction is essential to achieve sanitation and durability requirements. The vibratory conveyor belt would measure 15 ft. long, spanning the space prior to the metal detector and before the transparent conveyor belt, and be 2ft. wide in keeping with the existing conveyor belt width. Given that it must be capable of conveying 18.9 tonnes of trim per hour, the selected model must be highly durable while also resisting bacterial growth via hygienic surface finish (Obi-Njoku, 2012). A vibratory conveyor from the Key Technology company was selected due to their prevalent applications in the food processing industry, customization capabilities and low total cost of ownership (Key Technology, 2020). A vibratory belt shaker with high amplitude, low frequency motion boasting the ability to distribute products along a production line will cost an estimated \$20,000 given the required dimensions (Key Technology, 2020).

RGB Camera Type and Positioning Two different types of RGB cameras are to be implemented in the design of the detection system – high-speed video cameras and line scan cameras. Four high-speed video cameras designed for industrial monitoring of production lines are to be placed at 90° angles from each other, 45° angles from production line facing towards the trim on the transparent conveyor belt to detect plastic contamination. The Fastec IL3-S model by ClaraVision was selected for this application as it is specifically aimed at industries that run production lines in the food processing industry and enables diagnostic capabilities that help in understanding anomalies and defects in a production line (ClaraVision, 2021). The cameras come with a pre-installed software on a touchscreen tablet allowing for a simple user experience and is also capable of handling speeds ranging from 225 fps to 2500 fps (ClaraVision, 2021). The JAI Sweep Series SW-4000TL-10GE model was selected for line scan purposes due to its notable colour line scan performance in addition to being one of the fastest line scan cameras on the market; there are two of these in the detection system, located above and below the transparent conveyor belt (JAI, 2020). It features built-in colour space conversions to multiple standard colour gamuts, such as HIS and sRGB, while also allowing for custom RGB colour gamuts (JAI, 2020). The line scan camera also allows for encoder signals to be daisy-chained from one camera to another in multi-camera set ups while offering a maximum line rate of 99kHz (66,000 lines per second) (JAI, 2020).

Image Pre-Processing Both line scan and area scan cameras will be connected to the switching hub (NETGEAR GS308PP) via an Industrial ROBOT CAT6 Ethernet-Cable with RJ45 horizontal connection. To control and configure both line scan cameras, the eBUS for JAI software will be installed on the compact vision system (NI CVS-1458RT) (JAI, 2019). To control and configure the four area scan cameras, the FasMotion software will be installed

on the compact vision system (Fastec Imaging Corporation, 2017). To optimize the image quality, configuration of their basic function will be done in the following order:

- Configuring the line rate to match the scanning speed of the camera to the feeding speed of the object (JAI, 2019) (Fastec Imaging Corporation, 2017);
- Configuring the exposure time to start when the line starts and stop when the line stops (JAI, 2019) (Fastec Imaging Corporation, 2017);
- Performing dark signal non-uniformity/pixel black correction (DSNU) (DSNU is the variation between pixels in the dark areas generated by the sensor (JAI, 2019) (Fastec Imaging Corporation, 2017));
- Performing photo response non-uniformity/pixel gain correction (PRNU) (PRNU is the variation between pixels generated by the sensor under bright conditions) (JAI, 2019) (Fastec Imaging Corporation, 2017);
- Adjusting the black level/brightness;
- Adjusting the white balance/contrast;
- Performing spatial correction through the spatial compensation function (JAI, 2019) (Fastec Imaging Corporation, 2017)

The function automatically corrects the spatial pixel differences individually for the R, G, and B lines captured by the sensor. During image acquisition colour shading correction will be performed through the shading correction function. The shading correction function corrects the non-uniformity (i.e., shading) in the amount of light generated by the lens and lighting equipment (JAI, 2019) (Fastec Imaging Corporation, 2017). Refer to Appendix C- Camera Setup, for setup and configuration of camera and settings.

### Image Acquisition/Processing/Removal Action

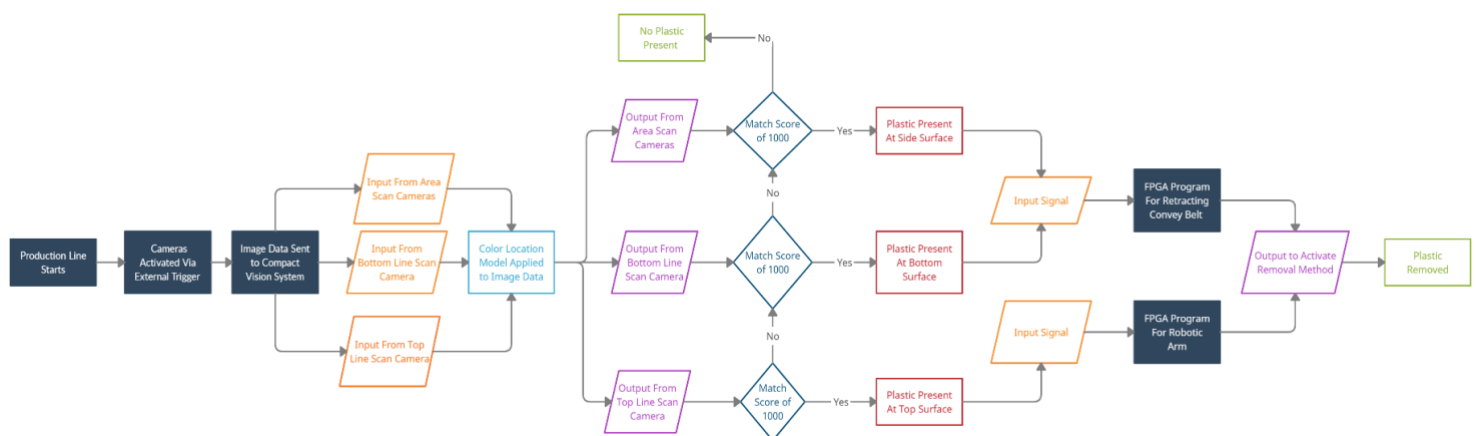


Figure 7. Flow diagram of inputs, processes, and outputs for detection and removal of plastic.

The NI Compact Vision System (NI CVS-1458RT) will be used to process the image data from all 6 cameras. Compact Vision Systems from National Instruments are robust automation controllers that embed industrial camera integration, open networking, and field programmable gate array-based (FPGA) I/O into a compact form factor (National Instruments, 2015). These cameras provide rapid acquisition and real-time image processing for computer vision. Each Compact Vision System from National Instruments includes a production license for Vision Builder for Automated Inspection (AI). Vision Builder AI is a configurable software environment that enables the rapid development, testing, and deployment of applications for pattern matching, character recognition, presence detection, and component classification (National Instruments, 2015). The RGB values will be converted to HSL colour space then a colour location algorithm will be used to quickly locate known colour regions in an image. With colour location, a model or template will be created that represents the colours being searched for (National Instruments, 2015). The machine vision application then searches for the model in each acquired image and calculates a score for each match (National Instruments, 2015). The score indicates how closely the colour information in the model matches the colour information in the found regions (National Instruments, 2015). Colour location is based on the colour matching functions. Colour matching is a two-step method (National Instruments, 2015). The computer vision program begins by learning a reference colour distribution, in this case blue representing plastic contaminants. The second stage compares the colour details in other images to the reference image and returns a score indicating the degree of resemblance. Through generating a colour spectrum, the computer vision program will acquire a colour distribution (National Instruments, 2015). The software is provided with the image containing the colour information that will be used as a reference (National Instruments, 2015). The colour spectrum is then generated based on the image provided (National Instruments, 2015). The colour spectrum then becomes the basis of comparison during the matching phase. The matching process compares the colour spectrum of the target image to the reference colour spectrum acquired during the learning stage (National Instruments, 2015). A match score is determined using the Manhattan distance between two vectors to evaluate the similarities between the two colour spectrums (National Instruments, 2015). Prior to calculating the distance between the two colour spectrums, a fuzzy membership weighting algorithm is applied to them (National Instruments, 2015). The weighting feature corrects for any errors that might occur during the colour space binning operation (National Instruments, 2015). The match ranking, which ranges between 0 and 1000, indicates the degree of resemblance between the colour spectrums (National Instruments, 2015). A score of 0 indicates that there is no correlation between the colour spectrums, whereas a score of 1000 indicates an exact match. The comparison phase is depicted in the following diagram.

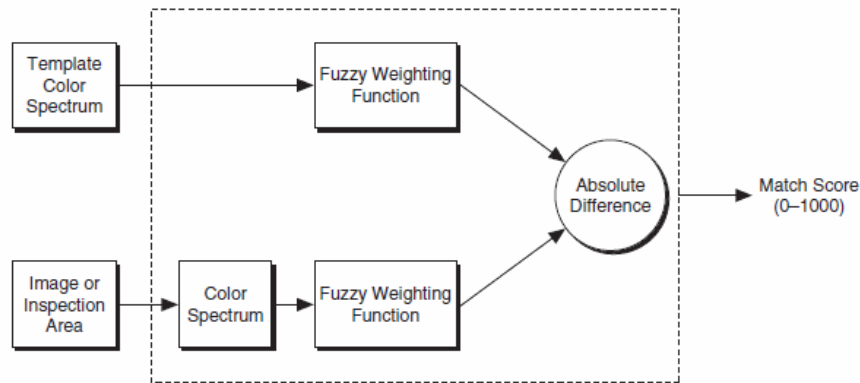


Figure 8. Flow diagram of the colour matching function (National Instruments, 2015)

Colour location functions allow colour matching to be used in applications where the location of the objects in the image is unclear, such as plastic contamination on pieces of moving beef trim. Colour location searches for instances of a template picture in the search image using the colour information contained in the template image (National Instruments, 2015). The colour location process is divided into two stages: learning about the template and searching for the template inside an image. During the learning process, the program analyzes the template picture and derives the colour spectrum (National Instruments, 2015). This colour spectrum is used to equate the template's colour information to the colour information contained in the image (National Instruments, 2015). During the search process, a region the size of the template is moved from top to bottom of the image, pixel by pixel (National Instruments, 2015). The function computes the colour spectrum of the area under consideration at each pixel. This colour spectrum is then compared to the colour spectrum of the template to determine a match score (National Instruments, 2015). The step of conducting a search is divided into two phases. To begin, the program conducts a coarse-to-fine search process in which it recognizes all possible locations, including those with extremely low match results (National Instruments, 2015). This phase's objective is to rapidly identify locations within the picture that may contain potential matches to the template data. Due to the time involved in stepping through the image pixel by pixel and calculating match scores, the following methods are used to accelerate the search process:

- **Subsampling.** As the image is stepped through, the colour information is extracted from just a few reference points to compare to the template (National Instruments, 2015). This significantly decreases the amount of data required to compute the image's colour spectrum and increases the speed of the search process.
- **Step Size.** Instead of moving the template pixel by pixel around the image, the search process skips a few pixels between each colour comparison, significantly speeding up the search process (National Instruments, 2015). The step size

parameter specifies how many pixels to skip. The initial step size for colour position may be as high as half the size of the template.

The second stage utilizes a hill-climbing algorithm to locate the best match on the list (National Instruments, 2015). The process of colour location is represented in the following diagram.

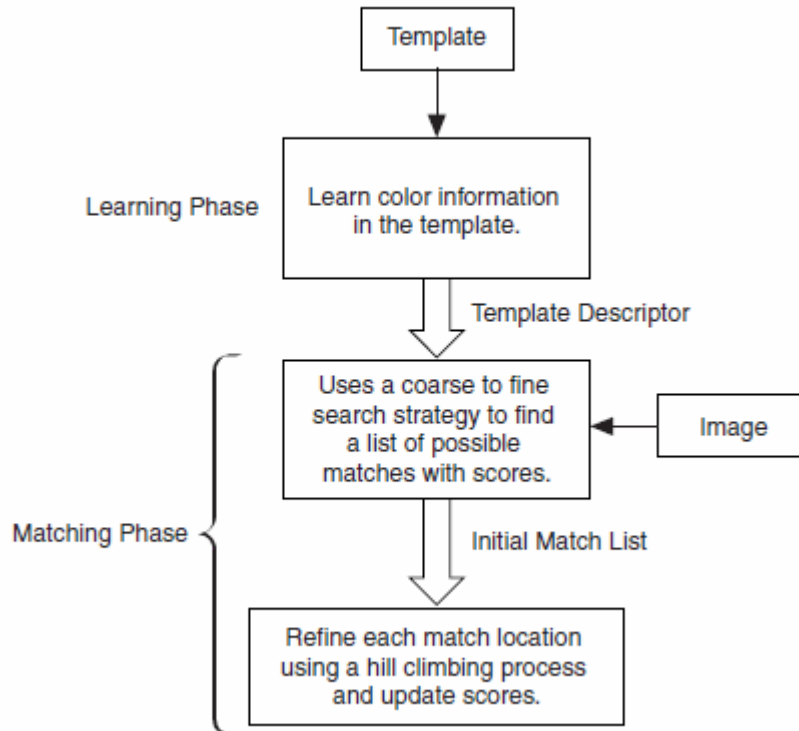


Figure 9. Flow diagram representing colour location template learning phase and matching phase.

With NI Compact Vision Systems comes the onboard field-programmable gate array (FPGA) for enhanced I/O performance. The controllers contain a pre-programmed FPGA personality named Vision RIO, an API that enables the use of FPGA-enabled I/O without programming the FPGA (National Instruments, 2021). With Vision RIO, a queue of pulses and set line states will be setup to accurately synchronize I/O with visually inspected beef pieces without having to know FPGA programming (National Instruments, 2021). The Vision RIO API will be configured for triggered acquisition with managed ejectors controlled with programmable logic controller (PLC) issued timestamps.

### Transparent Conveyor Belt Parameters

Conveyor Belt Material: To effectively detect all plastic pieces on meat samples, a camera and light source must be placed under the conveyor belt to capture an image of the bottom surface of the meat. A transparent plastic belt allows the RGB camera to form a detailed view of the underside of the meat sample to accurately detect any plastic contamination. Gao et al. discussed the significance of time dependence, failure rates, and property degradation in choosing the correct material for a belt system (Krawiec, 2020). Belts made of thermoplastic materials, such as polyesters and polyurethanes allow belts of any length to be obtained, high resistance to abrasion, fats, and some chemicals, a high friction coefficient (good anti-slip properties), considerable elasticity at a relatively low level of stretching, and safe use in contact with food (FDA certified) (Krawiec, 2020). Heat conditions plays a crucial role in the safety of machine parts, so any wearing and damaging to the belt can cause restraining conditions on the operational service life of the belt (Krawiec, 2020).

According to Persak et al., a transparent conveyor was used with an integrated vision camera to successfully detect defects in passing granulates, as well as the positions and conditions of each particle (Persak, 2020). The experiment used a 3 mm thick transparent belt made of polyurethane (Persak, 2020). The plastic contaminants were transparent polycarbonate (PC) in the granules which averaged to have around 3 mm diameters (Persak, 2020). The results calculated an average accuracy of 90.5% (Persak, 2020). The belt must coherently fit with the existing set up, thus must measure 0.5 m wide, 6.75 m long, and 3 mm thick. For this reason, a translucent thermoplastic polyurethane belt from PAR Direct was chosen for this food processing application and excellent durability (PAR Direct, 2020).

Conveyor Belt Cleaning System: During the transport of meat, the conveyor belt accumulates fat build-up from the meat pieces which creates an undesired film on the surface of the belt. In order for a clear, detailed RGB photo to be captured underneath the belt, a clean surface must be maintained. Several methods and processes have been tested to provide clean conveyor belts, however a system which provides efficiency in regard to time, water usage, chemical usage, and labour are preferred (Pentzien, 2016). The dry steam vapour blast method is best at removing meat debris from the belt, while keeping the surface dry to eliminate any microorganism contamination that would travel with a wet belt (Pentzien, 2016). A powerful vacuum is used and can be customized to fit the desired width of the conveyor belt (Pentzien, 2016). High temperature steam cleans the conveyor belt by softening dirt, grease, or oil from the surface, while using pressure to dislodge them (Equipment Briefs, 2017). To eliminate the spread of microorganisms, the steam is set to 140°C to kill bacteria on contact and sanitize the surface of the belt (Equipment Briefs, 2017). Vacuum suction assures total extraction of steam and residual water (with debris), leaving the belt completely dry (REA, 2018). Fast drying is ideal in maintaining a dry surface for safe transport of meat as well as sensitive electronics such as the RGB cameras (Equipment Briefs, 2017). By minimizing water usage, the system is

less likely to cause steam or water leaks, while maintaining a dry belt to prevent bacteria contamination (REA, 2018).

The dry steam method ensures the system drains the water waste removed with the steam, ensuring the surface is clean and dry (REA, 2018). The system presented from REA demonstrates an easily removable device from the conveyor belt to conduct efficient maintenance that allows food processing facilities to reach HACCP standards without the use of detergents. The cycle can be ongoing during production and based on studies with the VDA belt cleaner, it is recommended that it is installed on the underside of the belt (REA, 2018). The steam generator uses less than 15 L of water per hour to produce 30 kg of steam at a constant pressure of 12 bar. The device is made entirely of AISI 304 stainless steel and in turn, does not damage the belt (REA, 2018).

A secondary purpose of the conveyor belt cleaning system would be to wash away any minuscule pieces of plastic that may be too light to fall down from the conveyor belt or that get stuck to the conveyor belt due to sticky fat. The steam cleaning would eliminate these small pieces, preventing them from contaminating the final beef trim combos.

Retracting Conveyor Belt Parameters In compliance with HACCP principles in the aim of developing a systematic and preventative approach to food safety in regard to physical contaminants identification and elimination, a metal detection procedure is often implemented (Mettler Toledo, 2020). As is the case in most beef production facilities, metal contamination is identified as a risk on the production line, calling for the implementation of a critical control point featuring a metal detection machine (Mettler Toledo, 2020). Typically, a metal detector will be installed over a main conveyor line wherein it emits a signal when metal is detected that triggers a removal mechanism; removal mechanisms usually include either a push off mechanism or a retracting conveyor belt that displaces the contaminated product onto a reject path for further inspection (Mettler Toledo, 2020). The plastic detection system would be located in the area of the existing metal detection critical control point in order to optimize space and equipment utilization. In the instance that the RGB camera detection system detects the presence of plastic smaller than what is able to be safely removed by the robot arm (<100cm<sup>2</sup>) on the conveyor belt, a signal will be sent to the existing retracting conveyor belt for rejection. This mechanism is timed so that the plastic or metal-contaminated trim is ejected from the main conveyor line and discharged onto a designated rejection line for employee manual inspection.

Robotic Arm The robotic arm selected for picking up pieces of plastic with an area greater than 100cm<sup>2</sup> located on the top surfaces of beef is from FANUC, a leading robotic automation company. Only relatively large pieces of plastic contaminants were selected to be removed by the arm due to the uncertainty of the technology on a fast-moving conveyor belt. Moreover, the robotic arm would be ineffective in removing pieces of plastic located on the underside of meat. The chosen model is the LR Mate 200iD/4SC, boasting a maximum loading capacity of 4kg and a maximum reach of 550mm (FANUC,

2020). This model's primary applications are pick, pack and place as well as material removal and load transfer in a manufacturing setting, specifically clean room or food processing facilities (FANUC, 2020). It rotates around 6 controlled axes at high speeds (450-1000°/s) with large motion ranges (245-720°) and able to transmit data at a TCP speed of 11m/s maximum (FANUC, 2020). Moreover, this model offers full flexibility in terms of mounting placement due to its compact design and sealed mechanical units, making it ideal for placement on a conveyer belt in a beef production setting (FANUC, 2020; FANUC, 2020). This model can have different types of attachments on the end allowing for the trial and error of gripping claws of varying sizes and configurations.

### SolidWorks Model for Overall System



Figure 10. Overall structure of the plastic detection and removal system

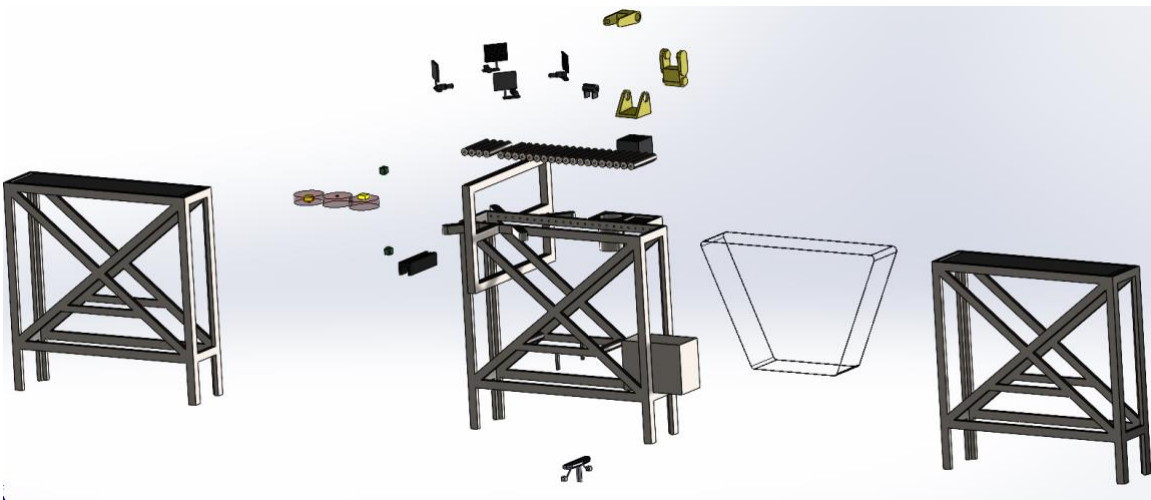


Figure 11. Separation of components of plastic detection and removal system

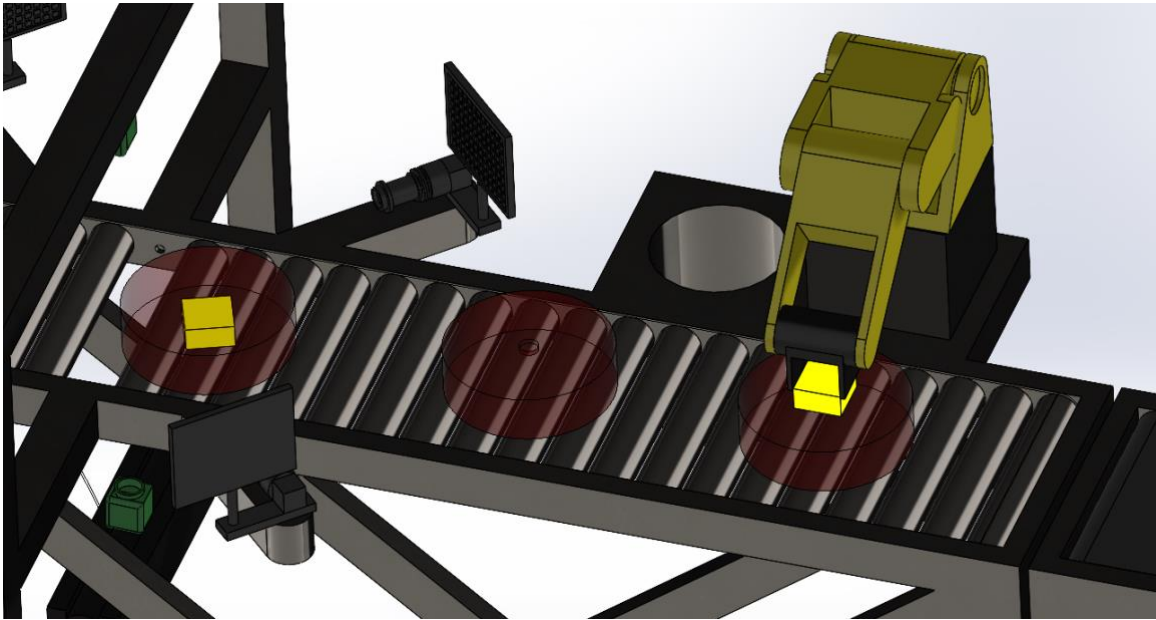


Figure 12. Robotic arm to remove plastic on the surface of meat

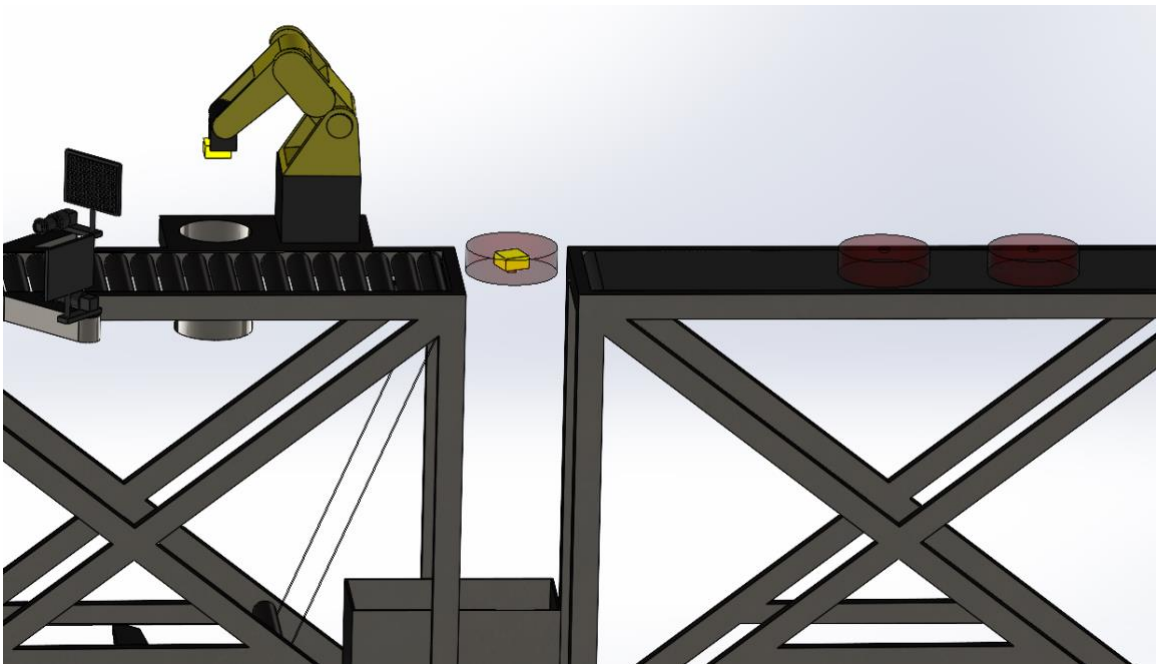


Figure 13. Retracting conveyor belt to remove plastic-contaminated meat; either located on underside or  $<100\text{cm}^2$

## DESIGN DEFENSE

**Safety** Food safety is of utmost importance and the main priority with regard to this project. One facet of this encompasses consumer safety in regard to accuracy of

contaminant detection and removal. In order to ensure total consumer safety in regard to physical contaminants, the vibrational conveyer belt, RGB camera detection system, detection algorithm and both removal mechanisms must be accurate and mechanically sound as to not allow for loose and broken pieces to enter the final product. Moreover, the food contact components of the design, such as the vibrational conveyer belt, transparent conveyer belt, retracting conveyor belt and robot arm claw must allow for easy dismantling and reassembly for thorough cleaning and sanitization during the clean out of place (COP) cleaning program that takes place every day after production. They must also be made of food-grade materials to prevent any chemical leachate, toxicity issues, corrosion, pitting and scoring. This includes the ability to maintain its integrity during cleaning where high temperatures, high pressures and strong chemical concentrations are used. To comply with these safety requirements, the vibratory conveyer belt will boast an all stainless-steel construction that is low maintenance, easy to clean and has an easily-adjustable drive that requires no lubrication. The transparent conveyer belt would be made of one solid piece of either polyurethane, silicone or another plastic-based material in order to ensure food safety and easy cleanability. The degree of transparency of the belt should be maximized in order to allow for the clearest images possible by the RGB camera on the underside of the belt.

The food safety aspect of the plastic removal methods must be analyzed by its individual components – the retracting conveyor belt and the robotic arm. In regard to the retracting conveyor belt, given that it is a common, well-established fixture in beef processing environments, it is reasonable to assume it is a safe and effective in diverging food products and that it will continue to be this way once connected to the RGB camera output signals. After all, it is a standard piece of equipment in regard to removal of metal contamination. Proper calibration and maintenance would have to be regularly conducted as with the existing metal detector system linked to the retracting conveyor belt. In regard to the robotic arm, a “clean room” variety was selected as it meets standard IP67 requirements for highly demanding pharmacy, lab, and food and beverage handling applications. It is suited for standard COP procedures, such as hot high pressure cleaning and sanitation (FANUC, 2020).

For all pieces of equipment in this system, an adequate maintenance plan, standard operating procedure, cleaning procedure and HAZOP analysis as well as a pre-start and safety review of the system by a professional engineer will be required under Section 7(2) of the Industrial Establishments Regulation under the OHS Act, wherein the process involves a new apparatus or protective element to be constructed (Ontario Ministry of Labour, Training and Skills Development, 2016). The professional engineer who possesses expert knowledge and qualifications on food safety systems conducting the review must provide a dated, signed and sealed report indicating the result of the assessment of any potential risks or hazards involved.

## Economics

To determine the total costs associated with implementing this system, component costs, installation fees, operational and maintenance costs were estimated.

The following bill of materials outlines the equipment types, quantities and cost involved in the execution of the detection and removal of plastic contaminants.

Table 3. Bill of materials for detection and removal system

Component name	Supplier	Quantity	Price	Total cost
Vibratory conveyor belt	Key Technology (Key Technology, 2020)	1	\$20,000.00	\$20,000.00
Transparent conveyor belt	PAR Direct (PAR Direct, 2020)	1	\$755.00	\$755.00
Transparent conveyor belt cleaning system	REA Belt Cleaner (REA, 2018)	1	\$4,280.00	\$4,280.00
Line scan camera	JAI (JAI, 2020)	2	\$3,035.00	\$6,070.00
Line scan camera lens	Schneider Kreuznach (Schneider Kreuznach, 2013)	2	\$837.00	\$1,674.00
Line scan camera illumination unit	Metaphase Lighting Technologies (Metaphase Lighting Technologies, 2019)	2	\$3,030.00	\$6,060.00

Area scan illumination unit	GSVITEC (GSVITEC, 2018)	4	\$1,000.00	\$4,000.00
High speed video camera	ClaraVision (ClaraVision, 2021)	4	\$2,000	\$8,000.00
Compact vision system	National Instruments (National Instruments, 2021)	1	\$6,535.00	\$6,535.00
Switch hub	NETGEAR (NETGEAR, 2019)	1	\$139.99	\$139.99
Robot arm	FANUC (FANUC, 2020)	1	\$42,147.54	\$42,147.54
CAT6 Ethernet-Cable	Stemmer Imaging (STEMMER IMAGING, 2012)	7	\$97.60	\$683.20
Retracting Conveyer Belt	NA	NA	NA	\$0
<b>Total Component Costs</b>				<b>\$100,344.73</b>

When it comes to operational costs, it is anticipated that one full time quality assurance analyst will be responsible for monitoring the automated plastic detection and removal system for a presumably short amount of time in order to evaluate performance, consistency and watch for pieces of plastic that could be missed - particularly during the start-up phase. Thus, the total operational costs in the first year is estimated to be \$67,111.69 including cost of personnel, water, electricity and annual maintenance. This is greatly reduced once the supervision and aid of the quality assurance analyst is no longer needed; after the first year, operational costs will only amount to \$12,365.69.

Table 4. Operational costs for the first year of automated plastic detection and removal

Item	Description	Cost
Personnel	1 full time quality assurance analysts will be employed. The average salary for Canada is \$54,746 (Pay Scale, 2021)	\$54,746.00
Water	The system uses 15 L of water/hour. Thus, 43,800 L or 43.8 m <sup>3</sup> of water is required per year.  The rate of water in the city of Toronto is \$3.9549/m <sup>3</sup> if consumption is under 5000 m <sup>3</sup> .	\$173.22
Electrical	A sample monthly bill was calculated from the Ontario Energy Board (Appendix A).	\$2,158.00
Annual Maintenance	Estimated to be 10% of component costs.	\$10,034.47
<b>Total Operational Costs</b>		<b>\$67,111.69</b>

The installation fees of the detection system are estimated to be 20% of the total cost of the components.

Table 5. Total summary of expenses for first year of operation

Total cost of components	\$100,344.73
Installation fees	\$20,068.95
Operational and maintenance	\$121,857.69
<b>Total</b>	<b>\$187,525.37</b>

The total cost for the first year of operation would be approximately \$187,525.37. Subsequent years would operate at an approximate cost of \$12,365.69, which only considers the operational and maintenance cost excluding the quality assurance personnel. When considering ground beef retails for \$11/kg, a wasted 1000 metric ton combo contaminated with plastic could cost the company \$11,000 CAD in profit. If the proposed design detects only 17 pieces of plastic in one year that could have resulted in this sort of food losses, the system is economically justified.

**Environmental** An environmental monitoring program (EMP) is critical to evaluating the efficacy of hygiene practices in a food processing facility (Lakshmikantha, 2013). The program acts as an early warning system for microbiological hazards and provides information on indicator organisms, spoilage organisms and pathogens of concern in order to validate the facility’s sanitation program, (Lakshmikantha, 2013). In keeping with an effective EMP, the added equipment in the plastic detection and removal system must be included and continually monitored. For each piece of equipment, both contact and non-contact, risk levels of different surfaces must be established in order to establish appropriate sampling frequency, method and analysis (Lakshmikantha, 2013). The sampling procedure would be implemented into the plant’s already-existing pre-operation activities, which include swabbing for chemicals and pathogens and visual inspection, in the mornings prior to production. In terms of the impact of the plastic detection and removal system on the environment, the process should aim to minimize greenhouse gas emission, have a long service life and minimize disposable parts. In terms of greenhouse gas minimization, the chosen equipment fulfills this requirement as all components rely on electricity rather than fossil fuels for power.

A life cycle assessment was performed to determine the environmental impact of the proposed plastic detection/removal system. First, a system boundary, shown below, was created to determine which aspects of the detection process would be considered in the analysis. The production line prior to the vibratory belt, as well as the production line after the removal methods was not included in the environmental impact of the system. The transmission of power signals and energy used during image acquisition and analysis was also excluded because it was outside the scope of the design.

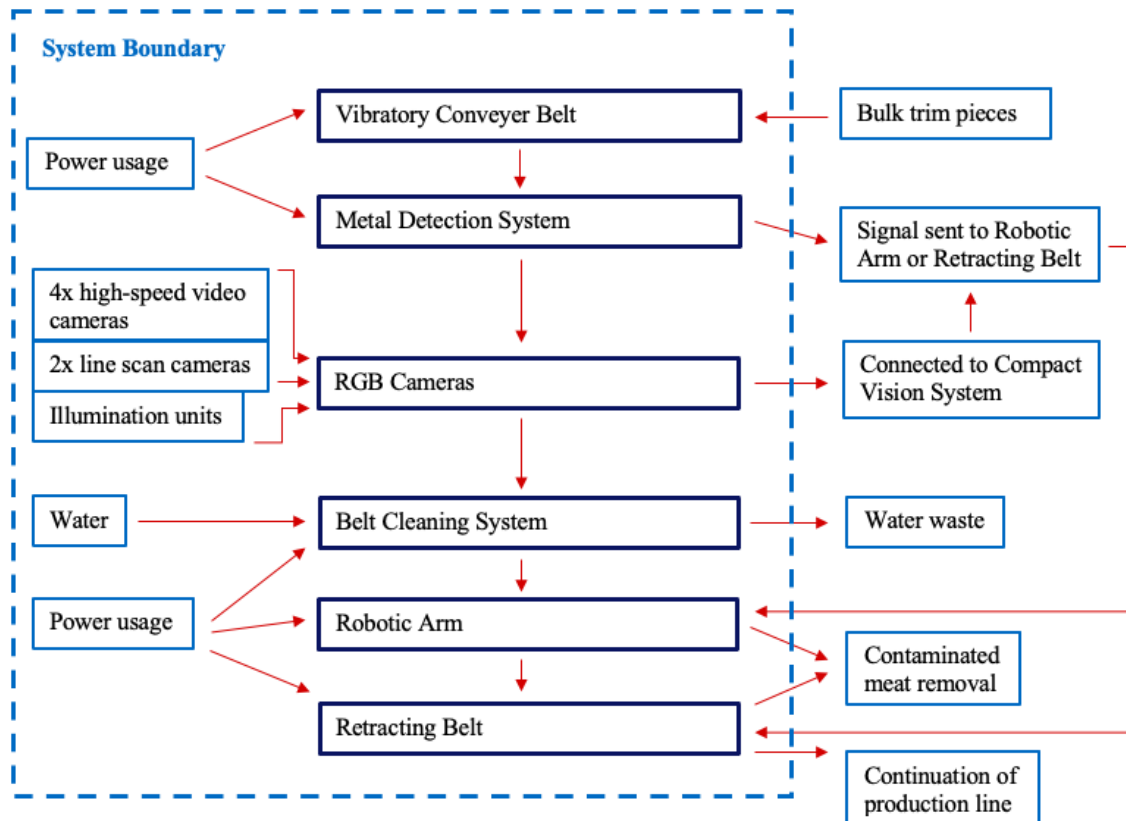


Figure 14. System boundary for life cycle assessment of plastic detection and removal system

The energy consumption associated with the production of the raw materials used to manufacture the entire system is shown in Table 5. The main materials of the conveyer belts, RGB cameras, belt cleaning system, and robotic arm were considered as well as the associated energy cost of production. From there, each material's total energy cost was determined.

Table 6. Energy consumption for material production

Material	Amount	Eco-Profile (Energy cost/kilogram produced)	Energy Cost of Production
316 Stainless Steel	1000 kg	80 MJ/kg (Ahmed, 2020)	80,000 MJ
304 Stainless Steel	150 kg	56.7 MJ/kg (Lamontagne, 2020)	8,505 MJ
Polyurethane	11 kg	90 MJ/kg (EuroPUR, 2015)	990 MJ
Aluminum Alloys	35 kg	65.5 MJ/kg (Energetics, 1997)	2,292.5 MJ
Total			91,788 MJ

Assuming the detection system has a life expectancy of 20 years before needing to be replaced, the energy consumption from production was divided by 20 years to determine the energy consumption per year of 4,590 MJ/year. Assuming the system is powered for 8 hours a day, the energy consumption due to power consumption was calculated. The energy consumed daily was approximately 40 kWh/day. Considering that the system was run 5 days a week, the yearly energy usage was determined to be 37,584,000 kJ/year. The final stage of the detection system to be considered is the disposal process. Since majority of the components are recyclable, the system would be disassembled and recycled. Separate components like monitors, cables and wiring, camera lens, etc. were not included in this process as they have individual lifespans which are outside the scope of this report.

The total yearly energy consumption from the production of the system to the usage were converted to the equivalent mass of CO<sub>2</sub> emissions. From there, the total yearly environmental impact of the detection system was determined to be 8,302 kg of CO<sub>2</sub> per year.

**Social** Increased food safety measures and communication of them to stakeholders and the wider public may have the effect of increased consumer trust in beef products as well as an increase in the purchase of beef products. This is particularly true given the increase in beef consumption and production outlined in the introduction. As consumers become more aware of concepts such as food safety and foodborne disease, their attitudes and behaviours toward products manufactured utilizing innovative technologies may be positively impacted.

**RISKS AND UNCERTAINTIES**

**Potential Risks and Uncertainties** One potential uncertainty of the proposed detection mechanism is the smallest size the plastic can be before it is unable to be detected by the RGB cameras. Although minuscule slivers of plastic are rare in the pre-sampling stage, there is still a possibility that a shred of plastic glove may be present on the trim line due to human error or a fragment of plastic vacuum-seal bags due to mechanical error. Under these or similar circumstances, it is unclear whether the detection system would be able to detect such small pieces of plastic and precise experimentation would be required to quantify the risk of this occurrence.

Another uncertainty regarding the removal mechanism is the fact that not all primary beef processing facilities will be equipped with a retracting conveyor belt subsequent to the metal detector, creating a potential gap in the removal process. If equipped with a push-on detect mechanism instead, adequate removal of smaller pieces of plastic is possible yet uncertain. Modifications to existing push-on-detect mechanisms may be for plastic removal. For facilities unequipped with an existing removal mechanism for contaminated product, one may have to be designed and installed for a comprehensive system.

**Limitations and Opportunities of the Design** Despite every effort being made to minimize plastic detection and removal loopholes, the chosen design does have some limitations that would require more intensive analysis and problem solving. One such limitation is the possibility that meat pieces on the vibrational conveyor belt may remain stacked on each other or a piece may be folded onto itself; this would allow for plastic to potentially be located in an imperceptible crevice where it would be concealed from the RGB camera's range of view. The prevention of this occurrence may entail the commissioning of a custom-made piece of vibrational equipment or the development of highly advanced detection capabilities by the RGB cameras in order to identify this phenomenon. Another limitation of the design would be the level of difficulty implicated in detecting pieces of plastic that do not possess high colour contrast with the red pieces of meat, such as clear packaging plastic or sampling bags. A possible solution to this would be to implement a facility-wide policy that only blue (or another contrasting colour) plastics may be used for packaging, sampling and personal protective equipment. This notion would be akin to existing facility-wide policies that mandate the use of metal-detectable pens, band aids, markers, cleaning equipment and cable ties.

Another limitation of the design is that plastic contamination generated at the beef trim sampling stage of production, which occurs immediately after the combo bins have been filled, is outside of the scope of the detection and removal system. Thus, any plastic that makes its way into a combo bin at this stage as a result of sampling error cannot be evaluated by the proposed system. Consequently, a plastic detection and removal system specifically devised for off-production line usage, such as handheld thermal cameras, may have to be implemented as well in order to ensure total plastic elimination from all phases of production.

Although potentially lacking in some aspects, the proposed plastic detection and removal design allows for the opportunity to be able to detect and remove other kinds of physical

contaminants as well as the possibility to execute automated grading and classification of beef. The implementation of the RGB cameras in tandem with Vision Builder for Automated Inspection allows for the programming of other physical contaminants that concern beef trim, such as bone fragments, bruises, hide, blood clots, detached ligaments, fecal matter, pathological lesions, discolouration or ingesta (Canadian Food Inspection Agency, 2019). Subsequently, both the robotic arm and retracting conveyer belt would be programmed and calibrated to remove these contaminants to minimize the amount of contaminants reaching the trim combos where they are often missed by human visual inspection. Moreover, the automation of beef trim grading could be made possible through extensive configuration of the RGB cameras and algorithm to evaluate characteristics such as marbling, muscling, fat measure, fat colour and fat texture in order for grading; Canadian quality grade include Canada Prime, A grade, B grade, D grade and E grade (Beef Cattle Research Council , 2019).

**Sources of Error of Design** One source of error in the conceptual plastic detection and removal system is the effect of lighting, dust and other possible obstructions in the view of the RGB cameras. This may affect the image quality and produce errors in the algorithm that could lead to pieces of plastic being undetected and contaminating the beef trim; a match score of zero may be produced when in fact it should be 1000, resulting in a false negative. In order to reduce this possible source of error, additional lighting and dedusting methods may have to be implemented to ensure the highest detection accuracy.

Another source of error in the design arises if the robotic arm were to miss the piece of plastic; the piece of plastic in question would continue on the conveyor belt and end up in the final product. In order to mitigate this occurrence, the robot would have to be programmed to signal when the piece of plastic was unsuccessfully picked up and further signal to the retracting conveyor belt to displace the contaminated beef trim to the reject line for manual inspection.

**Assumptions** One assumption made in the development of the plastic detection and removal system is in the amount of space available around the main line for the necessary equipment. The vibratory conveyer belt in particular is a large piece of equipment and it was assumed that its addition would be feasible and compatible in existing beef processing plants. There may exist some facilities that simply do not have the available floor space for such sizeable equipment; intensive accommodation and rearrangement of existing equipment may be in order.

Another assumption made was that the primary colour of plastic contaminants are blue based on first-hand experience in large-scale beef processing facilities. This assumption was made for simplicity purposes in developing a detection algorithm as well as its high rate of occurrence regarding common types of plastic contamination. There are, however, some types of plastic contamination that are not blue. These include conveyer belt pieces, sample bags and certain types of vacuum seal bags. To ensure complete detection capability when it comes to non-blue plastic contaminants, more advanced modifications

would have to be made to the detection algorithm to ensure unobtrusive plastics, such as transparent varieties, are identified by the cameras.

**CONCLUSIONS AND RECOMMENDATIONS** Food safety is the most important aspect of food processing, leading to a lot of effort being made to automate different inspection operations, namely computer vision systems. A plastic detection system with RGB cameras followed by size-dependent removal methods – either retracting conveyor belt or robotic arm – was conceptualized and modeled in order to increase food safety and decrease food losses associated with plastic-contaminated beef. Many studies have been conducted using RGB cameras for quality control purposes in food manufacturing, however there is a research gap in the beef processing domain. Research and development on machine vision and contaminant removal systems must be advanced in order to substantiate the efficacy of the proposed plastic detection and removal methods. Moreover, the proposed design must be installed and tested along a beef production line in order to validate and make improvements upon its decontamination abilities. Next steps in this project include expanding the initiative of plastic detection and removal to the post-sampling stage, which would ensure complete plastic contamination removal from the scope of the primary beef processing facility. Furthermore, conducting experiments in a beef processing facility in order to determine the smallest size of plastic possible that can be removed by the robotic arm is necessary to increase the automation factor of the removal system. If it is determined that pieces of plastic smaller than 100cm<sup>2</sup> can be removed by the robotic arm with great accuracy and repeatability, less beef trim will be diverted using the retracting conveyor belt resulting in less time lost to manual inspection.

## REFERENCES

- Aguiar, R. S., Esmerino, E. A., Rocha, R. S., Pimentel, T. C., Alvarenga, V. O., Freitas, M. Q., . . . Cruz, A. G. (2018). Physical hazards in dairy products: Incidence in a consumer complaint website in Brazil . *Food control*, 66-70.
- Ahmed, N. E. (2020). Energy modeling and eco impact evaluation in direct metal laser sintering/hybrid milling. *Heliyon*, 6(1). Retrieved from Heliyon.
- Al-Rahbi, S., Manickavasagan, A., Al-Yahyai, R., Khriji, L., & Alahakoon, P. (2013). Detecting surface cracks on dates using color imaging technique. *Food Science Technologies*, 795-804.
- Beef Cattle Research Council . (2019, April 29). *Carcass Grading* . Retrieved from Beef Cattle Research Council : <http://www.beefresearch.ca/research-topic.cfm/carcass-grading-41>
- Burd, S. B. (2007). Guidelines to detect foreign material contamination for food processors. ProQuest Information and Learning Company.

- Bwatota, S., Makungu, M., & Nonga, H. (2018). Occurrences of Indigestible Foreign Bodies in Cattle Slaughtered at Morogo Municipal Slaughterhouse, Tanzania. *Journal of Veterinary Medicine*, 1-6.
- Canadian Food Inspection Agency. (2019, January 15). *Operational procedure: Organoleptic evaluation of imported meat products*. Retrieved from Canadian Food Inspection Agency: <https://inspection.canada.ca/inspection-and-enforcement/guidance-for-food-inspection-activities/permission-issuance/organoleptic-evaluation-meat-products/eng/1546892808848/1546892874615>
- ClaraVision. (2021). *TroublePad: High Speed Camera for Production Lines*. Retrieved from ClaraVision: [https://www.claravision.com/en/produit/troublepad-high-speed-camera-for-production-lines/?fbclid=IwAR1uBgXbRbFxF2e-qdLqy4wRfKLNn\\_QC-ZOKN-PyPb\\_Vyjn7h6ehcE5V7lo](https://www.claravision.com/en/produit/troublepad-high-speed-camera-for-production-lines/?fbclid=IwAR1uBgXbRbFxF2e-qdLqy4wRfKLNn_QC-ZOKN-PyPb_Vyjn7h6ehcE5V7lo)
- Conveying With Metal Detection*. (2010, August 27). (Manufacturing) Retrieved February 7, 2021, from <https://www.manufacturing.net/home/article/13182748/conveying-with-metal-detection#:~:text=The%20pusher%20face%20is%20actuated,separate%20reject%20conveyor%20for%20disposal>.
- Di Wu, D.-W. S. (2013). Colour measurements by computer vision for food quality control – A review. *Trends in Food Science & Technology*, 29(1), 5-20.
- Einarsdottir, H., Emerson, M. J., Clemmensen, L. H., Scherer, K., Willer, K., Bech, M., . . . Pfeiffer, F. (2016). Novelty detection of foreign objects in food using multi-modal X-ray. *Food Control*(67), 39-47.
- Energetics. (1997, July). *Energy and Environmental Profile of the U.S. Aluminum Industry*. Retrieved from Energetics Inc: <https://www1.eere.energy.gov/manufacturing/resources/aluminum/pdfs/aluminum.pdf>
- Equipment Briefs. (2017). *Snack Food & Wholesome Bakery*, 106(1), 58.
- EuroPUR. (2015, August). *Flexible Polyurethane (PU) Foam* . Retrieved from EUROPUR.
- FANUC. (2020). *LR Mate 200iD/4SC*. Retrieved from FANUC: <https://www.fanucamerica.com/products/robots/series/lr-mate/lr-mate-200id-4sc-cleanroom-robot>
- Fastec Imaging Corporation. (2017). IL3, IL4 and IL5 High-Speed Cameras Operators Manual. Via Del Campo: Fastec Imaging Corporation.
- Ferrier, P. M., & Buzby, J. C. (2012). The Economic Efficiency of Sampling Size: The Case of Beef Trim. *Risk Analysis*, 368-384.

- Fu, K. (2010). Performance enhancement approaches for a dual energy x-ray imaging system.
- Gold, B. (2020, January 28). *Over 2,000 Pounds of Ground Beef Recalled Due to Plastic Contamination—Here's What You Should Know*. (Real Simple) Retrieved February 2, 2021, from [https://www.realsimple.com/food-recipes/shopping-storing/ground-beef-recall#:~:text=just%20announced%20that%20it%20is,and%20Inspection%20Service%20\(FSIS\).&text=Nevertheless%2C%20the%20FSIS%20and%20Amity%20Packaging%20Co.](https://www.realsimple.com/food-recipes/shopping-storing/ground-beef-recall#:~:text=just%20announced%20that%20it%20is,and%20Inspection%20Service%20(FSIS).&text=Nevertheless%2C%20the%20FSIS%20and%20Amity%20Packaging%20Co.)
- Guo, Z., Zhang, M., Lee, D.-J., & Simons, T. (2020). Smart Camera for Quality Inspection and Grading of Food Products. *Electronics*, 1-18.
- H. Watabiki, T. T. (2013). Development of Dual-Energy X-ray Inspection System. *Anritsu Technical Review*, 20, 59-66.
- Idrovo, A. (2014). Food poisoned with pesticide in Bihar, India: new disaster, same story. *Occupational and environmental medicine*, 228.
- JAI. (2019). SW-4000TL-10GE User Manual. Owatta : JAI.
- JAI. (2020). *Color imaging in machine vision: how to choose the right camera for your application*. Retrieved from JAI: <https://www.jai.com/machine-vision-color-imaging-cameras>
- JAI. (2020). *Sweep Series SW-4000TL-PMCL 4K trilinear line scan*. Retrieved from JAI: [https://www.jai.com/products/sw-4000tl-pmcl?fbclid=IwAR2TZuio\\_pco8Qfl6qdyQUETb2W5\\_BzxcrajxvID7XEDjvNqeaBgr0W\\_XHY](https://www.jai.com/products/sw-4000tl-pmcl?fbclid=IwAR2TZuio_pco8Qfl6qdyQUETb2W5_BzxcrajxvID7XEDjvNqeaBgr0W_XHY)
- Key Technology. (2020). *Choosing the Ideal Conveyer for your Food Product*. Retrieved from Key Technology: [https://www.key.net/en/wp-content/uploads/2018/11/WP\\_Conveyor-for-Food-Product\\_PDF.pdf](https://www.key.net/en/wp-content/uploads/2018/11/WP_Conveyor-for-Food-Product_PDF.pdf)
- Kottler, C., Pfeiffer, F., Bunk, O., Grünzweig, C., & David, C. (2007). Grating interferometer based scanning setup for hard x-ray phase contrast imaging. *Review of Scientific Instruments*, 78(4).
- Krawiec, P. R. (2020). Evaluation of the Thermal Stability and Surface Characteristics of Thermoplastic Polyurethane V-Belt. *Materials*, 13(7), 1502.
- Lakshmikantha, C. (2013, November). *Environmental Monitoring Program: An Early Warning System for Microbiological Hazards*. Retrieved from AIB International: [https://www.aibinternational.com/aibonline\\_/www.aibonline.org/newsletter/Magazine/Nov\\_Dec2013/EPMEarlyWarningHazards.pdf](https://www.aibinternational.com/aibonline_/www.aibonline.org/newsletter/Magazine/Nov_Dec2013/EPMEarlyWarningHazards.pdf)

- Lamontagne, M. (2020, April). *Embodied Energy*. Retrieved from Marspedia: [https://marspedia.org/index.php?title=Embodied\\_energy&oldid=135729](https://marspedia.org/index.php?title=Embodied_energy&oldid=135729)
- Lee, B. Y. (2020, January 28). *Plastic Found In Ground Beef: Over 2,000 Pounds Recalled From 9 States*. (Forbes) Retrieved February 2, 2020, from <https://www.forbes.com/sites/brucelee/2020/01/28/plastic-found-in-ground-beef-over-2000-pounds-recalled-from-9-states/?sh=5021d9b53f86>
- Martini, S., Suzuki, A., & Hartel, R. (2008). Effect of high intensity ultrasound on crystallization behavior of anhydrous milk fat. *Journal of the American Oil Chemists' Society*, 621-628.
- Mettler Toledo. (2020). *CombiChecker*. Retrieved from Mettler Toledo: [https://www.mt.com/dam/mettler\\_toledo/HiSpeed\\_Images/Product\\_of\\_the\\_month/App-79A\\_CombiChecker%20Critical%20Control%20Point%20-%20CCP.pdf](https://www.mt.com/dam/mettler_toledo/HiSpeed_Images/Product_of_the_month/App-79A_CombiChecker%20Critical%20Control%20Point%20-%20CCP.pdf)
- Mettler Toledo. (2020). *Metal Detector Conveyor Systems*. Retrieved from Mettler Toledo: [https://www.mt.com/ca/en/home/products/Product-Inspection\\_1/safeline-metal-detection/conveyor-detectors.html](https://www.mt.com/ca/en/home/products/Product-Inspection_1/safeline-metal-detection/conveyor-detectors.html)
- Momose, A., Yashiro, W., Maikusa, H., & Takeda, Y. (2009). High-speed X-ray phase imaging and X-ray phase tomography with Talbot interferometer and white synchrotron radiation. *Optics Express*, 17(15), 12540-12545.
- National Instruments. (2015). *Color Location*. Canada: National Instruments.
- National Instruments. (2021). *Compact Vision Systems User Manual*. Canada: Compact Vision Systems.
- Obi-Njoku, O. (2012). Process plant equipment: operation, control and reliability. In M. D. Holloway, C. Nwaoha, & O. A. Onyewuenyi, *Process Plant Equipment: Operation, Control and Reliability* (pp. 213-223). Hoboken: Wiley.
- Ontario Ministry of Labour, Training and Skills Development. (2016, November 24). *Section 7*. Retrieved February 3, 2021, from [https://www.labour.gov.on.ca/english/hs/pubs/psr/psr\\_3.php](https://www.labour.gov.on.ca/english/hs/pubs/psr/psr_3.php)
- PAR Direct. (2020). Retrieved from Thermoplastic Polyurethane - Translucent: <https://www.par-direct.co.uk/Products/TP95>
- Pentzien, S. D. (2016). Multi-Width Vapor Steam Conveyor Belt Cleaner. *Journal of Engineering*, 5959.
- Persak, T. V. (2020). Vision-Based Sorting Systems for Transparent Plastic Granulate. *Applied Science*, 10(12), 4269.
- R. Haff, N. T. (2008). X-ray detection of defects and contaminants in the food industry. *Sensing and Instrumentation for Food Quality and Safety*, 2, 262-273.

- REA. (2018). *Steam Cleaner Conveyor Belts*. Retrieved from REA Steam Cleaning.
- Reuters. (2016). Mars Recalls Chocolate Products in 55 Countries. *New York Times*, 2.
- Stier, R. F. (2020, June 10). *How processors can use robots to enhance food quality and safety*. (Food Engineering ) Retrieved February 7, 2021, from <https://www.foodengineeringmag.com/articles/98926-how-processors-can-use-robots-to-enhance-food-quality-and-safety>
- Sun, D.-W., & Brosnan, T. (2004). Improving quality inspection of food products- a review. *Journal of Food Engineering* , 61, 3-16.
- Teena, M., Manickavasagan, A., Al-Sadi, A., Al-Yahyai, R., & Deadman, M. (2016). RGB Color Imaging to Detect *Aspergillus Flavus* Infection in Dates. *Emirates Journal of Food and Agriculture*, 683-688.
- Trinderup, C. (2015). Multispectral Imaging of Meat Quality - Color and Texture. (p. 358). Technical University of Denmark.

**APPENDIX A – ELECTRICITY CALCULATION** From the life cycle analysis, it was determined that a detection system consumed approximately 144,000 kJ/day or 40 kWh/day.

Although the system will only be running 5 days a week, the calculation will assume energy costs for all days of a month to account for various other operations in the system (image analysis, X-ray system, vacuum suction, etc.).

$$40 \text{ kWh} * 30 \text{ days} = 1200 \text{ kWh}$$

According to the Ontario Energy Board, assuming energy is used during on peak working hours, a sample monthly bill is presented in the following figure:

**SAMPLE MONTHLY BILL**  
**Time-of-Use Pricing**

Account Number: 000 000 000 0000  
 Meter Number: 0000000

**Your Electricity Charges**

<b>Electricity</b>	
On-peak @ 17.6 ¢/kWh	\$38.02
Mid-peak @ 11.9 ¢/kWh	\$25.70
Off-peak @ 8.5 ¢/kWh	\$65.28
<b>Delivery</b>	\$61.82
<b>Regulatory Charges</b>	\$5.07
<b>Total Electricity Charges</b>	<b>\$195.89</b>
HST	\$25.47
<b>Ontario Electricity Rebate</b>	<b>(-\$41.53)</b>
<b>Total Amount</b>	<b>\$179.83</b>

Figure 15. Sample monthly bill for operating detection and removal system (Ontario Energy Board, 2020)