Final Report

AUSTRALIAN MEAT PROCESSOR CORPORATION

Robotic Hydraulic Saw Cutting Trials

Project Code
2021-1219

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1 Contents

1.0 Executive Summary

This project aimed to understand the considerations related to robotic cutting for the meat industry. Specifically, the suitability of a particular robot model for scribing, and the characteristics of the ideal saw to use for the application. This robot was selected due to its hygienic nature and the fact it does not require a bag to be used. The concern was whether the robot would be able to handle the external inertias involved with the scribing application without tripping out. Similarly, it was suggested that a hydraulic saw may be more fit-for-purpose for the application given previous issues of electric saws stalling in industry, and that it was worth examining the performance considerations including confirming that stalling does not occur, and investigating the impact of hose management and how performance changes with sharp vs blunt blades.

Trials were performed where the robot was setup to cut through rib bones at various speeds. Some bones were also cooked to simulate older, harder, ribs. The robot was able to cope with the external inertias of the saw blade spinning and cutting of the bone without any trip out issues. This was even the case when the cut was run at full robot speed into a cooked bone, resulting in the saw blade stalling. The robot was also able to cope with the moving mass of the hydraulic hoses when performing repetitive dry cycles of cut routines. Through the trials, as the blade had become blunt and the cut quality decreased, saw stalling was observed, albeit at faster robot speeds than would be utilised. The robot though was able to cope with the wear of the blade successfully without tripping.

After these trials, there was a high degree of confidence that the robot would be suitable for an automated beef scribing system.

With the robot shown to be suitable for performing cutting tasks without any issues, the focus was shifted towards selecting the ideal saw technology for scribing. Processors were consulted regarding their experiences trialling numerous scribing saws (pneumatic, hydraulic, and electric). A particular electric saw was named which had not presented any issues of stalling. The benefits of using electric versus hydraulic are significant, primarily due to removing any risks related to high pressure hydraulic fluid in an automated system with potentially no human supervision. An electric saw would be more widely accepted across the industry if used for an automated scribing system. After careful consultation with AMPC, it was agreed that a pivot should occur to examine this saw option more closely as the primary goal is to understand the best saw technology to use.

A site trial was performed where a current probe and data logger was used to examine the saw's performance across approximately 24 hours of production. This trial covered approximately 1740 carcase sides across the main carcase types the processor processes, and varying maturity levels. There was no indication of stalling by the saw across this period, with the saw operating well within its bounds throughout the trial. Critically, there was also **no** indication that the saw was slowing down and nearing a stall – something which an operator can 'feel' and adjust for to prevent a stall, but a robot cannot. There was no significant difference in performance across the carcase types, maturity, or whether a new or old blade was on the saw, in the context of operating close to its limits. It should also be noted that the manual operators currently take ~5s to perform the brisket rib cut and ~1-2s for spine cuts, which is faster than the cutting speed for the currently designed automated cutting system.

An off-the-shelf saw was found which has 35% more power than the saw being used currently by the processor. Given the lower power saw had no issues during the trials, there is a high degree of confidence that the higher power saw will be suitable for an automated scribing system. Furthermore, there are several contingency options available if required, including an even higher power saw. Given all of these points, the results of the trials, and the broader industry desire, it is felt that the correct path for automated scribing is to proceed with an electric saw. This electric saw has thus been designed into the scribing system which is to be installed at a processor's plant.

2.0 Introduction

AMPC (and the industry) have an innovation vision, and support R&D program, to eliminate all WHS incidents from processing operations. Where possible, dangerous tasks will be fully automated. Where automation is not currently viable (either due to technology limitations or return on investment), semi-automated/remote solutions will be developed that will remove the operator from dangerous tools and implements. Where semi-automated solutions are not viable then the remaining hands-on tools will be made as safe as possible (i.e. BladeStop and Guardian).

This project will involve performing trials and characterising the risks, challenges, and design considerations needed for a robust robotic solution in the Australian red meat industry. Such considerations will include the impact and handling of the motion control by the robot, hydraulic hose management, and handing of the reaction forces experienced by the robot. How the performance changes with sharp vs blunt blades will also be assessed.

3.0 Project Objectives

AMPC's 2020-2025 Strategic Plan identifies both within the Advance Manufacturing (pages 5 & 6) and People and Culture (pages 10 & 11) programs that:

- Removing staff from dangerous operations, via Hands-Off processing (Adv. Mft.),
- Carcase Primal Profitability Optimisation, via acc, and urate processing (Adv. Mft.)
- Digitisation, via acquiring product information and leveraging data insights (Adv. Mft.),
- Attraction, via demonstration and developing a wide range of operations (People & Culture),
- Retention, via improving working conditions and making tasks exciting (People & Culture),
- Development, via developing tasks that require higher skills and intellect – operational & technical (People & Culture),
- Safety and Wellbeing, via reducing the high-risk nature of processing operations (People & Culture),

are all foci of AMPC, and that this one innovation theme will aim to make a significant impact upon all seven by acting as an enabler for wider roll-out of automated robotic cutting.

The primary objective of this project is to perform trials whereby a hydraulic saw is mounted to a robot to perform cuts. The relevant risks and considerations will be noted across the trials (e.g. running of hydraulic cables, robot motion control and handling of reaction forces from the blade, effect of sharp vs dull blades, amount of carcase movement).

3.1 Project Methodology

The project methodology was as follows:

1) Lease a robot for the project and develop a trial setup to enable mounting of a hydraulic saw tool for cutting
2) Setup a trial to perform dry movement and cutting trials to assess the behaviour and implications with respect to the robot
3) Analyse trial results to assess feasibility of the robot selection
4) Perform trials on-site examining the performance of the selected saw technology over a large range of carcases to assess its feasibility for selection in a scribing system, and what factors and considerations may impact the system's design

4.0 Methodology and Discussion

4.1 Design Conceptualisation

The first stage for this project was the design conceptualisation. Producing a concept of our trial assembly which would allow us to assess the feasibility of our cutting application using a particular robot in conjunction with a hydraulic cutting saw. Such a system could have:

- A robot selected specifically for the environment it will be installed into (hygienic)
- A hydraulic cutting saw which can be tested with various cutting speeds and blade configurations
- A base designed with consideration to the robot selection and reach requirements for the cuts.

Robot Selection

An industrial robot will need to be selected with consideration to the environment that the robot will be positioned into, as well as the arm reach and payload requirements. There were a couple of options for us to seriously consider at this stage to accommodate the harsh washdown environment on site: -

- **Robot Bag Kit** – A food-grade protective robot bag to ensure the main body of the robot as well as the electrical equipment used are secured from caustic washdown procedures implemented on sites. There are a few options on the market for various robot brands and configurations. Below is an example: -

Figure 1: Robot Bag System

- **Hygienic Application Robot** – A robot designed specifically for processing in hygienic, humid or harsh environments. The materials used to manufacture this robot will not only need to provide a high IP rating, but also provide good resistance to caustic washdown.

In addition to the material selection and IP rating, we also need to consider the payload and reach attainable. The reach profiles can be simulated in the 3D space to ensure the robot can achieve desired scribe cuts.

Hydraulic Cutting Saw and Power Pack Selection

There are various options currently in use throughout the meat processing industry for cutting – these vary from one site to another and range from electric, hydraulic, and pneumatic solutions. The main variable which will drive our selection criteria will be the torque generated by each of these solutions. Since we will be required to carry out our cuts at high speed due to time constraints, the higher torque is desirable as it will ensure the saw does not stall as it is cutting through the carcase.

Here is a breakdown of design considerations for each of the options: -

Table 1: Saw Power Delivery Mechanism Comparison

	Advantages	Disadvantages
Hydraulic	- Generate extremely high force in relation to input forces.	- Cost will be higher relative to electrical or pneumatic options. - Messy to operate – leaks can create a hazard. - Offer a good power to weight ratio.
Electrical	- Fast moving and programable – will provide a higher degree of control.	- Power to weight ratio is not as efficient as hydraulics.
Pneumatic	- Hygienic and easily accessible.	- Inefficient due to heavy energy loses sustained over time (largely attributed to heat).

Hydraulic saws were seen to provide the best balance between power to weight (in terms of torque generation), which would in turn give us the best chance of overcoming saw stalling issues in practice.

4.2 Mechanical Design

Throughout the design conceptualisation phase, a list of design constraints as well as testing outcomes were developed and considered. These factors drove the final concept to ensure our design would meet the targeted throughput and answer any unknown variables.

4.2.1 Design Constraints & Variables

Some design constraints which were considered include: -

- **Robot Selection** – the following are the critical variables we need to consider during the robot selection.
    - Movement Range – The robot reach will need to allow us to make our desired scribing cuts
    - IP and Hygiene - The solution needs to have a high ingress protection rating and be able to sustain operation within a caustic environment.
    - Payload and Forces Induced – The robot will need to have a high payload specification to accommodate our saw system. It will also need to be able to sustain the loads induced when the

cuts are placed on our sample piece (this will be one of our unknowns - to be verified during the trial).

- **Saw & Power Pack Selection**
    - Saw selection – Power requirements for our solution deemed a high torque requirement for our application. A hydraulic saw will need to be selected that is suitable for the environment it will be placed in.
    - Power pack selection – Hydraulic power pack will need to be selected to accommodate the saw selected for our trial. These will generally be recommended by the saw manufacturer and hence will be based on our saw selection.
- **Saw Blade Selection**
    - Sharpness of Blade – Specifically how this impacts the reaction forces for the robot.
    - Cutting Speed – The harder the material we will be cutting, the slower the feed rate will need to be. Our ideal cutting speed is an unknown variable we will have to determine through our trailing phase.

Some of the unknowns we will need to answer through these trials include: -

- **Robot Selection**
    - Will the robot be able to sustain the external loads induced during cuts?
    - Will the robot be able to drive straight through the cutting piece at the desired speeds?
- **Saw and Power Pack Selection**
    - Will the saw and power pack combination generate sufficient torque in order to cut through our trial piece at the desired speed without stalling?
- **Saw Blade Selection**
    - How does blade sharpness impact robot performance?

4.2.2 Component Selection

The robot selected met all requirements from an IP rating, chemical washdown, and hygiene perspective, and also provided the required payload.

For the hydraulic saw and power pack, the Kentmaster HKM-1-H saw was selected in conjunction with the HPP-1 power pack. Both give the power requirements and adjustability required for the trials. Finally, a combination of sharp and dull blades can be used to assess cut efficiency on the sample pieces during the trials.

4.2.3 Trial Design

Before moving into the mechanical design, a cut simulation was conducted in Visual Components to determine the whether the robot's reach specification would be sufficient for the application.

Considering all the constraints and test variables, the below design was developed using 3D CAD.

Once in the 3D space, various configurations were simulated to ensure the assembly would accommodate the test requirements. Safety requirements were also assessed, hence, the decision to place an enclosure around the cut piece to ensure residual material was captured.

A mock end effector with the Kentmaster hydraulic saw mounted was also designed. This would allow us to conduct the cutting trials and observe the impact it has on our chosen robot. The end effector would also have a dummy weight bolted onto it in order to simulate the expected payload.

Assembly drawings were then developed for fabrication of the trial base and cutting table.

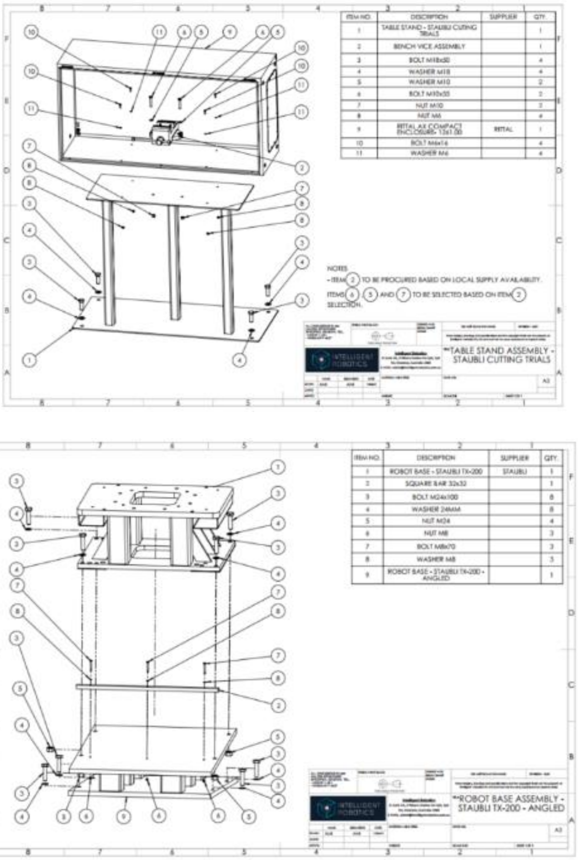


Figure 2: Assembly Drawings for Base and Cutting Platform

4.3 Trial Pivot

Due to the COVID-19 pandemic (various lockdowns, minimal access to sites), the first set of trials were to be performed overseas, at the robot manufacturer's factory. Given the lead time to receive a robot, this would also allow results to be acquired as soon as possible regarding the suitability of their robot for selection in the automated beef scribing concept system. Furthermore, it would reduce the risk of purchasing the robot only to find it not suitable for the task (see section 4.4 below for further details on this).

4.4 Risk Review

The primary objective for this project is to understand the risks and design considerations required for performing hydraulic saw scribing cuts with the robot selected for the task.

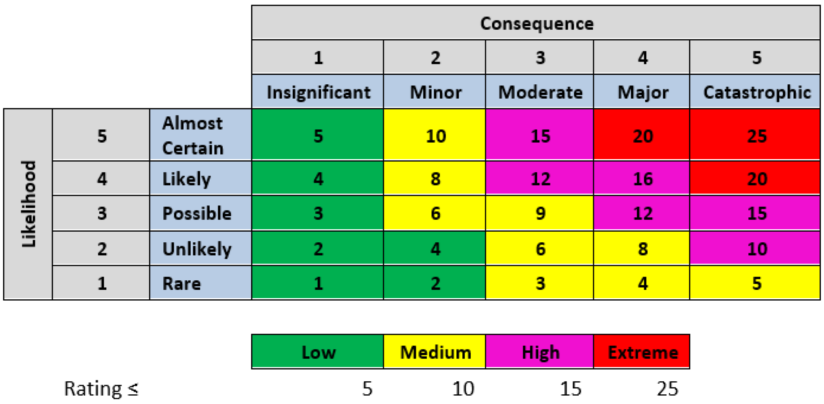
Firstly, the focus was particularly on performing factory trials with the robot to ensure it was the correct robot to be moving forward with for the project. The most significant risk for the project right now is ensuring this robot is suitable for cutting operations. This was therefore the focus for the factory trials performed.

The remainder of the project will then focus more heavily on the risks and considerations relating to the saw. As the saw is currently used in manual operation for beef scribing, the risk of it being completely unsuitable for the application is low.

Regarding the primary risk of the robot not being suitable for this application, there are a number of potential causes for this:

- External inertias experienced during cutting (as well as due to the hoses and cabling), especially rate-of-change in external inertia during initial engagement with bone, and at the required cutting speeds for the beef scribing concept to achieve commercial feasibility
- The effects from the spinning mass from the saw blade (particularly when stopping / starting)

The robot has been used in industrial milling and machining applications before, but not robotic cutting of beef carcases. Based on the consequence (Catastrophic) and likelihood (Likely) of this risk, the risk associated with the robot being unable to perform beef scribing was deemed “Extreme” (20/25).



			Consequence				
			1	2	3	4	5
			Insignificant	Minor	Moderate	Major	Catastrophic
Likelihood	5	Almost Certain	5	10	15	20	25
	4	Likely	4	8	12	16	20
	3	Possible	3	6	9	12	15
	2	Unlikely	2	4	6	8	10
	1	Rare	1	2	3	4	5

	Low	Medium	High	Extreme
Rating ≤	5	10	15	25

Figure 3 - Risk Table

During the planning of these trials, additional risk mitigation activities were also conducted to the scribing concept. These put lower pressure on the robot in terms of payload and cycle time. Extensive simulation work on the system also demonstrated ideal cutting speeds.

With these mitigation exercises, the consequence of the robot being the wrong robot to move forward with was maintained at “Catastrophic”, but the likelihood was re-assessed at “Possible”, leaving a residual risk of “High” (15/25).

4.5 Purchase Saw, Power Pack and Blades

The appropriate saw, hydraulic power unit and blades for our application then required procurement. For this we chose to work with Kentmaster, who are experts in meat processing equipment, specifically cutting tools.

- **Saw –** The saw selected was a Kentmaster HKM-1 Hydraulic Circular Breaking Saw. These saws are typically used to cut forequarters, chucks and briskets; however, the main characteristic of interest was its power (not likely to slow down whilst cutting through hard bones).

HKM-I

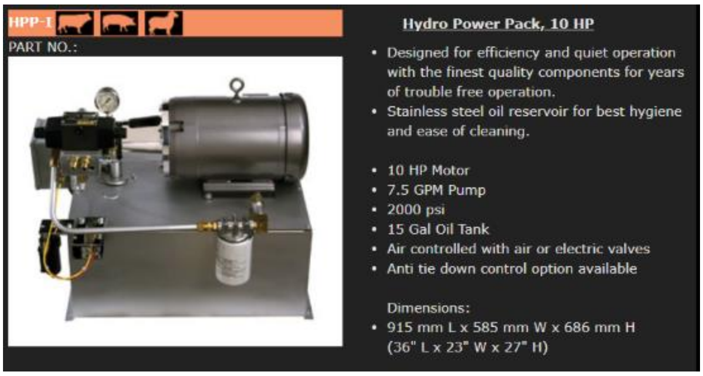
PART NO.: 6622000

Circular Breaking Saw, Hydraulic

- Swivel hanger for easy movement to any angle.
- Dual trigger for operator safety.
- Easy to clean and maintain.
- Constructed from corrosion resistance materials for sanitation.
- A powerfull, fast and versatile saw that will not slow down even in hard bones.
- Ideal for cutting forequarters, beef chucks, brisket and other beef and pork cuts.

Figure 4: Kentmaster HKM-1 Hydraulic Saw

- **<u>Power Pack –</u>** For the power unit, Kentmaster's largest 10HP kit was selected which would provide the saw with the maximum permissible torque, thus giving the best-case scenario by pushing the saw to its maximum capability.



HPP-I

PART NO.:

Hydro Power Pack, 10 HP

- Designed for efficiency and quiet operation with the finest quality components for years of trouble free operation.
- Stainless steel oil reservoir for best hygiene and ease of cleaning.

- 10 HP Motor
- 7.5 GPM Pump
- 2000 psi
- 15 Gal Oil Tank
- Air controlled with air or electric valves
- Anti tie down control option available

Dimensions:

- 915 mm L x 585 mm W x 686 mm H (36" L x 23" W x 27" H)

Figure 5: Kentmaster HPP-1 Hydro Power Pack

- **<u>Blade –</u>** For the blade, a Kentmaster 8" (200 mm) Diameter Saw Blade, 76 Teeth was chosen, which is a standard blade for bone cutting applications in beef.

C-BLADE

PART NO.:

Circular Blades

- Kentmaster stocks a variety of stainless steel and alloy steel circular blades with a variety of tooth design and thickness to suit the Kentmaster circular saw it manufactures.

Figure 6: Kentmaster C-Blade 8" with 76 teeth

All parts were manufactured by Kentmaster USA, and target delivery date was set for 2 weeks prior to trial start date. The manufacturer agreed to FAT the equipment in the US by connecting and running the saw prior to dispatching for the trials. Testing confirmed both the saw and power pack were operational.

4.6 Manufacturing Trial Equipment

The trial equipment (other than the saw) was manufactured both overseas and in Australia.

4.2.4 Robot Base & Cutting Platform

The robot base assembly was manufactured through a supplier overseas. Due to the weight and dimensions of the robot base assembly, manufacturing these components local to the trials was an ideal option as there would be less issues with the freight from a cost, lead time and logistical perspective.

- **Robot Base:** This was fabricated using thick plate steel which was later welded together and painted
- **Cutting Platform:** The cutting platform was fabricated using sheet steel and SHS. A vice was fastened to the front of the sheet steel enclosure which would be used to secure the test cutting pieces (i.e. Beef Rib). This vice was enclosed by a sheet steel case to ensure bone shards were captured during a cut thus reducing risk to the operator.

Figure 7: Cutting Platform

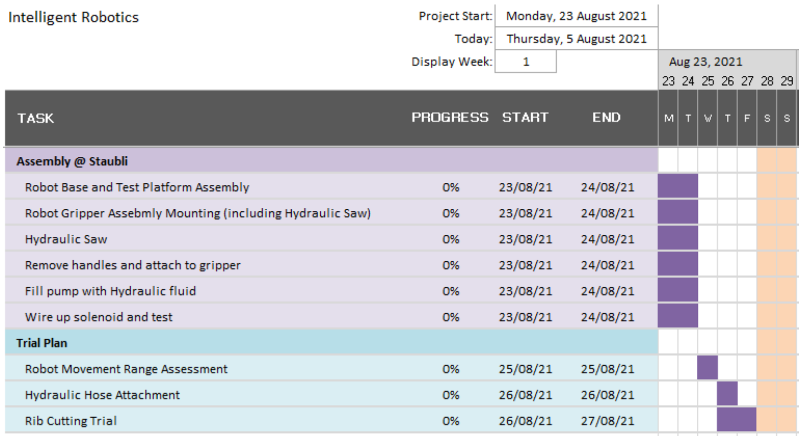
4.2.5 Robot End Effector – Saw Clamp

For the robot end effector, it was important to ensure the dimensions and weights would reflect what the ideal end solution would be. This the end effector was fabricated out of 6mm stainless steel plates and later welded together to the form factor which the scribing concept end effector assembly would take. While the scribing system concept had been modified, it was decided that it would still be worthwhile to understand this from a “worst-case” perspective and allow the concept to be revived at a future date if necessary.

The trial design was then fabricated in Australia with close attention allocated to the rollface of the gripper and also the saw clamp which were the two critical items to ensure everything fastened together smoothly once the parts come together at the test facility.

4.7 Trialling Plan & Methodology

Due to the small window of opportunity for the trials to be completed, it was critical to develop a test plan and methodology in order to capture the required data. In preparation for the trials, the following schedule was developed: -



Intelligent Robotics

Project Start: Monday, 23 August 2021
Today: Thursday, 5 August 2021
Display Week: 1

TASK	PROGRESS	START	END	Aug 23, 2021 23 M	24 T	25 W	26 T	27 F	28 S	29 S
Assembly @ Staubli										
Robot Base and Test Platform Assembly	0%	23/08/21	24/08/21	🟪	🟪					
Robot Gripper Assebmly Mounting (including Hydraulic Saw)	0%	23/08/21	24/08/21	🟪	🟪					
Hydraulic Saw	0%	23/08/21	24/08/21	🟪	🟪					
Remove handles and attach to gripper	0%	23/08/21	24/08/21	🟪	🟪					
Fill pump with Hydraulic fluid	0%	23/08/21	24/08/21	🟪	🟪					
Wire up solenoid and test	0%	23/08/21	24/08/21	🟪	🟪					
Trial Plan										
Robot Movement Range Assessment	0%	25/08/21	25/08/21			🟪				
Hydraulic Hose Attachment	0%	26/08/21	26/08/21				🟪			
Rib Cutting Trial	0%	26/08/21	27/08/21				🟪	🟪		

Figure 8: Trial Schedule

From this schedule, the test methodology for each trial was developed as per below outline: -

1) **Assembly of Trial Setup** – The first priority was to assemble all components delivered and ensure parts fasten together securely in preparation for cutting trials.
2) **Robot Movement Range Assessment** - Run the robot through trial cutting path routine and assess whether the movement range will allow us to make all our desired cuts. This will be done at various speeds.
3) **Hydraulic Hose Attachment and Pump Setup** – Connect hydraulic lines to the saw and activate the hydraulic power pack. Once powered, calibrate the power pack to the correct pressure for testing – 1,500 PSI which correlates to 1,450 rpm on the saw (a standard saw speed and pressure).
4) **Rib Cutting Trial** - This will involve clamping a raw beef rib (chilled) onto the cutting platform vice and programming the robot path to cut through the rib sample whilst observing cut performance using the hydraulic saw. Robot performance will also be assessed through both observation and test logs to ensure the robot does not trip during its cut cycles.

   The robot linear cut speeds can be raised incrementally by 0.1m/s until a stall point on the saw is hit. Tests will be repeated up to five times for each linear speed configuration. All changes to both robot and saw parameters to be logged if modified (i.e. blade changes etc.). Below is an image showing the planned cut cycles for each bone and checklist to go along with the data collection.

4.8 Pre-shipment Testing

Since most of the components were manufactured in different locations and then being shipped to the test facility, it was difficult to verify that everything would go together smoothly by carrying out a physical test fit with the robot. Thus, the pre-shipment testing mainly involved tolerance checks against drawings provided by the robot manufacturer and simulations were performed.

- **Robot Base & Cutting Platform**: Hole centre points were verified against the flat base drawings and robot models. Factory base mount hole locations for the angled base and the cutting platform were also verified against dimensions provided.
- **Robot End Effector- Saw Clamp**: The end effector rollface and saw clamp were also verified against tolerances provided by the manufacturers. It was critical to verify this as best as possible.

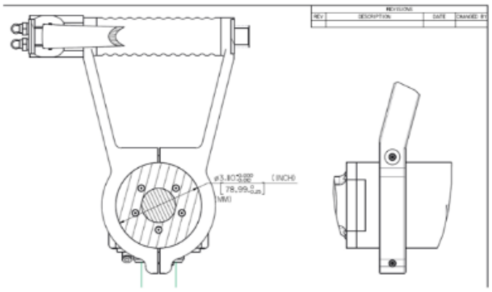


Figure 9: Saw Clamp Tolerances

- **Programming Robot Cut Path:** The CAD model of the end effector was loaded into simulation software to calculate a tool definition for use during the trials. The engineer would then program the paths required for the trials based on the final mounting position of the robot with respect to the cutting box.

4.9 Assembly of Trial Setup

This stage involved unpacking all the items at the test facility in France in preparation for the cutting trials.

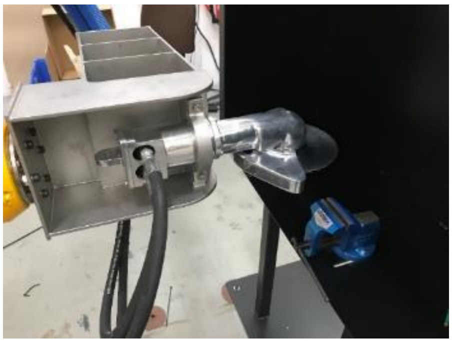


Figure 10: Saw Mounted to End Effector

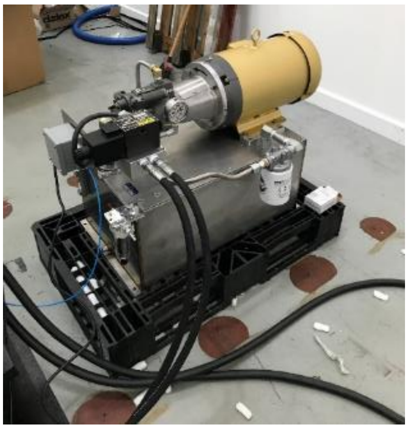


Figure 11: Hydraulic Power Pack Setup

Figure 12: Test Setup with Ribs

The trial setup came together without any major issues. All parts were fastened to the robot and by the end of this stage we were able to power up the saw and robot for testing.

4.10 Robot Movement Assessment

Once the cut path was programmed, the robot movement was tested at different linear speeds. The below image shows the cut path testing conducted with the saw blade stopped at its end position. This was conducted multiple times to ensure there were no issues with the Hydraulic hose fixtures, starting off with slow runs to ensure robot work envelopes could be set in order to avoid any collisions with the vice on the cut platform.

Figure 13: Cut Path Testing

One of the learnings from this stage, whilst trying to avoid collision with the blade lock nut, was that care was needed with carcase cuts that vary in depth along the scribing cut paths. Any depth variations need to be compensated for by the robot cut path program so that the saw blade locking nut does not collide or catch on any part of the carcase. Alternatively, a blade with a larger diameter compared to the 8” blade used during the trials could be utilised.

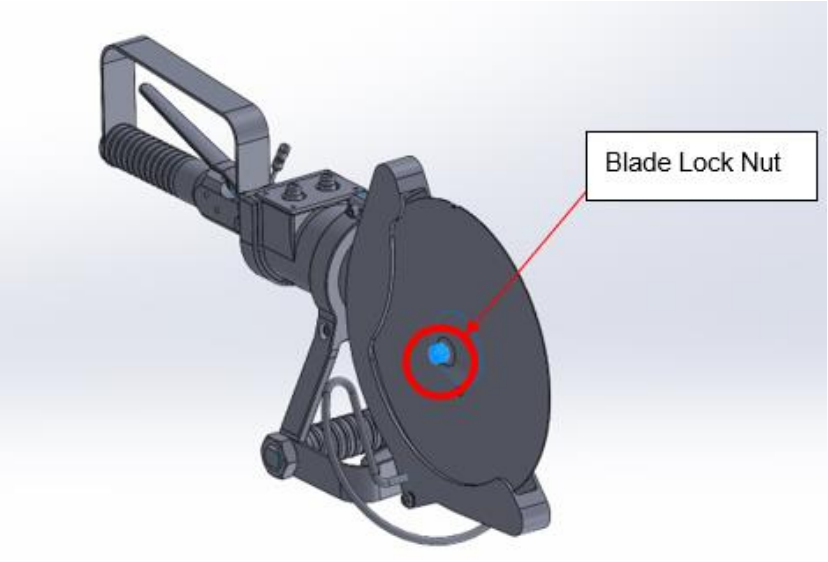


Figure 14: Blade Lock Nut

4.11 Rib Cutting Trials

This part of the trials was critical in understanding how the robot reacts as the saw is cutting through bone. There were certain variables we needed to control and measure throughout each cut cycle to determine their impact on the resulting cut quality, these include: -

- **Blade Condition –** This includes the sharpness and deformation of the blade as well as the condition of each tooth along.
- **Blade Specification -** Kentmaster 8" (200 mm) Diameter Saw Blade, 76 Teeth. This is a standard blade used in beef cutting.
- **Saw RPM –** Set to the standard 1,450 RPM.
- **Robot Linear Cutting Speed –** This would vary between 0.1m/s and 0.4m/s. We can test this up to 0.8m/s to assess impact.
- **Bone Specification –** Cooked and Raw Beef ribs kept in a chiller.
- **Robot Payload –** The overall payload including the saw mounted was 31kg.

As each cut is carried out, how the robot reacts will be observed, as well as the cut quality in order to understand the limitations of the robot. Any changes to the configuration such as blade changes were logged to help draw correlations with observations during the cut cycles.

4.11.1 Robot Stall Testing

One of the unknowns that needed to be determined during the trials was whether the robot would hit a stall point with the linear speed was too high. During one of the initial test cuts, the robot was run at maximum speed into the bone at full speed. The bone in this case was also a cooked test bone, which is much harder than a raw bone. This gave an absolute worst-case scenario in terms of stall testing with the robot.

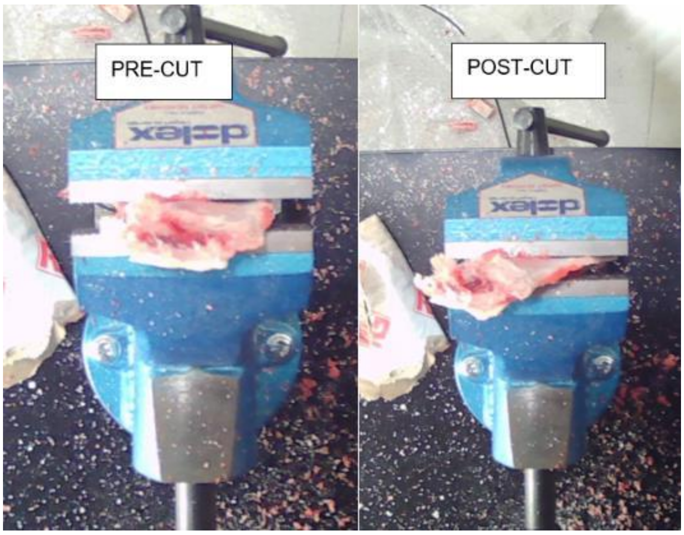


Figure 15: Full Speed Cut - Before and After

During the full speed impact the robot did not stall or deviate from its cutting path in the slightest. The bone did pivot in the vice which can be seen in the post cut image. This tells us that the robot definitely has enough strength to push through bone at high speeds.

4.11.2 Cut Cycle Testing

After the test cycles were complete, the trials moved into cut cycle testing with different bones and at linear speeds ranging.

Figure 16: Cut Cycle Trial - Camera Setup

The camera set up as seen above gave a good view of the cut cycle from a couple of different angles which helped to understand how both the robot and the bone react to each cut at their various linear speed cycles. Throughout all the cut cycles there were no issues experienced at linear speeds ranging from 0.1m/s to the second highest speed trialled.

Once cutting commenced on the fourth bone (23 cuts into testing, including initial test cuts with cooked bones), the faster cuts started failing to go through the bone completely. The observation was like what was seen with the full speed impact cut where the robot did not trip whilst trying to reach its end point. Instead, the bone was pushed and damaged at the point where the vice was clamping around it. Assuming it may have been something to do with the way the bone was clamped (not secure enough), another attempt was made at this speed with a new bone and the same issue was experienced.

A decision was then made to change the blade, assuming it may have been damaged slightly during the full speed collision we saw in the initial testing phase. Once the blade was changed, we experienced no more issues with the bone being pushed, and all subsequent cuts were clean straight through the bone.

The learnings from this were that the condition of the blade as well as the blade RPM's can have quite a critical impact on our cut quality. We could interpolate that as we go higher in linear speed, there is an increased likelihood that the saw will push the carcase enough to require re-fixturing with the vision system, especially if the blade is also worn or damaged over time. Different blades and RPMs could be explored in a future trial to assess what gives us our optimal results for the linear speeds we want to cut at.

4.12 Risk Review

With the trials being completed, Intelligent Robotics is confident of the following conclusions about the robot:

- It can handle the external inertias to perform cutting of bones, particularly with respect to the high rate-of-change during cut engagement, without tripping out, even when the blade isn't cutting optimally.
- The spinning mass associated with the saw blade did not cause the robot to trip

The residual risk rating regarding the robot not being suitable for beef scribing with a hydraulic tool has now been classed at “Moderate”.

4.13 Review of Results to Date

This project primarily aims to understand the considerations related to robotic cutting for the meat industry. Specifically, the suitability of the robot for scribing, and the characteristics of the ideal saw to use for the application. The robot was selected due to its hygienic nature and the fact it does not require a bag to be used. The concern was whether the robot would be able to handle the external inertias involved with the scribing application without tripping out. Similarly, it was suggested that a hydraulic saw may be more fit-for-purpose for the application given previous issues of electric saws stalling in industry, and that it was worth examining the performance considerations including confirming that stalling does not occur, and investigating the impact of hydraulic hose management and how performance changes with sharp vs blunt blades.

Due to the COVID-19 pandemic (various lockdowns and inability to access sites), a pivot was made early in the project to perform trials at the robot manufacturer's facility overseas. The required robot base, saw end effector, custom dress-pack, and cutting platform were designed and manufactured. A Kentmaster hydraulic saw and powerpack were purchased and shipped. Trials were then performed where the robot was setup to cut through rib bones at various speeds. Some bones were also cooked to simulate older, harder, ribs. The robot was also setup to perform dry cycles of cut paths continuously to observe how the robot coped with the hydraulic hoses.

The key outcomes from this trial were:

- The robot was able to cope with the external inertias of the saw blade spinning and cutting of the bone without any trip out issues. This was even the case when the cut was run at full robot speed into a cooked bone, resulting in the saw blade stalling and the rib being pushed within the vice rather than cut. The robot did not trip out on any of the trials performed.
- The robot was able to cope with the moving mass of the hydraulic hoses when performing repetitive dry cycles of cut routines.
- Engagement and cutting speeds up to the second fastest speed trialled did not result in any issues through the trials, for either the hydraulic saw or the robot.
- As the blade had become blunt, the cut quality decreased, and the saw eventually stopped cutting completely through the bone. The rate of wear was accelerated by cutting through cooked bones and attempting to engage the cut above the fastest speed trialled for some trials. Saw stalling was observed in some of these instances, albeit at faster robot speeds than would be utilised for the automated system. The robot was able to cope with the wear of the blade successfully without tripping out.
- The hydraulic hoses were able to be managed through the repetitive dry cycles without any issues of getting caught in the robot.

4.14 Processor Engagement and Proposed Pivot

Since this work was performed, extensive consultation was performed with an Australian processor. They have performed a lot of work in the past on saw and blade selection which they were willing to share with us. This journey has included trialling pneumatic saws, then electric saws, then hydraulic saws, and eventually back to a certain electric saw. The hydraulic saws were pulled out within a week as they “didn’t have enough power and would grab and stop”. The processor has kept with the final electric saw since switching to it from the hydraulic and believe they have had zero issues with it stalling. After trialling numerous saws powered various different ways, and acknowledging past issues with electric saws/with other suppliers, the processor is very happy with this electric saw. This aligns with some of the preliminary findings from the factory trials that the risk of saw stalling is not eliminated completely if moving to a hydraulic saw. Their experience of a hydraulic scribing saw “grabbing” would be potentially problematic in a robotic application.

There are also a number of additional challenges associated with hydraulics which must be managed, such as maintaining of hoses, detecting and dealing with leaks (particularly pinhole leaks) or complete breakages (which pose a safety hazard as well as significant risk to product). While hydraulic tools are used elsewhere in the plant, there is a human operator which is able to detect the presence of any leaks, no matter how small or early, and react accordingly. A fully automated system would lack this continual oversight – while automated monitoring could be implemented, the detection of small or pinhole leaks may not be possible. This is in contrast to an electric saw where failure of its power cable can be automatically detected and handled quickly, reliably and safely. It is believed that an electric saw with the system will be more readily accepted by the industry for these reasons.

The most important consideration however is selecting the right saw for the job (regardless of whether it is electric or hydraulic).

<u>Proposed Pivot:</u>

Since this feedback, Intelligent Robotics has been reconsidering whether an electric saw would be best suited for the scribing system.

The robotic component of the project has been de-risked with a high-level of confidence that the robot is able to cope with all the required implications of cutting and therefore a fit-for-purpose selection with respect to automated beef scribing. It was therefore proposed the next stage focus on the saw technology, specifically confirming the processor's experience with electric saws.

IR has also been investigating different options for electric saws and found a higher power version of the saw that was mentioned (35% more power). If moving to electric, this would be the saw of choice.

Furthermore, there are further back-up options planned if needed, including higher power options or a custom saw with similar torque capabilities as a hydraulic saw.

For the next milestone of the project, the following methodology was therefore proposed:

- Perform a trial on-site to investigate the performance of the current electric saw
    - Design and procure a trial setup to log the current drawn by the saw on their processing line
    - Perform logging over at least one full shift to capture a large dataset of carcases processed, as well as characterise any change in performance with the blade becoming blunt
    - Analyse the data to investigate for any instances of stalling, and characterising how hard the saw is working
- Make a conclusion on the feasibility of using the electric saw based on these trial results

A key benefit in taking this approach with these trials is the vast amount of data that can be generated to assess the saw's suitability and performance in-depth - they can be performed on a large number of carcases (1000+ sides) and wide variety of carcases which are processed.

4.15 Trial Preparation

The trial was seeking to understand the following key items:

- In general, how hard is the processor's existing saw currently working?
    - How much current is it drawing when performing cuts?
    - How does this relate to the saw's specifications?
- Are there any instances of saw stalling which are observed?
    - How close does the saw come to drawing stall current?
    - Is the saw significantly slowing down under load (and approaching a stall)? In this instance, the operator could be slowing down the cut when they 'feel' this to prevent the saw from stalling. This would be challenging to implement for a robot however.
- How does the saw current draw change across different product (e.g. carcase types and maturity levels)?

Characterising these key points will allow an assessment of the current saw, and the suitability of the saw with 35% more power proposed for the scribing system.

Breakdown (peak) torque occurs at approximately 1975rpm. Under normal operation, the saw will be running at rated speed and torque. As it is loaded above the torque it produces at its rated speed, it will slow down, draw more current, and produce more torque. It will do this until it hits its peak torque. If this torque is still insufficient, the motor will continue to slow down and eventually stall as its torque output actually drops as it slows down past this point and it is unable to speed back up.

During the trials we will be interested in understanding whether there are any instances of the saw stalling, which will be indicated by extended current draws around the breakdown torque current draw. How hard the saw is working will also be assessed by observing how close to this point the saw operates during cuts through the trial period. Note, it is prolonged current draws at these levels which are of interest – transient spikes are not of concern, particularly as the saw is turned on (inrush current draw). The saw used has a trigger which means the saw is turned on while the operator is performing a cut, and turned off otherwise. A high inrush current will be encountered each time the saw is turned on for a short period of time, but this is normal.

The trialling equipment used needs to be matched to the saw specifications. The targeted sampling rate was less than 100ms – assuming a minimum cut time of 0.5s this would allow five samples to be taken for the smallest cut. As fast a sampling rate as possible would be ideal from a data analysis perspective but would produce the largest amount of data. The ability to record data is also critical as the data is to be captured over approximately 24 hours. Ideally this capture could be stopped and started remotely to allow the data capture to be stopped during production breaks without needing to be physically present at the device. Logging the data in sessions also serves as a safety net by reducing the amount of data lost in the case of a failure (e.g. loss of power).

A number of solutions were examined, including Fluke power/energy meters and loggers (e.g. Fluke 1732, Fluke 1738, Fluke MDA0550), various oscilloscopes (e.g. Fluke ScopeMeter 190-240/S, Hioki PW3198, Hioki MR8847, PicoScope 2000 and 4000 series), and various dataloggers (e.g. PicoLog CM3, PicoLog 1000 series). Many of these were ruled out due to insufficient sampling intervals or memory sizes, cost, or long lead times. Eventually the PicoScope 2206B was selected due to its balance of functionality, availability, and cost.

A GMC ProFlex ACP3005/24 Rogowski coil current transducer was selected for the current measuring. This unit is able to work with the Picoscope. Being a Rigowski coil rather than a clamp, it is also lower weight and smaller footprint which makes it easier to mount around a core in the electrical panel feeding the saw.

Figure 17 - PicoScope 2206B digital oscilloscope (left) and ACP3005 Rigowski coil current transducer (right)

A tablet was then setup with the Pico logging software. AnyDesk remote desktop software was loaded onto the tablet as well. This would allow the tablet to be accessed remotely via the internet to allow logging sessions to be started and stopped remotely, as well as providing remote access to the data from previous sessions to allow it to be analysed while on-site on a separate laptop to identify if there were any major issues with the data. The use of this software was coordinated with the site’s IT team to ensure it was suitable for their security policies.

The timing of the trial was coordinated with the site to ensure the greatest mix of carcases through the trials. The best window identified was approximately midday on Monday through to midday on Tuesday to get the desired range of product.

The equipment was taken on-site and setup in the maintenance workshop housing the electrical panel feeding power to the scribing saws. The panel was opened by a site electrician and the current transducer was placed around one of the phases for one of the saws. The site was operating two boning room lines during the day shift and one boning room line on the night shift, so care was taken to setup on the saw that would be used for the night shift as well. A spare ethernet port in the workshop was patched to allow internet access and this was connected to the logging tablet. The PicoScope was connected to the tablet and the current transducer, and some sample acquisitions were performed to ensure the equipment was operating as expected. The logging interval was set to 1ms, which gives 20 samples per electrical cycle (electrical supply at 50Hz).

4.16 Data Analysis

Dry run with saw:

A dry run with the saw was first performed to confirm the equipment was setup correctly. This involved an operator pressing the trigger on the saw and observing the data produced. This also confirmed that the equipment was setup on the correct saw.

The data produced are shown on the figures below. It can be seen that after the initial inrush spike of the current draw of the saw settled to about the rated current of the saw. The initial peak lasts for less than one (20ms) and completely subsides in less than 50ms. The frequency of the saw current draw can be seen to be 20ms (50Hz) which is to be expected. These observations are all in line with what was expected.

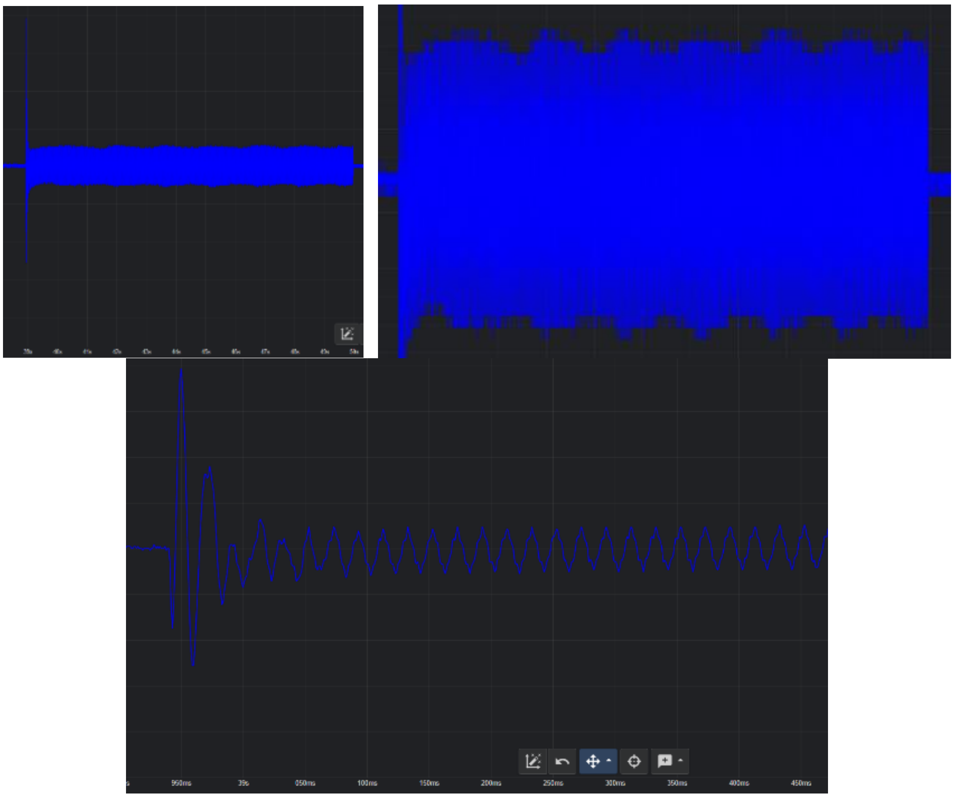


Figure 18 - Current draw for saw motor dry run

Initial Carcase Cut Observations:

The trials were conducted from approximately 11:45am Monday to approximately 11:15am Tuesday across four data acquisition runs (Mon 11:45am to 5:40pm, Mon 7pm to 12am, Tue 5am to 8am, Tue 8:30am to 11:15am).

An example of the data produced through a run of carcases is shown below. It can be seen that the inrush transient for the saw is present every time the operator presses the trigger to start the saw, which then dissipates within ~50ms. The saw current draw then drops significantly.

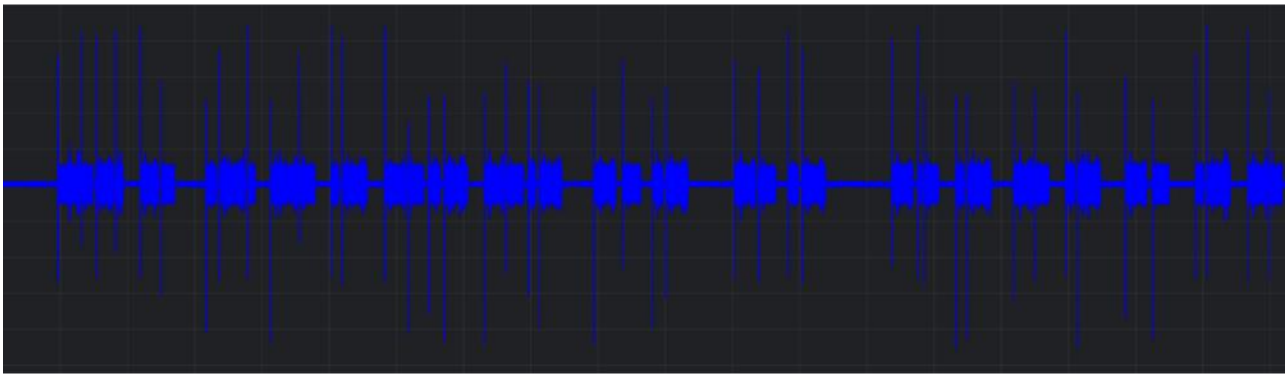
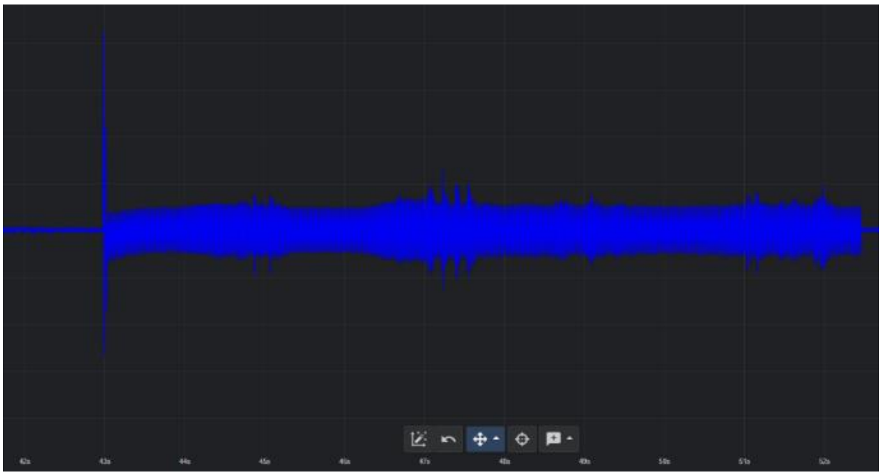


Figure 19 - Carcase cutting data

When performing the cuts, small ‘spikes’ can be seen through the cut. The example snapshot below shows a rib cut. The ‘spikes’ look to correspond to where the saw engages with various ribs. It can be seen that these are not very pronounced when compared to the rated running current of the saw, and some ribs don’t appear to be visible at all in terms of increased loading on the saw. The current draw on the saw also seems to drop fairly quickly back towards rated current when passing through each rib, rather than one prolonged period of extended current draw throughout the whole cut. This suggests the saw is working well within its capabilities.



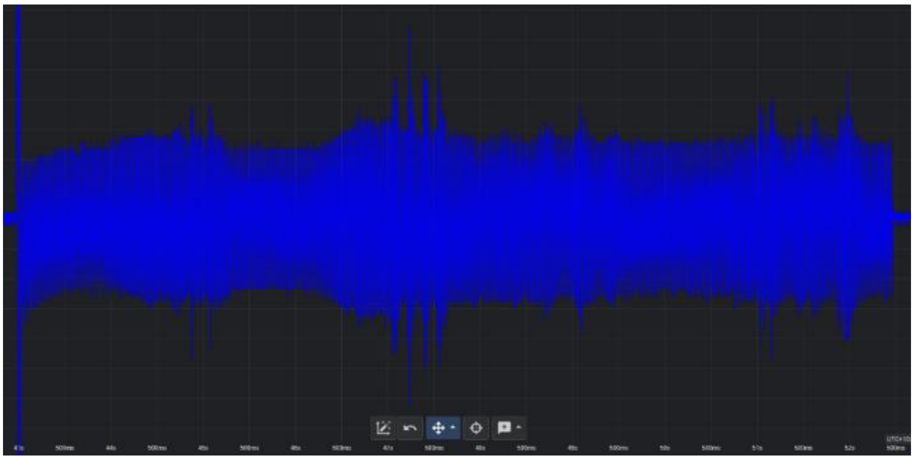


Figure 20 - Current draw when performing rib cuts

Similarly, when performing the spine cuts, there appears to be a spike as the saw initially engages the chine. There also appears to be a second spike shortly after. It is theorised that this may indicate when the saw blade reaches the rib where it attaches to the spine. As with the rib cuts, it does not appear as though the saw is loaded significantly above its rated current throughout the cut – there is only a small period of higher loading at these spikes.

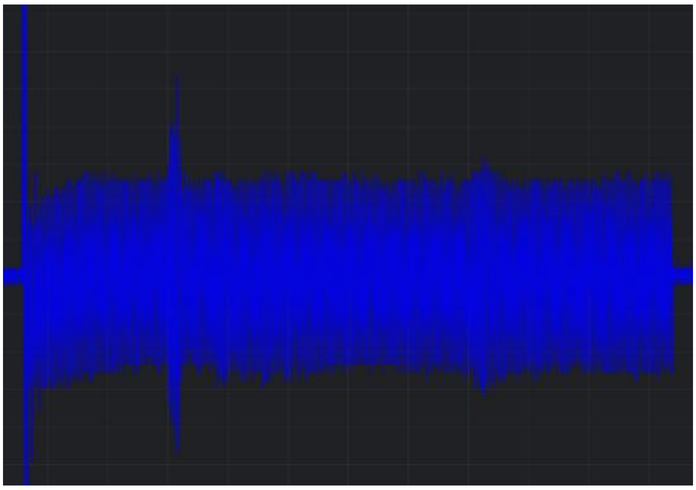


Figure 21 - Spine cut current draw

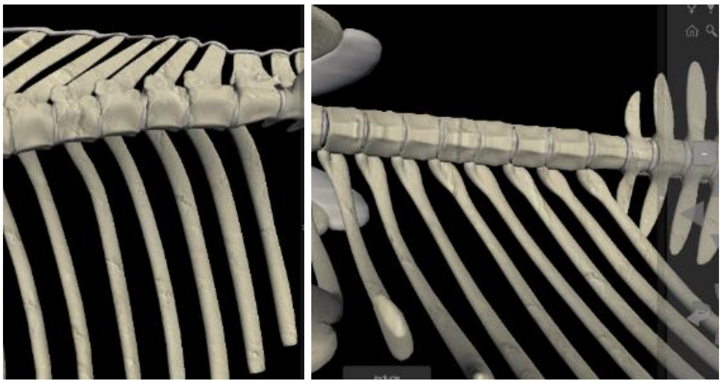


Figure 22 - Anatomy of beef carcase - note the attachment of the rib to vertebrae. When performing a spine cut, the top part of the rib at this attachment is often cut as well

Data Preparation

Figure 23 below shows all the data from the first data capture run (from ~11:45am to ~5:40pm). It can be seen that it is extremely difficult to make observations at this level when viewing the data due to the density of the transient inrush spikes. When zooming into the data (Figure 24), it can be seen that the average current drawn by the saw is significantly less than what is seems when observing Figure 23.

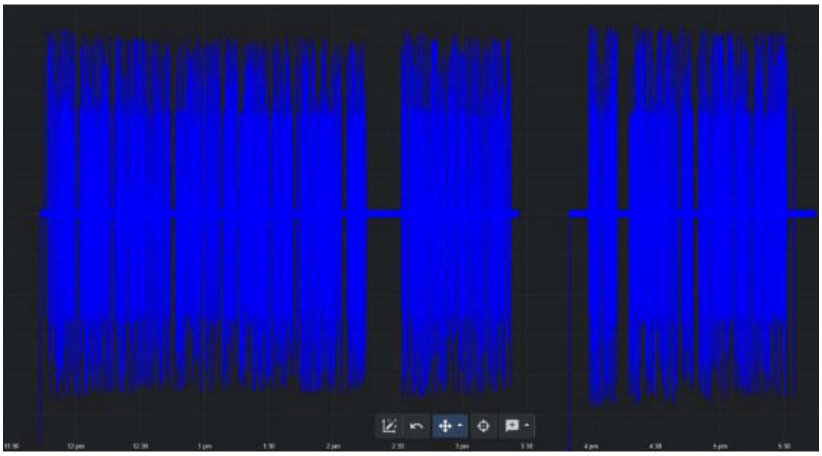


Figure 23 - Data capture from Mon 11:45am to 5:40pm

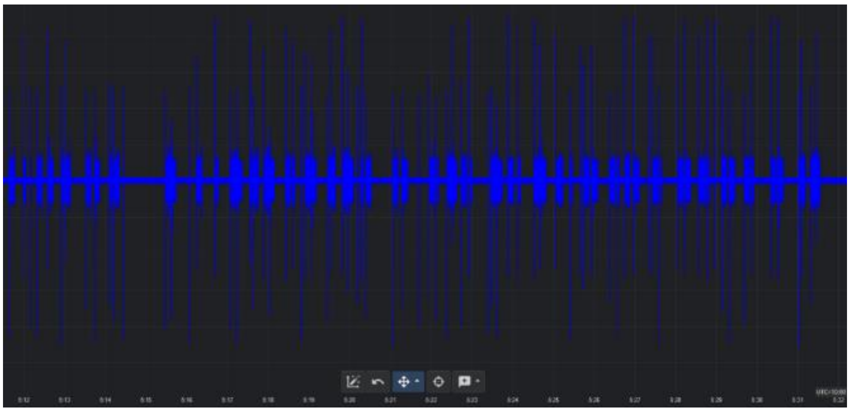
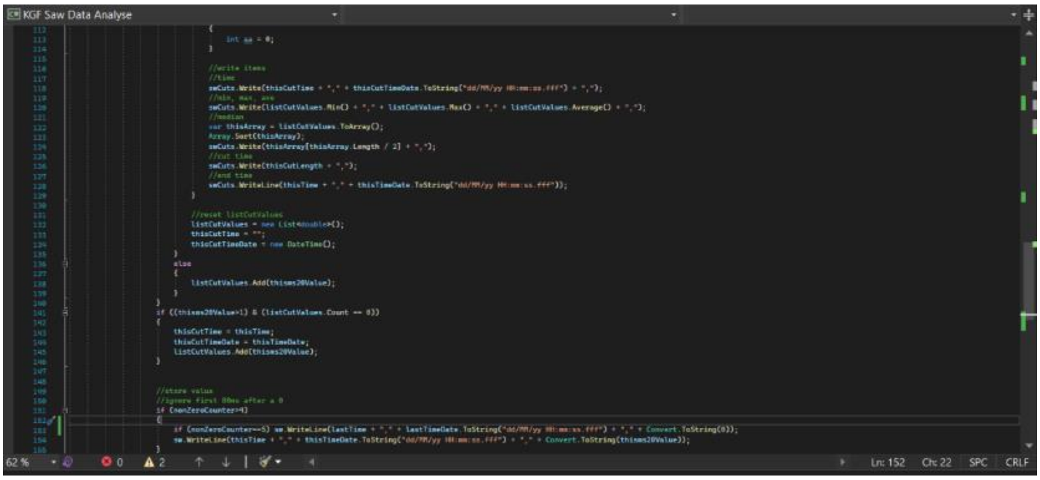


Figure 24 - Zoomed in data from 5:12pm to 5:32pm

In order to better analyse the data across the entire trial period, a script was written to first filter the data. The data were consolidated into one dataset (58,529,784 data points at 1ms intervals). A C++ script was then written to perform the following tasks:

- Create an initial filtered dataset:
    - Quantise the data into 20ms points (i.e. one cycle at 50Hz) where the maximum absolute current value in each 20ms block was isolated
    - Identify and remove inrush transient spikes
    - Remove any large gaps where the saw is not running
- Create a second dataset seeking to isolate and characterise each “block” where the saw is running (generally speaking each cut, although there would be instances where the operator kept the trigger pressed while performing multiple cuts, or where they’ve pressed the trigger but not performed a cut)
    - Isolate each saw running “block” of data from the dataset

  - Log the time, minimum current, maximum current, mean current, and median current for that block



```
            {
                int aa = 0;
            }

            //write items
            //time
            swCuts.Write(thisCutTime + "," + thisCutTimeDate.ToString("dd/MM/yy HH:mm:ss.fff") + ",");
            //min, max, ave
            swCuts.Write(listCutValues.Min() + "," + listCutValues.Max() + "," + listCutValues.Average() + ",");
            //median
            var thisArray = listCutValues.ToArray();
            Array.Sort(thisArray);
            swCuts.Write(thisArray[thisArray.Length / 2] + ",");
            //cut time
            swCuts.Write(thisCutLength + ",");
            //end time
            swCuts.WriteLine(thisTime + "," + thisTimeDate.ToString("dd/MM/yy HH:mm:ss.fff"));
        }

        //reset listCutValues
        listCutValues = new List<double>();
        thisCutTime = "";
        thisCutTimeDate = new DateTime();
    }
    else
    {
        listCutValues.Add(thisms20Value);
    }
}
if ((thisms20Value>1) & (listCutValues.Count == 0))
{
    thisCutTime = thisTime;
    thisCutTimeDate = thisTimeDate;
    listCutValues.Add(thisms20Value);
}


//store value
//ignore first 80ms after a 0
if (nonZeroCounter>4)
{
    if (nonZeroCounter==5) sw.WriteLine(lastTime + "," + lastTimeDate.ToString("dd/MM/yy HH:mm:ss.fff") + "," + Convert.ToString(0));
    sw.WriteLine(thisTime + "," + thisTimeDate.ToString("dd/MM/yy HH:mm:ss.fff") + "," + Convert.ToString(thisms20Value));
}
```

Figure 25 - Data preparation script written in C++

The data were then imported into excel for visualisation and analysis.

20ms Quantised Dataset

The figure below is a scatterplot of the quantised dataset across the whole trial. Each datapoint represents one 20ms sample, where each sample is the maximum absolute peak current within that sample. From this data we were looking to identify if there are any prolonged stretches of points which are close to the stall current for the saw. It can be seen that at no point during the trial does it look like any stalling occurred with the saw.

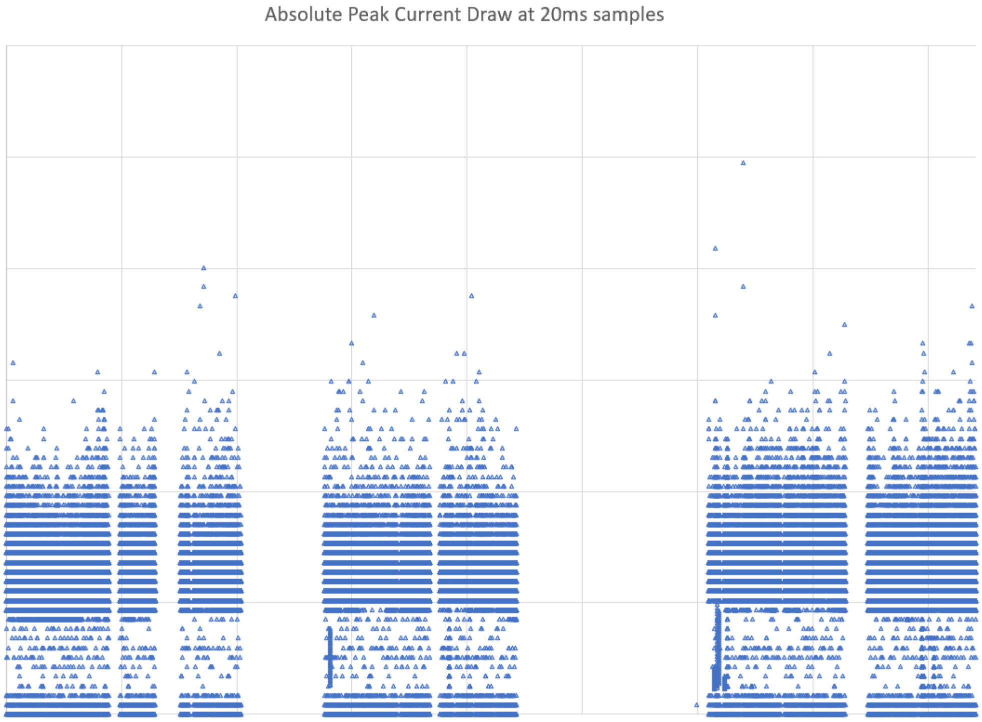


Figure 26 - Quantised 20ms data across full trial

There are some data points visible at the higher end. Zooming into the data and checking against the raw data, it was confirmed that these points are in fact standalone rather than a series of sequential datapoints which were not visible due to the level of zooming. Hollow markers were selected to make consecutive datapoints more visible, but this was checked just in case.

Figure 27 shows the waveforms for the cuts which registered the highest currents. It can be seen that the datapoints genuinely corresponds to a cut (rather than noise or inrush). The peaks were observed for what looks like two spine cuts and one rib. Most importantly, in all cases the peaks dissipate quickly (within one cycle) and do not look to indicate consistently high workload on the saw or present a risk of stalling.

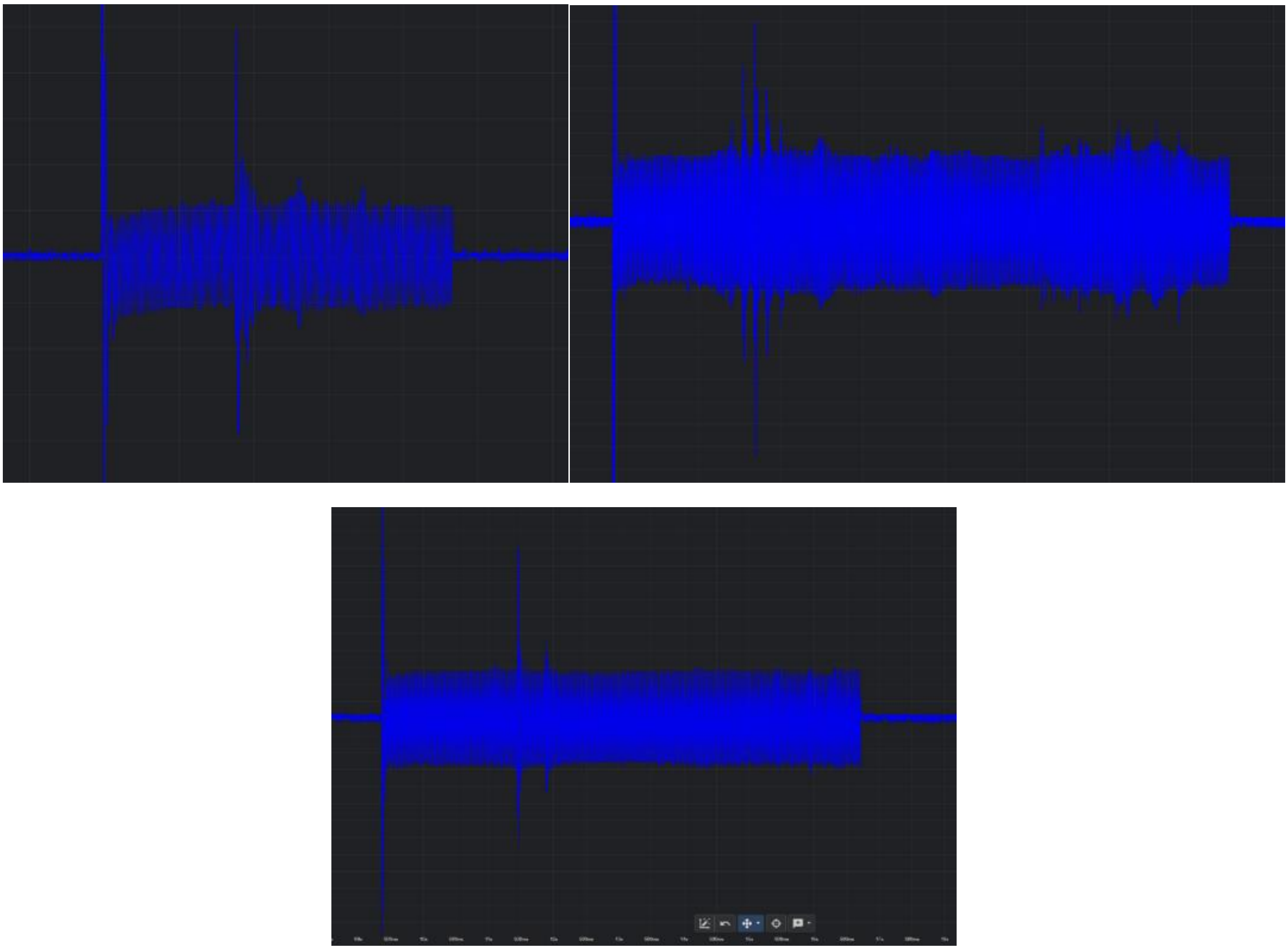


Figure 27 - Largest current draw peaks observed

From the quantised data the saw looks to be operating well within its capabilities. There are no instances or stalling encountered and no draws close to the breakdown torque current threshold. The largest draws seen during cuts were momentary and appeared to dissipate within one cycle. This gives a high level of confidence that the current saw is operating well within its design limits.

<u>Carcase Type Analysis</u>

Throughout the trials there were a range of different carcases processed with varying maturity levels. Approximately 1740 sides were processed during the trial period.

Within these runs, a range of maturity levels were processed. The maturity levels are indicated at “0 to X tooth” for a given product code, with “0 to 2 tooth” being the youngest product, and “0 to 8 tooth” including the most mature product. Table 2 below summarises the production information relevant for the trial period. Figure 28 shows a scatterplot of the carcases processed through the trial period.

It should be noted that the production timestamps will not align perfectly with the saw data, as the point at which the carcases are scanned into the boning room is positioned a couple of minutes downstream of the scribing saws. So while the saw current data can be aligned in terms of approximate production run, it cannot be aligned on a carcase-by-carcase level.

Table 2 - Production overview

Time	Type	Maturity
Day 1 – ~11:45am to ~2:30pm	A	0-4 tooth
Day 1 – ~2:30pm to ~3:07pm	A	Mainly 0-7 tooth
Day 1 – ~3:07pm to ~3:30pm	A	0-4 tooth
Day 1 – ~4pm to ~11:30pm	B	Varies from 0-2 tooth to 0-8 tooth
Day 1 – ~11:30pm to ~12am	A	0-4 tooth
Day 2 – ~5am to ~11:15am	C	Mainly 0-2 tooth with some 0-4 tooth and 0-8 tooth

Figure 28 - Maturity levels and carcase type across the trial period

Figure 29 below shows the saw current data aligned with the production runs. Gaps in production runs have been removed to give the data as much spread as possible. As with the waveform data, the sheer density of points (1,200,000) makes it difficult to draw many inferences on how much the saw is operating within the lower range, but there are some key observations that can be made on the upper end of the data.

- At a high level, it looks like there's no noticeable increase in saw current when processing the older grainfed cattle in run #2 (orange, 0-7 tooth) when compared to run #1 (dark blue, 0-4 tooth).
- The B product appears to see higher spikes in current than the A product. This suggests that B product may be 'harder' on the saw, which is in line with expectations.
- The short 0-4 tooth A run at the end of the day on Day 1 (light blue) appears to draw the same saw currents as the first run (dark blue) which suggests a negligible blunting of the blade after the harder B run.
- Interestingly, the C run on Day 2 (green) appears to have higher peak current draws than the trials on Day 1. This is despite having a new blade and the product being the least mature (0-2 tooth). At this processor's site, each day they replace both the saw and the blade. They also use resharpened blades. It could be that the blade was not sharpened to as high a quality level, or there are differences in this particular saw (e.g. it is older). It may also be that the different operator uses the saw differently.
- With respect to the waveforms shown in Figure 27 above corresponding to the three highest datapoints, the top two waveforms are for C product, and the bottom is from the B run. As can be seen in these waveforms though, the current draw dissipates quickly and the average draw through the cut remains well within the saw's capabilities.

Despite these observations, it should be re-iterated that these appear to have a marginal impact on the performance of the saw, and the key takeaway is that the saw doesn't appear close to its stalling limits at any point.

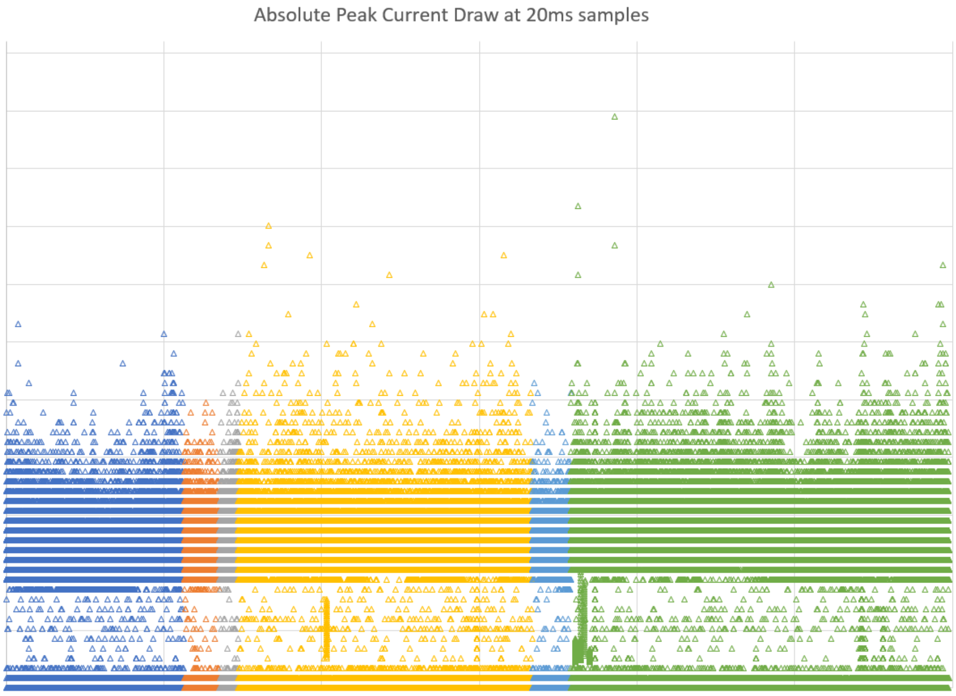


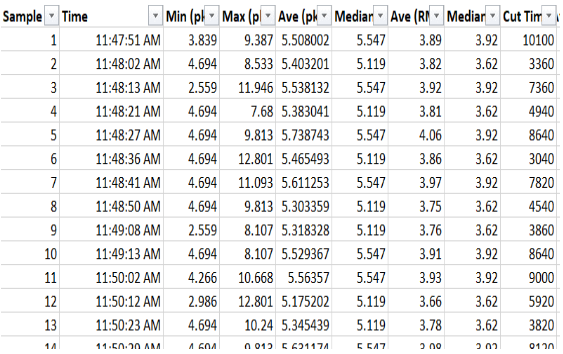
Figure 29 - Quantised 20ms saw current data aligned in production runs

Cut Analysis

The quantised dataset was useful for making high level observations of the current draw during the trials, particularly in terms of highlighting any potential instances of sustained high current draw or stalling (neither of which was found). The density of the datapoints however makes it difficult to understand how hard the saw was working through the cut, as can be seen by the waveforms in Figure 27.

As mentioned previously, a script was written to isolate the sections of data where the trigger was being held by the operator. In most cases this will correspond to one cut, but there may be instances where a cut was not performed, or where multiple cuts were performed without releasing the trigger. Observing the operators, it looks like they generally released the trigger between cuts however, which would also make sense from a safety perspective.

The data generated by the script was then put into excel for analysis (Figure 30). The data were segmented according to the production runs and plotted on a scatterplot (Figure 31).



Sample	Time	Min (pk	Max (p	Ave (pk	Median	Ave (RI	Median	Cut Tim
1	11:47:51 AM	3.839	9.387	5.508002	5.547	3.89	3.92	10100
2	11:48:02 AM	4.694	8.533	5.403201	5.119	3.82	3.62	3360
3	11:48:13 AM	2.559	11.946	5.538132	5.547	3.92	3.92	7360
4	11:48:21 AM	4.694	7.68	5.383041	5.119	3.81	3.62	4940
5	11:48:27 AM	4.694	9.813	5.738743	5.547	4.06	3.92	8640
6	11:48:36 AM	4.694	12.801	5.465493	5.119	3.86	3.62	3040
7	11:48:41 AM	4.694	11.093	5.611253	5.547	3.97	3.92	7820
8	11:48:50 AM	4.694	9.813	5.303359	5.119	3.75	3.62	4540
9	11:49:08 AM	2.559	8.107	5.318328	5.119	3.76	3.62	3860
10	11:49:13 AM	4.694	8.107	5.529367	5.547	3.91	3.92	8640
11	11:50:02 AM	4.266	10.668	5.56357	5.547	3.93	3.92	9000
12	11:50:12 AM	2.986	12.801	5.175202	5.119	3.66	3.62	5920
13	11:50:23 AM	4.694	10.24	5.345439	5.119	3.78	3.62	3820

Figure 30 - Snippet of excel data analysis spreadsheet

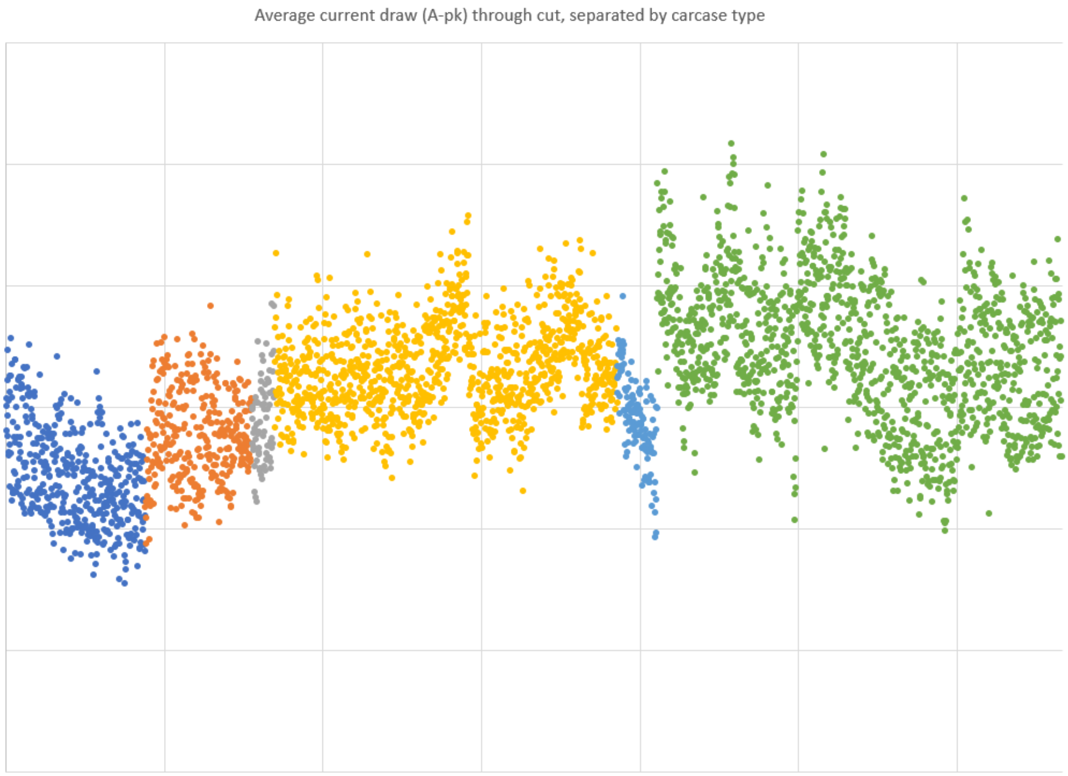


Figure 31 - Average current draw (A-pk) through cut, separated by carcase type

The first thing to note is the narrow range for the average current draw on the vertical axis on the plot. The average draw varied well within the saw's capabilities.

As with the plots in the previous section, it can be seen that the B product drew slightly higher average saw currents compared to the A product processed on the same day. Furthermore, the C product processed on the morning of day two seemed to draw higher average current, and with a much larger spread than was observed on the first day of trialling. Figure 32 below shows the original waveform data for some of the cuts which registered the highest average current draws. There does not appear to be anything particularly noteworthy in these waveforms, although it can be seen that the current draw during the cuts (indicated by the peaks) may last slightly longer than in some of the other data. These draws are still well within the capabilities of the saw however. In contrast, Figure 33 below shows some of the waveforms for the lower average current draw cuts. These have smaller and narrower peaks but are not too dissimilar in presentation.

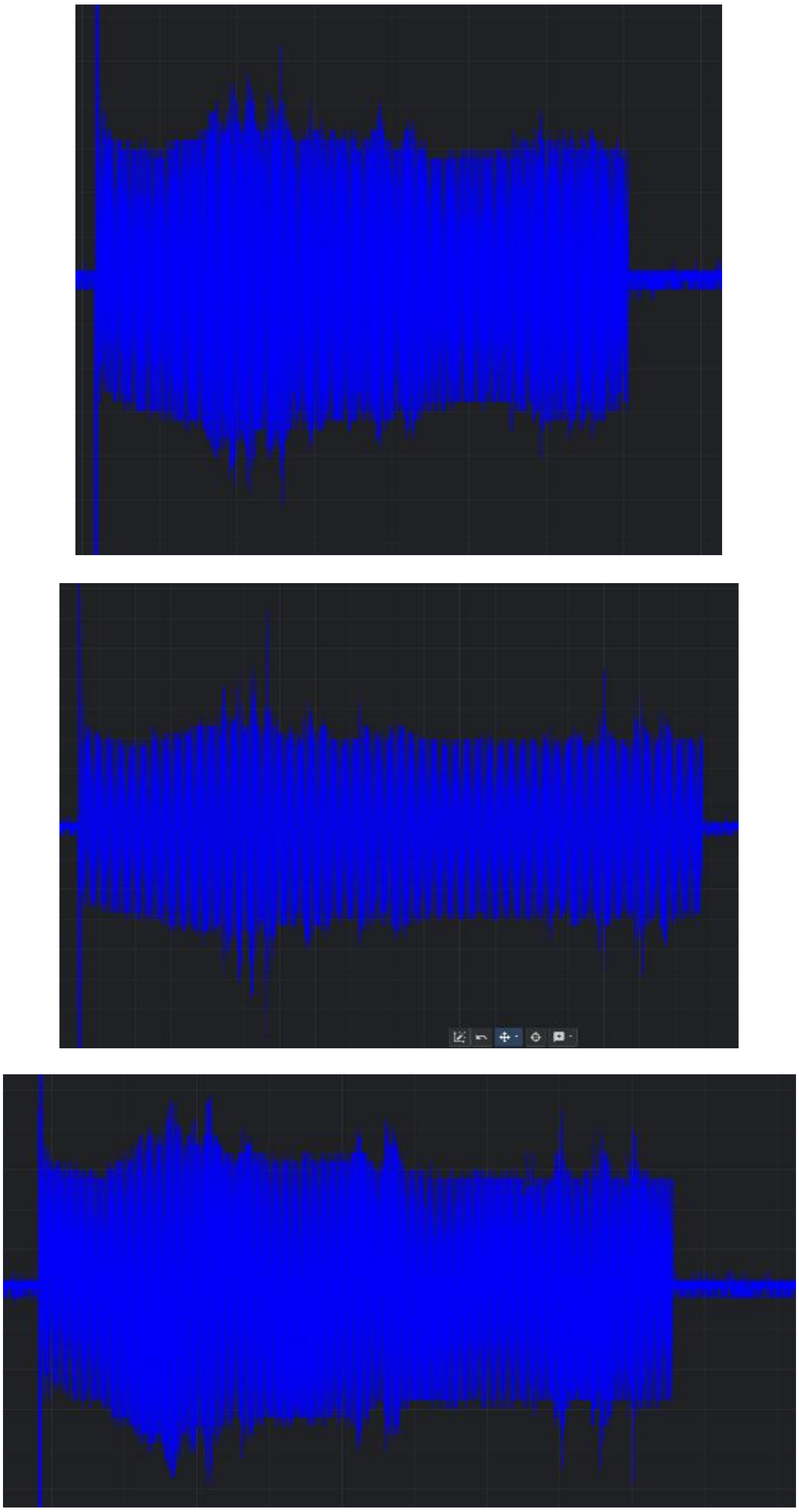


Figure 32 - Examples of higher average cut draw waveforms

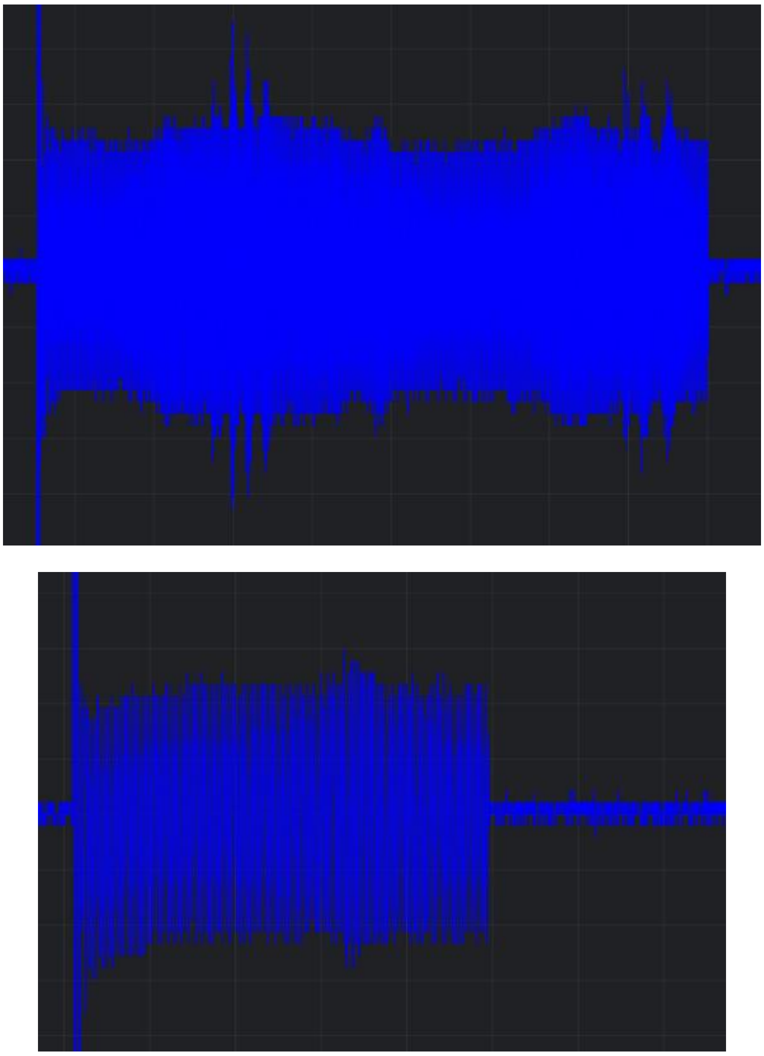


Figure 33 - Lower average current draw waveforms

5.0 Conclusions / Recommendations

This project aimed to understand the considerations related to robotic cutting for the meat industry. Specifically, the suitability of the selected robot for scribing, and the characteristics of the ideal saw to use for the application. The robot was selected due to its hygienic nature and the fact it does not require a bag to be used. The concern was whether the robot would be able to handle the external inertias involved with the scribing application without tripping out. Similarly, it was suggested that a hydraulic saw may be more fit-for-purpose for the application given previous issues of electric saws stalling in industry, and that it was worth examining the performance considerations including confirming that stalling does not occur, and investigating the impact of hose management and how performance changes with sharp vs blunt blades.

Trials were then performed where the robot was setup to cut through rib bones at various speeds. Some bones were also cooked to simulate older, harder, ribs. The robot was also setup to perform dry cycles of cut paths continuously to observe how the robot coped with the hydraulic hoses. The key outcomes from this trial were:

- The robot was able to cope with the external inertias of the saw blade spinning and cutting of the bone without any trip out issues. This was even the case when the cut was run at full robot speed into a cooked bone, resulting in the saw blade stalling and the rib being pushed within the vice rather than cut. The robot did not trip out on any of the trials performed.
- The robot was able to cope with the moving mass of the hydraulic hoses when performing repetitive dry cycles of cut routines.
- As the blade had become blunt, the cut quality decreased, and the saw eventually stopped cutting completely through the bone. The rate of wear was accelerated by cutting through cooked bones and attempting to engage the cut at the fastest speed for some trials. Saw stalling was observed in some of these instances, albeit at faster robot speeds than would be utilised for the automated system. The robot was able to cope with the wear of the blade successfully without tripping out.
- The hydraulic hoses were able to be managed through the repetitive dry cycles without any issues of getting caught in the robot.

After these trials, there was a high degree of confidence that the robot would be suitable for an automated beef scribing system.

With the robot shown to be suitable for performing cutting tasks without any issues, the focus was shifted towards selecting the ideal saw technology for scribing. One processor shared with Intelligent Robotics and AMPC their journey of trialling numerous scribing saws (pneumatic, electric, hydraulic, and then electric again). They eventually found a particular electric saw perfect for their needs, and believe they had had no issues of stalling since installing it. The benefits of using electric versus hydraulic are significant, primarily due to removing any risks related to high pressure hydraulic fluid in an automated system with potentially no human supervision. An electric saw would be more widely accepted across the industry if used for an automated beef scribing system. After careful consultation with AMPC, it was agreed that a pivot was warranted to examine this saw option more closely as the primary goal is to understand the best saw technology to use.

A site trial was performed where a current probe and data logger was used to examine the saw's performance across approximately 24 hours of production. The key benefit in performing this trial was the ability to cover a large number, and wide variety, of carcases - approximately 1740 carcase sides across varying carcase types and maturity levels (0-2 tooth, to 0-8 tooth) were processed during the trial period. There was no indication of stalling by the saw across this period, with the saw operating well within its bounds throughout the trial. Critically, there was also **no** indication that the saw was slowing down and nearing a stall – something which an operator can 'feel' and adjust for to prevent a stall, but a robot cannot. There was no significant difference in performance across the carcase types, maturity, or whether a new or old blade was on the saw, in the context of operating close to its limits. It should also be noted that the manual operators are currently taking approximately 5s to perform the brisket rib cut (ribs 1-13) and approximately 1-2s for each spine cut, which is faster than the cutting speed for the currently designed automated cutting system.

The manufacturer can provide an off-the-shelf saw which has 35% more power than the saw being used currently by the processor. Given the lower power saw had no issues during the trials, there is a high degree of confidence that the higher power saw will be suitable for an automated scribing system. Furthermore, there are several contingency options available if required - they also produce a saw which has 235% more power, or a custom saw could be utilised. Given all of these points, the results of the trials, and the broader industry desire, it is felt that the correct path for automated scribing is to proceed with an electric saw. The electric saw has thus been designed into the scribing system which is to be installed at a processor’s plant.