RoBUTCHER

D4.1 Review of Available Cutting Tools:

Recommendations regarding direction to develop such tools

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Abstract:	Saws, knives and bespoke tools are evaluated for use in robotic slaughtering and primal cutting in an autonomous slaughter cell. As the project is in the initial phase further testing is necessary to make a final decision on the appropriate tools.
Keywords:	Robotic slaughtering; cutting tool; saw; knife

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Disclaimer

Executive Summary

To demonstrate and evaluate a pilot prototype of an autonomous Meat Factory Cell (MFC), as is the aim of RoBUTCHER, having the proper cutting tools is essential. Various cutting tools with potential for adaptation to robotic tooling and use in the MFC in the RoBUTCHER project, are identified and evaluated against a set of selection criteria.

It has been stated that the number of tools should be reduced to a minimum to reduce costs and time for tool shifts. The project has revealed the need for three tools: a saw, a knife, and a bespoke tongue/trachea cutting tool. The number of tool changes is also dependent on how many operations one tool can complete.

At this early stage of the project, it is important to commence practical testing, and the choices made for the project do not need to be the optimal for a commercial solution. During the progress of the project and in a future commercial application, the tool choices may change due to increased knowledge and new requirements.

To start the work in other work packages, the saw that met our criteria the best is the EFA SK 30/18. This is due to its light weight, sufficient cutting depth, potential for robotic adaption, reasonable delivery time, and affordable price. The choice of saw is expected to change during the project and a saw made for automation may be a better choice at a later point.

The choice of knife will develop through the project. To start testing how knives behave on a robotic arm, handheld passive knives will be the first choice, using a bespoke adaptor for mounting to the robotic arm. When sensors are to be attached to the knife blade, a bespoke knife will be needed. A quote has been sent to steel producer for production of six bespoke test knives, and these knives will be evaluated and further developed to fit the needs in the RoBUTCHER project. The potential of a powered knife, potentially vibrating or sonic, should be evaluated further.

A commercial or shelf ware tool optimised for cutting the tongue/trachea does not exist and developing a bespoke tool for this operation is aimed for in the project. A combined gripping and cutting tool is suggested, as the gripping and cutting positions are very close to each other and the operations must be performed in a rather confined space.

Abbreviations and Acronyms

MFC	Meat factory cell
CHU	Carcass handling unit
WP	Work Package
CAD	Computer aided design
IP67, IP24	Ingress protection code, refers to the solid and liquid particle protection of the material
HRC	Degrees Rockwell C; expression of hardness of tooling steel

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1. Introduction

To demonstrate and evaluate a pilot prototype of an autonomous Meat Factory Cell (MFC), as is the aim of RoBUTCHER, having the proper cutting tools is essential. It is indicated especially that RoBUTCHER should adapt existing tools rather than inventing new ones. This document gives a comprehensive overview and evaluation of available and relevant cutting tools possibly to be used **in the MFC in the RoBUTCHER project**. The goal is to identify tools with potential for adaptation to robotic tooling. This will form the basis of the final tool evaluation, selection, and adaptation for robotic use in the MFC, in T2.3 *Expert training input using skilled cutters*. The tools identified are evaluated against a set of selection criteria, and the findings are summarised and concluded with concrete tool recommendations.

2. Tool type and number of tools to be used

In D1.1 *Consolidated Technical Specification*, it is stated, "The principle to be applied is that the number of tools should be reduced to a minimum to reduce costs and time for tool shifts." While the optimal situation would be to identify one tool to be used for all cuts in the MFC, the discussion with experts and potential end-users at the RoBUTCHER kick-off meeting revealed the need for three tools: a saw, a knife, and a bespoke tongue/trachea cutting tool (will be addressed in T5.5, *Internal gripper development*). Scissors were also suggested, but as scissors cannot completely substitute any other tool, they are only briefly discussed in this review. Developing a bespoke combi-tool was also proposed; however, this was regarded out of scope for this project. The need for the three tools is both because of the characteristics of the cuts themselves and due to hygiene requirements. The relevant tool for the different cutting processes are suggested in Table 1. The number of tool changes is also dependent on how many steps can be completed by one tool. Because of this, and from the nature of the cuts, it is assumed in this review that we use and change tools as follows:

- Starting the cutting using a knife in step 1-4.
- Tool change to saw as background activity during step 5 (rotation), using the saw in step 6 (cutting the ribs).
- Tool change to knife before step 7 (separate organs from the back) may be needed to avoid damage of the tenderloin.
- Tool change to bespoke tool during step 7 (cut around and remove organs), back to knife (separate organs from belly) – and continue with knife back in step 1.
- The considerations in the current deliverable are limited to the RoBUTCHER application; however, other tools may be more relevant for a commercial application. More tools are listed in WP1 "Wiki equipment", hosted internally on the project Microsoft Teams platform[1].

[1] Due to confidentiality, this content is currently not publicly available at the time of writing.

Table 1. An extract from Table 1 in D1.1 (*Consolidated Technical Specification*). The table describes the tools envisaged for the relevant cutting processes.

Step	Activities	Tool
1	Left shoulder grasped by robot	
	Left shoulder outer cuts performed	Knife* Saw
	Left shoulder stretched and cutting continues	Knife* Saw
	Left shoulder removed and placed on rack	
2	Left ham removed: *see Step 1 process*	Knife
3	Right ham removed: *see Step 1 process*	Knife
4	Right shoulder removed: *see Step 1 process*	Knife* Saw
5	CHU "tail-bones" fixation	
	Rotate carcass from belly up to belly down	
6	Cut ribs, right	Saw
	Cut ribs, left	Saw
7	Fixate belly, left and right	
	Begin lifting saddle of carcass to expose organs	
	Separate organs from back	Knife Saw**
	Bring container for organs	
	Cut around the trachea	Knife Bespoke tool
	Cut around the diaphragm	Knife Bespoke tool
	Separate organs from belly	Saw Knife***
	Remove organs from area	

**suggested tool by D4.1. **Saw was suggested in Table 1 in D1.1, but is not considered as a good option in this review due to risk of damaging the high-value tenderloin. ***Not listed as an option for "Separate organs from belly" in D1.1.*

3. General considerations for tool selection

There are several well-functioning cutting tools available for human operators. For tools attached to a robot arm, their functionality and performance is somewhat uncertain. There are cutting tools available for robot use, but these have not been tested for slaughter operations. This must be further explored, and it might be necessary to develop and evaluate a bespoke tool.

D1.1 sec. 4.3 gives technical criteria for saw, knife and the tongue/trachea cutting tool, and these are included as part of the tool specific criteria described later in this deliverable. In addition to technical criteria, practical and economic considerations must be made when selecting the tools to be used. Practical and economic considerations common for all tools are:

Availability (supplier): The tool should be shelf ware and internationally available. It will first be demonstrated at NMBU in Ås. A local supplier is time and cost efficient because of delivery time, easier access to service and spare parts, therefore a local supplier agency should be chosen. The concept will also be demonstrated in Germany. The supplier or agency should be noted.

Readiness and adaptability: It must be possible mount on or to adapt to a robot. The process of adapting the tool to do the required cuts and to be attached to the robot will be considered. A high degree of readiness is preferred to save time and adaptation cost.

Tool sketch: It should come with an electronic sketch of the tool in CAD format if possible (e.g. STEP, Parasolid, or SolidWorks). This will considerably ease the sensor integration in T4.2 *Development of sensor interface for adaptable cutting*.

Intelligence: Necessary sensors must be possible to integrate (e.g. force, microwaves), ref. the individual tool criteria below. Sensor integration is addressed in T4.2.

Robot tool exchange: The tool must preferably be easy to mount to the robot, and easily changed.

Weight: The cell has two lifting robots, capable of 40 kg and 60 kg payloads. The tool weight should be kept as low as possible, preferably less than 20 kg, to optimise the inertia of the mechanical movement. The tool weight limitation will in practice also depend on the tool length and weight distribution, as weight load close to the flange can be higher, while the tool weight must be reduced when the load is further away. Also, the robot arm will have to lift the weight of the tool in addition to the force resistance from the cut itself, and higher tool weight implies less force to move and cut in a different direction. More details are given under the "force applied" criteria for saw.

Capacity. The capacity is the cutting speed including time needed for tool change, cleaning etc. This is important in a commercial application but is not important in the RoBUTCHER project. Timing information for the operations performed with the CHU during testing at a slaughter plant in Norway, is given in Table 4 in D1.1. In a commercial application the cutting speed must be sufficiently high, the need for tool exchange, blade exchange etc should be minimized, time for cleaning and disinfection as low as possible, etc. As an example, the saw blade of a breast opener robot has an interval between planned regrinding of approx. 1000 carcasses in a typical Danish plant. From the MFC video the loosening of viscera is performed in approx. 30 seconds and the procedure includes a similar number of delicate cuts, so one cut/sec including movement of knife between cutting positions.

Safety: Safety concerns regarding robot interaction with humans will not be considered in this document as there will not be human-robot-interaction in the MFC in RoBUTCHER. Also, the safety of the robot itself within MFC is not dealt with in this document, including safety sensors in the robotic arm, Force Control etc. To the authors knowledge, there are no safety regulations specific for robotic tools if it does not interact with humans.

Cost: The tool cost includes both the price at which the tool is available, and the acquisition costs (price including adaption and installation). Considerable differences between comparable products should be accounted for.

Hygienic design: This is of less importance under the testing at NMBU as the meat from the tests there will not be offered for sale; however, cutting at MRI must comply with industrial hygienic standards. Any part of the tool in direct contact with the carcass (e.g. saw and knife blades) must be easy to clean and decontaminated by e.g. steam. The cables, tubes, wiring, etc. and potential "adaptors" for attachment to the robot must either be protected against contamination or be washable. An official procedure for hygiene approval of equipment does not exist. The legislation only states it needs to be washable and hygienic, which means it needs to be easy to clean after each operation where the tool has been contaminated. Stainless steel is preferable as it withstands the humid and corrosive environment and the impact of the washing and disinfection agents. Saw blades and knife blades must therefore be stainless steel. Cleaning and decontamination should be performed either during tool exchange or while the tool is still attached to the robot. The robot arm is rated at IP67. The robot itself is protected by a cuff. Tools of IP65 is necessary in an industrial application and preferred in RoBUTCHER, however, lower IP (e.g. IP24) can also be used. IP24 tools are splash proof. They must be covered during cleaning of robot or cell and must be removed from the robot for manual and careful cleaning.

Cutting precision: From D1.1 it is noted: "*… an important mentality in RoBUTCHER is "to make it work". Therefore functionality (e.g. removal of limbs) is considered more important than perfection (…). Therefore, consider applying simple first, and improving second*". Thus, the tool should be able to perform the relevant cuts while detailed cutting pattern and focus on clean cuts are less important in the project. Cutting depth is important for the saw, see specification under saw specific criteria. Also, the saw will need a guiding pin to keep the viscera away from the saw blade. A saw is not suited for high precision cutting operations like fine curves and around bones etc; however, the cutting ribs operation is a quite straight cut through bones and a saw is both well suited and required. Using a saw to cut bluntly through the joint of the head of the femoral bone in the ham has been suggested. However, using a saw for this cut will leave too much meat on the saddle while the ham will be too short. This reduces the quality as well as the commercial potential of the ham. A knife is well suited for such cuts. How well a knife can follow the curves needed is affected by the size, flexibility, and hardness of the knife blade, se specification under knife specific criteria.

Electrically driven: The tools to be used in the RoBUTCHER MFC at NMBU must be electrically driven rather than pneumatic or hydraulic. This is due to lack of compressed air capacity at NMBU and may be different in a commercial application. Electrical driven saws will have a more stable and controllable blade speed than a pneumatic saw because of the pressure variations in air supply. Note that electrically driven tools generally are heavier than air driven. Air powered tools are lighter and easier to use, and are regarded as more durable, but as the air compressor is necessary, it is not suitable for our use. Only electrically driven saws are evaluated in this review.

4. Saw

The saw is necessary to undertake the "Cut ribs" operations, Step 6 in Table 1. If the saw configuration allows it, the saw is an alternative to a knife for cutting the shoulders and separating the organs from the back. The saw will be operated by pulling the saw, and blade direction and placement of the guiding pin must reflect this.

Two main saw categories are circular saws and reciprocating saws. A circular saw has a circular blade that rotates, and a reciprocating saw has a straight blade that reciprocates (moves back and forth) in a straight line. The obvious choice for the MFC purpose is a circular saw. A reciprocating such as an electrical jigsaw or bayonet saw (breastbone saw) could possibly be used, but the muscle rupture from such a saw would be to extensive for it to be considered relevant. Thus, this review focuses solely on circular saws. Pneumatic and hydraulic saws are not considered.

4.1 Saw specific criteria and considerations

Technical criteria for the saw are based on the criteria detailed in D1.1 section 4.3.1, with some modifications:

Guiding pin: A guiding pin to press or keep viscera away from the blade is necessary, such as the one used in the existing MFC saw (see Figure 1). This is a customisation of shelf ware saws. The tip of the guiding pin should be shaped like a round spear tip to penetrate the diaphragm.

Intelligence: It is assumed little/no intelligence is required provided one can define a start- and endpoint. This will be found by the AI in WP2. The possibility for sensor integration in the saw is not evaluated.

Blade material: The blade should be made of stainless steel and be available from a suitable supplier. How often regrinding, sharpening or blade change is required (e.g. after how many cutting hours, how many cuts) is not important in the RoBUTCHER project, but of high importance in a commercial application.

Blade teeth: As many as required to give a clean rib cut, without breaking the ribs leaving sharp edges or shards of bone. This is of less importance for the demonstration of the MFC in RoBUTCHER.

Cutting depth: Cutting depth is less than the blade radius, how much less depending on the saw design (see Figure 2). The cutting depth (the effective radius from centre to blade edge) must be somewhat bigger than the maximum expected thickness of the side and ribs, expected to 120 mm or more in large/fatty sows. In the RoBUTCHER MFC only the considerably smaller slaughter pigs will be cut, and the effective cutting depth should be at least 80 mm.

Force applied: The saw/robot must provide enough force to cut through layered tissue (rind, fat, muscle, rib bones and peritoneum/pleura) without causing the carcass (or parts of it) to be dislodged from the CHU. The maximum force needed is for cutting through the ribs. The maximum force that the robot can apply during sawing of the ribs is limited by the mass of the tool and the required force to move the saw[2]. A higher saw blade speed reduces the force applied from the robot arm, and a higher saw blade speed is thus favourable.

Rotation direction: The blade must rotate away from the guiding pin to avoid accumulation of tissue in front of the blade (Figure 1).

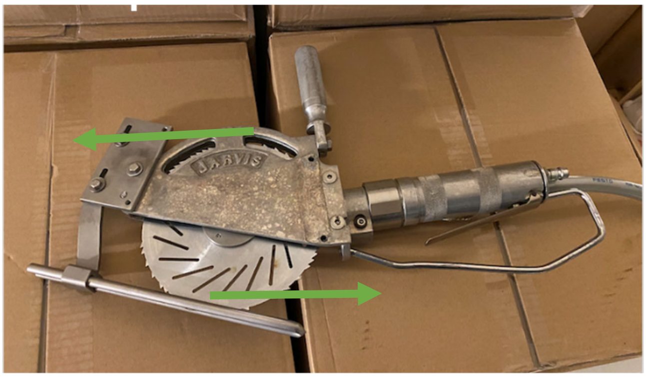


Figure 1. Jarvis pneumatic tool used pre-RoBUTCHER for manual rib cutting, with bespoke guide pin for ensuring no penetration into the abdomen during cutting. Blade direction indicated by green arrows. *Image source:* Per Håkon Bjørnstad, Animalia

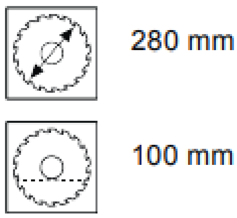


Figure 2. Illustration of the difference between blade diameter and cutting depth. *Image source*: Freund

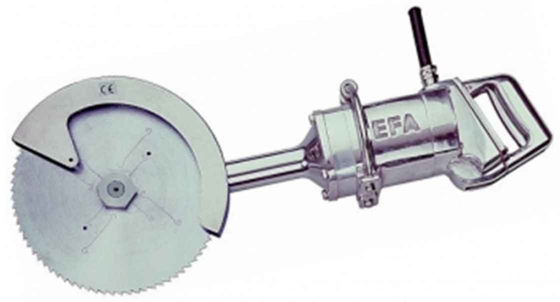
4.2 Evaluation of saws

The selected saw must be attached to the robot arm, either by choosing a saw intended for robotic use, or by rebuilding a manually operated saw. Most saws are made for manual operations, and there are a few relevant robotic saws available on the market. Both manual and robotic saws are considered. The saw blade itself is an important part of the saw and is also evaluated.

[2] With the Force Control option on the robot, it is possible to specify the necessary force for both pulling in the direction of cutting and the reactive force perpendicular from the rib. This counts for both maximum and minimum load. The robot must be programmed such that the reactive force during process does not result in an activation of collision. This is done by reducing the sensitivity at this specific task or movement.

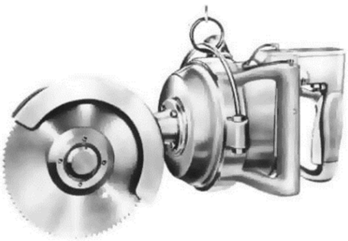
(a) Freund K32-06

(b) EFA SK 30/18



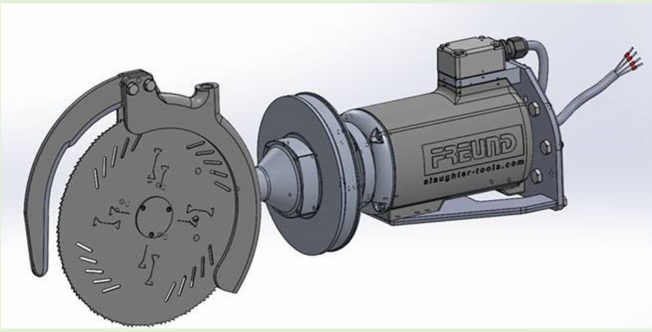
(c) EFA 185 Quartering saw

(d) Jarvis SEC 280 04



(e) Best & Donovan

(f) Kentmaster circular breaking saws



(g) Freund GMB23-06r-ROB saw for automation

(h) EFA-SKR-23 “Tool for hog processing”

Figure 3. (a-d) Manually operated saws relevant for RoBUTCHER use; (e-f) saws considered but regarded not relevant in this review; (g-h) Robotic saws (green background) relevant for RoBUTCHER use. *Image sources:* (a) and (g) https://www.freund.eu/, (b); (c) and (h) http://www.efa-germany.com/efa/index.php, (d) http://www.jarvisproducts.com/index.htm, (e) https://www.bestanddonovan.com/, (f) https://www.kentmaster.com/.

There are different types of circular saws, breaking saws and some extent quartering saws being most relevant. Breaking saws are slightly lighter saws used for cutting bones such as ribs. Quarterings saws are used for quartering cattle and are thus heavier and more powerful. Splitting saws have water connection for cooling and rinsing the cutting surface. This feature is undesirable for our purpose, and splitting saws are thus not evaluated. Non-relevant saws such as the heavy (120 kg) circular cutting knife Freund ZKM60-08-DA-MS-JA are also not listed or evaluated.

The list of manual saws is extensive with variations in weight, motor size, and cutting depth. All considered saws are not detailed in the review, but rather relevant representatives are evaluated. E.g., the Freund K32-06 is selected before K28-06 because its power and cutting depth makes it a potential candidate for a future application treating larger pigs (e.g. sows). Considered saws are shown in Figure 3, with specifications listed in Table 2. Saws from the manufacturers Freund, EFA, Kentmaster, Best & Donovan, and Jarvis are considered. Some alternatives are listed at the bottom of Table 2.

Best & Donovan has an electrical saw, Mark "II" ham marker available for $ 3276; technical specifications 1.12 kW; 24 V; 13.17 kg; saw blade diameter 203 mm (Figure 3e). This saw is less powerful than desired, use a non-compatible voltage, and has a cutting depth probably around 70 mm, which is below the criteria set. This saw is thus not further reviewed.

Kentmaster has two electrical breaking saws, both powerful (2.8 hp) and light weight (7.7 kg), one cutting horizontally (Figure 3f). They have no relevant robotic saw available according to their webpage. Kentmaster has been contacted directly and via suppliers, but the project has not succeeded in contacting them. Thus, their saws have not been evaluated further. The other saws are shelf ware and available for the project and internationally.

Cutting precision: How clean the cuts are made depend on the saw blade toothing, and different saw blades for different tasks are available from the manufacturers. EFA categorizes their blades as fine (3,5 mm) medium-fine (6-8 mm), medium rough (12-20 mm), and rough (40-45 mm), and delivers sawblades with toothing 3.5, 6, 12,16.5 and 42 mm; availability depending on saw type and blade material hardness (normal or hard). All the saws meet our requirements when it comes to the cutting precision. However, all of them need to have the guiding pin mounted.

Hygienic design: The EFA SK 30/18 (Figure 3b) has IP24, the other saws have IP65, so the hygienic design of all the saws are satisfactory. IP24 implies this saw must be manually cleaned and disinfected.

Force: All the saws meet our requirements when it comes to electronic output (1500 – 1800 W). The maximum force that the robot can apply during sawing of the ribs is limited by the mass of the tool and the required force to move the saw. The heaviest saws are the robotic saws, both weighing 26 kg, well above the desired "20 kg or less". These saws are probably touching an upper weight limit, although the force required to move the saw has not been tested. The manually operated saws are all 20 kg or less. The EFA SK 30/18 weighs only 11 kg which makes this saw the preferred one when it comes to weight. Saws for quartering (e.g. the EFA 185, Figure 3c) has an extension between the saw blade and the motor. This is a disadvantage in the sense that the further away from the motor (and robot arm) the blade is, the larger the weight moment becomes.

When it comes to the *power connection*, the operating voltage is an issue. Many saws operate at 400 V. If only 230 V is available at NMBU, the options are either to select a saw operating at 230 V, or to buy a transformer (approx. 14.000 NOK). The EFA SK 30/18 is both 230 V and 1 phase, which makes it a preferred choice.

Rotation direction: All blades rotate in the correct direction (away from the guiding pin, Figure 1). The direction can be adjusted for saws operating at 400 V.

Table 2. Evaluation of circular breaking saws relevant for the MFC in RoBUTCHER. Robotic saws have green background colour in the table.

Manufacturer and model	**Freund K32-06**	**EFA SK 30/18**	**EFA 185**	**Jarvis SEC 280 04**	**Freund GMB23-06r-ROB**	**EFA SKR 23**
Link	https://www.freund.eu/k32-06.html	http://www.efa-germany.de/efa-en/products/daten/EFA-SK-30-18.php	http://www.efa-germany.de/efa-en/products/daten/EFA-185.php	http://www.jarvisproducts.com/Jarvis%20Beef%20SEC2804CS.htm	See attachment	http://www.efa-germany.de/efa-en/products/daten/EFA-SKR-23.php
Supplier (MFC)*	Bokken	Skala	Skala	Bokken	Bokken	Skala
Readiness **- adaptability** **- tool sketch** **- CAD model**	 manual not requested at purchase	 manual requested requested	 manual yes not requested	 manual not requested not requested	 robotic yes at purchase	 robotic yes requested
Physical characteristics: **- Weight** **- Rotation speed**	 20 kg 1320 rpm	 11kg 1350 rpm	 17 kg 1150 rpm	 18,1 kg 1650 rpm	 26 kg 1320 rpm	 26 kg 1150 rpm
Electronic output	2.4 hp/ 1800W	2.4 hp/ 1800W	2.0 hp / 1500W	2.25 hp/ 1700W	2.4 hp/ 1800W	2.0 hp/ 1500W
Electronic input **Protection**	400 V 3 phase IP65	230 V 1 phase IP24	220V~; 5,5A *or* 400V~; 3,2A IP65	230V 60Hz 3 phase IP65	400V; 3.4A; 50Hz 3 phase IP65	400 V; 3,2A; 50Hz 3 phase
Saw blade **- Material** **- Diameter** **- Cutting depth**	 Stainless steel 320 mm 120 mm	 Stainless steel - 102 mm	 Stainless steel 300 mm 100 mm	 Stainless steel 280 mm 102 mm	 Stainless steel 200 mm 85 mm	 Stainless steel 230 mm 65 mm
Price (NOK)**	42.300,-	44.000,-	43.800,-	78.500,-	110.400,-	51.400
Delivery time		1-2 weeks			-	6-9 weeks
Alternatives	Freund K28-06; Freund K23-06	EFA SK 23/18	EFA 85; EFA 86; EFA 186	Jarvis Model SEC 230-4		

** Norwegian supplier, may be used in MFC development. ** Ex VAT (25%) and delivery costs, incl. discounts, ex rebuilding costs. *** Cannot be increased for now, according to Skala, but they will follow up EFA on this.*

Saw blade: The saw blades are all made from stainless steel, but the diameter and cutting depth varies considerably between saw models. The selected saws all have suitable cutting depths, except the robotic saw EFA SKR 23 (Figure 3f) which cuts slightly shallower (65 mm) than desirable (at least 70 mm). The saw is still interesting as one of only two relevant robotic saws available on the market. It is not clear yet if the cutting depth can be increased (request sent to manufacturer). Freund K-32-06 (Figure 3a) is a powerful saw and with a cutting depth of 120 mm it is also an option for a future industrial application where large or fatty sows could make such a cutting depth necessary.

Price: The Freund GMB23-06r-ROB (Figure 3g) robotic saw is considerably more expensive than the others, and above the 100.000 NOK limit. However, they are constructed for robot arm mounting. How easy or difficult it will be to rebuild a manually operated saw depends on the individual saw design. A robotic saw needs bolt holes and brackets for robot arm attachment and a solution for powering the saw without having to press a button manually. Price estimates for a simple customization from manual to robotic use are difficult to attain but will probably be between 20.000 – 50.000 NOK. The Jarvis saw is almost twice the price of the other manual saws, which makes it less relevant.

Delivery time: The EFA SK 30/18 has 1-2 weeks delivery time, and the EFA SKR 23 has 6-9 weeks delivery time. Delivery times of the other saws are not given.

4.3 Summary – saw selection

There is a wide assortment of saws available in terms of technical specifications, hygienic design etc. Most manufacturers have similar variations of the different types of saws. At this early stage of the project it is important to select a saw quickly available and "good enough" to get started with practical testing. At a later point in the project, the needs and criteria may change, and the selected saw may be exchanged in favor of another saw. In a future commercial application, other considerations may be more relevant and may lead to a different saw selection, e.g. variations in the size of the pigs such as use on sows can lead to a need for a saw with a larger cutting depth.

The choice at this stage greatly depends on weight, electric input, cutting depth, availability, price and the possibility of conversion to fit a robotic arm. The easiest choice would be to choose a saw from that is constructed for automation and robotic use, but the price or delivery time make this choice less relevant.

The saw that best meets our criteria is the EFA SK 30/18 (Figure 3b): It is the lightest of the evaluated saws with a weight of 11 kg which is below the requested limit of 20 kg. It has a cutting depth sufficient for cutting a great variation of pig sizes. Delivery time is between 1 to 2 weeks, which means rebuilding and testing can start quickly. It is possible to convert it to fit a robotic arm, as evaluated by ROBOTNORGE from the pictures. It is 230V single phase which means it does not require any reconstruction of the electric system at NMBU. Although it has a certification of IP24, which is less than the other saws, it is considered sufficient for our use. Our recommendation, based on these criteria and at this point in the project, is the EFA SK 30/18.

5. Knives

Knives are essential to traditional slaughtering methods. They are used for bleeding the animals after stunning, in addition to the evisceration and further processing of the meat. In RoBUTCHER, a knife is necessary to undertake the "ham removed" operations, Steps 2 and 3 in Table 1. There are many different types of knives. Knife blades can be straight or circular (mostly trimmers), and may be unpowered, or powered electrically or pneumatic (air driven). Although often preferred, pneumatic knives (e.g. EFA-PK-25 http://www.efa-germany.de/efa-en/products/daten/EFA-PK-25-EN.php) cannot be used in RoBUTCHER and are thus not further evaluated in this review, but vibrational and sonic knives are discussed. The various knives are described and considered for use in the MFC in the project. Other cutting tools considered are laser cutting, water jet cutting and radio frequency ablation.

Most cutting procedures are made with dedicated knives, developed for each specific procedure. As a specification often includes high capacity, the cutting speed is of major importance. The weight of the complete knife has to be kept as low as possible to optimise the mechanical movement of the unit to be able to adapt to the required high-speed impact to the carcass. Therefore, the drive force often is remote to the cutting blade and using a power transmission based on air or mechanical flexible drive shaft (wire). The remote position of the bulky power unit improves the dynamic capability of the cutting process. The required dynamic may be determined using an assessment of the mechanical impedance of the tissue to cut.

One other advantage of the remote power source is the often-confined space of the cutting position, so the cutting knife may be small yet powerful and may be combined with nearby grasping of anatomical details.

5.1 Knife specific criteria and considerations

The criteria for knives to be used during the RoBUTCHER project will constantly evolve during the project. In the beginning it is important to have some knife blades that fits the robot and works “well enough”. Through experience, more precise specifications will be formulated.

In this specification, the knife blade is regarded as the combination of a shaft part and a cutting part. The shaft part can be embedded in an attachment like a standard handheld deboning knife, or an attachment can be bespoke. The technical criteria are focused on unpowered knife blades, but various powered knives are also discussed. Technical criteria to be made for knife and knife blade are (see also D1.1 section 4.3.2):

Force applied: Refers to the force required to cut through any meat tissue in contact with the blade. To date, no measurement of this required force has been made. Equipment made for this purpose is made by ATI which produce a range of force/torque sensors for robot tooling (ex. https://www.ati-ia.com/products/ft/ft_models.aspx?id=Mini40).

Criteria related to *blade material* and *blade design* are specified below:

5.1.1 Blade material

Most cuts are through soft tissues like skin, fat, connective tissue and muscles. However, the cut through the hip joint has complicated anatomy. The joint capsule is a narrow band of soft connective tissue, but on both sides, there are bone tissue that should be avoided to protect the cutting edge. The blade should be the optimal compromise of hardness[3] (HRC), thickness, elasticity and form to be able to perform all necessary cuts.

Material stiffness: The blade should not bend when mounting the blade to the block/robot arm and applying a force of 10 kg pushing the tip to hard surface. At applying 30 kg, the blade should not be plastically deformed.

Hardness: If a traditional deboning knife is used, their hardness is customized for deboning by hand. They are a good starting point for testing hardness (and flexibility) of knife blades on the robot. If a bespoke knife is to be made, the first edition should have a tolerance for the distance from the tip to the hole closest to the tip of ±1 mm or better. High tolerance is not important in the first stage of the project, geometry and function must be solved first. Later in the project the tolerance requirements will be high.

Sharpness: It should be sharp enough to cut smoothly through connective tissue, muscles, tendons, without the blade sticking to the meat. It must be ready to use at the project, have high durability and be easy to regrind and sharpen for the butcher during the project. The durability is not critical for this stage in the project but generally an advantage. Regrinding should be as seldom as possible, because the length from the holes for the robot until the tip should not be changed.

Robustness: Wear resistance is more important than corrosion resistant. At a later stage, when the design and material is optimised, the blades must be more robust.

Food grade: As the meat processed in this part of the project is not for consumption, this is not critical for the first knives. After the first six knives, the material must withstand hot water disinfection 82 ^{0}C for longer

[3] Hardness is the resistance of the steel to permanent distortion at microscopic level. The hardness of the steel is measured by pressing a pointed object with a certain force against the steel and measuring the size of the imprint. The hardness of tooling steel is expressed in degrees Rockwell C, often abbreviated as HRC. (https://www.knivesandtools.com/en/ct/knife-steel-types-and-information.htm)

periods (e.g. 10 min every hour), regular antibacterial disinfectant (alcohol), and daily cleaning using standard detergents (will be specified later). For a more permanent application, the blade should be stainless steel.

Electric conductivity: This should be as high as possible for the knife blade. Stainless steel conductivity is generally low, 1.2-1.4x10^6 S/m. If e.g. a coating (electroplating?) can increase the conductivity without reducing the durability (and later food safety), it would be positive.

5.1.2 Blade design

The blade width should enable following of various anatomical formations, especially the hip bone (ca. 1-2.5 mm thick, and 15-25mm high). Specially developed robotic knives are developed, as illustrated in Figure 5. A suggested design for the first edition of a bespoke knife is specified under the section 5.4 *Bespoke passive knife shaft and blade* below.

Knife blade dimensions (shaft part and cutting part): The blade or the robot attachment must be long enough to keep a proper distance from the end of the robot arm.

Blade thickness: For bespoke robotic knives, the blade should be of equal thickness along the entire blade as it is easier and cheaper to produce. The thickness should be 1-1,5 mm. A thin blade is needed to cut through the pelvis. However, if the blade is too thin, it may reduce the conductivity.

Blade edge: A traditional deboning knife has an edge on one side of the blade. In RoBUTCHER it is desirable to test a blade with a sharp edge on both blade sides and on the tip. This way the robot may perform cuts both moving back and forth. Grinding angle on the edge: 21 degrees is standard for deboning knives.

Tip: The tip should be pointed; 35 degrees is suggested for a first edition if a bespoke knife is made.

Knife shaft: If a traditional handheld deboning knife is used, a bespoke adaptor must be made to be able to fit the knife on the robot arm, and a solution for mounting a sensor must be made. If a bespoke knife blade is used, the shaft must be designed making the knife mountable on the robot. This means an area for two 5 mm mounting holes placed 15 mm apart in the longitude direction. The angle between the shaft and the blade should not be 90°, rather tapered, to avoid fracturing while heating during processing. Also, free space for the sensor is needed. As it is not yet determined where the sensor should be placed, two areas is desirable in an early phase; at the end of the shaft part, and just before the edge part of the blade. Both sensor areas need approx. 30x30. The knife shaft must be fixated to a block/adaptor unit on the robot.

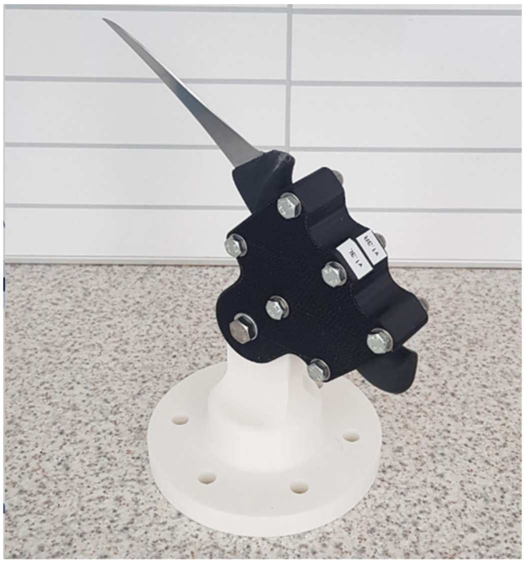
Intelligence: Some level of intelligence will be required to determine tissue type being cut and provide feedback to the robot. This can be achieved by the means of a sensor as addressed in T4.2 *Development of sensor interface for adaptable cutting*. The sensor will probably need an area of 3x3 cm^2. It must be possible to build into some part of the knife tool, however not on the cutting part of the blade (Figure 6a).

5.2 Handheld, passive knives

A shelf ware, ordinary handheld knife is the simplest knife considered (see Figure 4a). The greatest advantage of these knives is the accessibility. They are commercially available and already in use by professional butchers. A passive knife needs all its power from a robot. An early phase test of an ordinary knife mounted to a robot for testing in the RoBUTCHER is illustrated in Figure 4b. A bespoke robot attachment for the Victorinox knife is illustrated in Figure 4c.

(a)

(b)



(c)

(d)

Figure 4. (a) The Victorinox 5.6503-15 standard deboning knife has a 15 cm curved blade *(http://bokken.no/index504.html). Image source*: Per Håkon Bjørnstad, Animalia. (b) Knife mounted on robot. *Image source:* Oddgeir Auklend, ROBOTNORGE. (c) Knife mounted on a bespoke robot attachment. *Image source*: Alex Mason, NMBU. (d) The Frost FK-144 PSG dagger. *Image source:https://www.skalanetshop.no/stikkdolk-frost-fk-144-psg.html*

Victorinox, Global, Dick, Raadvad, Giesser, Swibo, and Frost are all acknowledged manufacturers of various models of deboning knives. They differ in terms of steel qualities and alloys, giving differences in hardness and flexibility. All manufactures have different qualities and sizes available.

For initial testing of a handheld deboning knife, we suggest using the Victorinox 5.6503-15 (see Figure 4a), as it is available for testing from Animalia's pilot plant and is regarded a well-suited knife when it comes to hardness.

The dagger pictured in see Figure 4d has an edge on both sides of the blade which means it can cut in both directions. This feature has been suggested for a bespoke tool and testing with such a knife is beneficial in the beginning of the project to plan how the arm of the robot will perform cuts with a double-edge dagger.

5.3 Robotic knives and complete automation solutions

A knife or knife blade made for robotic use could be useful. Scott Automation delivers complete solutions for automatic cutting lines primarily of lambs. However, their solutions are not considered due to challenges with patent. The manufacturer Mayekawa is developing a full automation system for ham deboning and is producing knife blades intended for robot arm mounting. However, the solution shown in Figure 5 is a bespoke tool for the specific operation, not a generic knife comparable to the manual knife for meat cutting in Figure 4a. This represent the common approach in automated cutting: The cutting tool is adapted and optimised to the specific operation. So, it distinguishes significantly to manual cutting where quite few knives can perform the entire process, killing, slaughtering, and cutting of the carcass. Mayekawa do not wish to deliver knives to the project in the early phase but will consider it at a later point.

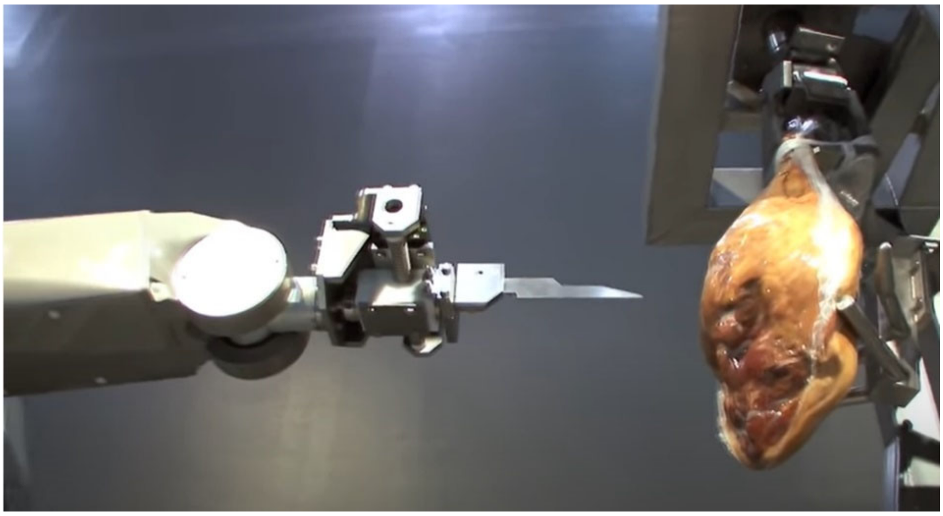


Figure 5. Mayekawa robotic knife mounted on a robot. *Image source*: Snapshot from *https://www.youtube.com/watch?v=UrVFcqqHSLQ*.

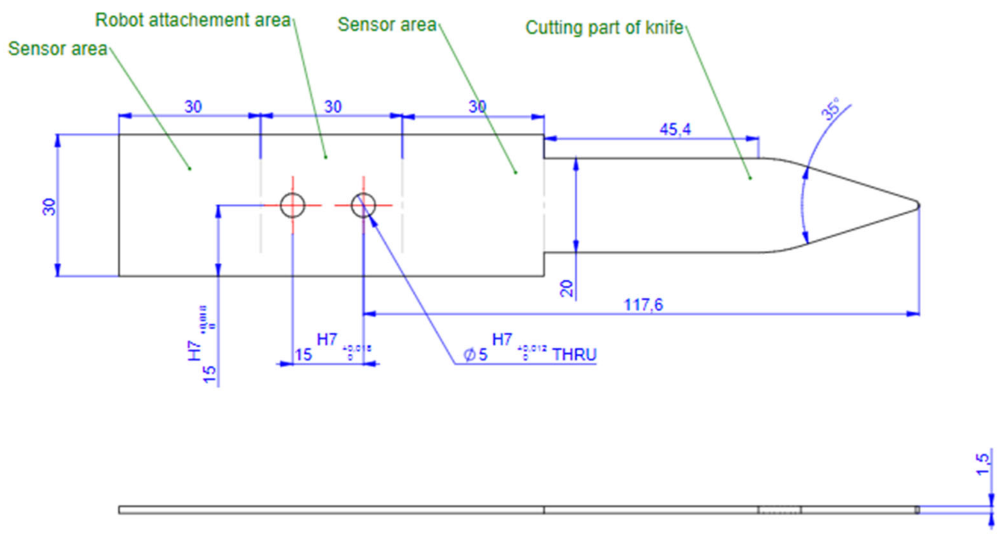
5.4 Bespoke passive knife shaft and blade

The advantage of a bespoke tool is that it can be customized to suit our requirements, e.g. have space for the robotic sensors. It can also be adapted during the process of the project as functionality is optimised.

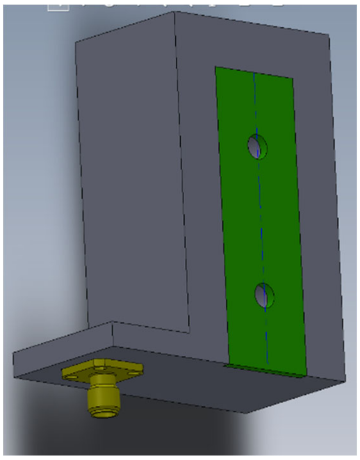
Uddeholm is a steel producer which delivers bespoke knives. Contact with them has been established to develop a custom-made knife to the project. We have chosen a knife with two edges. This makes it possible for the robotic arm to cut in both directions. For the first 6 knives used for trial in the project, a standard available steel quality will be used to keep the price low. Figure 6 shows a sketch of the first edition of a bespoke knife on which we have requested an offer from the steel producer Uddeholm, except a tapered angle between the shaft and the blade is requested.

Robotic knives should, according to Uddeholm, have a design making them simple (and cheaper) to machine produce. This means the blade should be short and with straight cutting edges and have an even blade thickness from the shaft side to the tip. They are cheaper and easier to produce and regrind. Uddeholm also advise not to use the shape of a handheld knife for robotic knives, partly because of the regrinding procedure. In addition, they suggest wear resistance steel grade prior to corrosion resistance (both are food grade). Various coatings can be used to reduce friction; however, this will not increase the corrosion resistance.

The knife/blade chosen needs to have sensors attached. Not to the blade itself but to something that is connected to the blade like a shaft or a mounting block. It is uncertain if a sensor has any value on a vibrating knife because the frequencies that the vibrations create will disturb the blades signals to the sensor. This has to be further examined.



(a)



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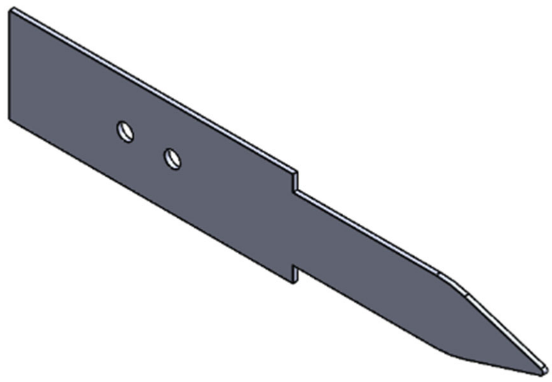


(c)

Figure 6. (a) Possible design of a bespoke knife; areas for sensors and robot attachment indicated in the first 90 mm. This constitutes the shaft part of the knife. However, the angle between the shaft and the blade should not be 90°. (b) Knife-to-robot adaptor/block with the shaft part of the knife blade indicated in green and a sensor in yellow. Such a shaft design is fixated to the fastening block on the robot using wing nuts or a steel plate cover. (c) Sketches illustrating knife with shaft. *Image source* (a-c): Oddgeir Auklend, ROBOTNORGE.

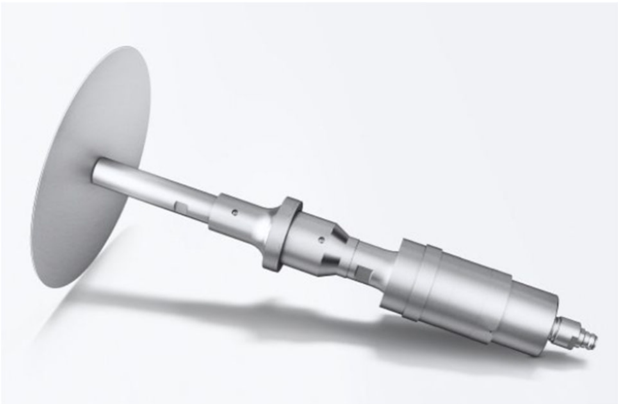
5.5 Circular knives

Circular knives are powered externally, electrically or pneumatic. They can be used to trim bones from excessive meat and to make thin slices of meat from any muscle or prime cut. Few electrically driven circular knives are available. Figure 7a shows a trimming knife, which means it can be used for instance to remove rind from pigs. The knife pictured is air driven, but other types can be electrically powered. However, there is a protective barrier around the knife-edge, which means it is unfit for our use (step 1-7 in Table 1). Cutting through the cartilage in the pelvis of the pig, for example, will not be possible. Figure 7b shows a knife used for removing the hide of cattle. It is air driven and cannot be used for our purpose. In addition, the blade (10-11 cm diameter) is too big to come around the hip bone of a pig. More manufacturers and suppliers are listed in the “Wiki: Equipment” in the WP1-channel in the RoBUTCHER Teams.

Weber has an ultrasonic circular knife pictured in Figure 7c. The blade pictured could possibly be too wide, but with a smaller blade this knife could be an interesting alternative to further explore. A smaller blade would probably be able to follow the narrow curves of the hip bone. Cutting of the femoral joint would have to be tested but is not expected to be ideal. Another operation to be evaluated is splitting of the pelvis bone. As we have no experience with ultrasonic cutting tools it is uncertain how it will perform this operation. On straight cuts such as on the shoulder this knife would probably work fine.

(a)

(b)



(c)

Figure 7. (a) Trimmer used to remove thin layers of skin, fat and meat. (b) Dehider used to dehide cattle. *Image source* (a-b): *http://www.efa-germany.de/*. *(*c) Weber ultrasonic circular knife. *Image source: https://www.weber-ultrasonics.com/en/products/*.

5.6 Oscillating and ultrasonic knives

Use of an oscillating or ultrasonic knife in the project has been suggested. *Ultrasonic*[4] is an acoustical term, normally describing sound and vibrations at frequencies above 20 kHz; ultrasonic cutters normally operate at 20-40 kHz (that is, the blade vibrates 20 000 – 40 000 times per second). An ultrasonic knife moves itself backwards and forwards twenty thousand times a second. This reduces the cutting force significantly and makes it possible to make accurate cuts through areas of different densities and consistencies. Other advantages are for instance the possibility of cutting very slim slices, elimination of adhesion of products to the knife blade, and that the cut products are not deformed by cutting due to pressure-free cutting. This type of knife is mainly suitable for straight cuts and thus challenging to conform to our use e.g. around the hip bone,

[4] The term *supersonic* normally describes a velocity above the speed of sound (330m/s in air) and is sometimes (mis)used to describe vibrating or oscillating knives. To be supersonic the vibration/oscillation amplitude needs to be more than 1.6 cm at 20 kHz, which is very difficult to achieve in harmonic movement. This means supersonic knives may simply be fast oscillating knives at some frequency.

while straight cuts like removing the forelimb could be possible. It is also not clear if the vibrations interfere with the signals from the sensor to be attached to the knife; this should be tested if an ultrasonic knife is to be used. This will depend on the frequency of the sensor signals; ultrasound sensing will probably give interference.

Oscillating or vibrational knives cuts material at frequencies below 20 kHz, originally used for paper industry and clothing sector. Oscillating knives may use electricity or pressurized air to perform the oscillation parallel to the cutting edge. On the contrary, the ultrasonic knives oscillate normally perpendicular to the cutting edge (guillotine type) and thus they “melt” their way through the object by tissue ablation. However, also “knife shaped” ultrasonic knifes exists, e.g. http://en.utinlab.ru/articles/ultrasonic-knifes.

Ultrasonic knives are used in the food industry e.g. for cutting cakes. Examples of ultrasonic knives are given in Figure 9c and Figure 9d. The potential of ultrasonic knives for applications in the meat industry must be demonstrated and they are not used in the industrial settings for fresh red meat cutting in the participating countries, but scarcely for frozen products. An ultrasonic knife has been tested by DTI-DMRI for meat cutting (Figure 8); however, it was not successful due to the fragility of the design. The disappointing experiences suggests performing a preliminary test of the ultrasonic technology at an external third party.

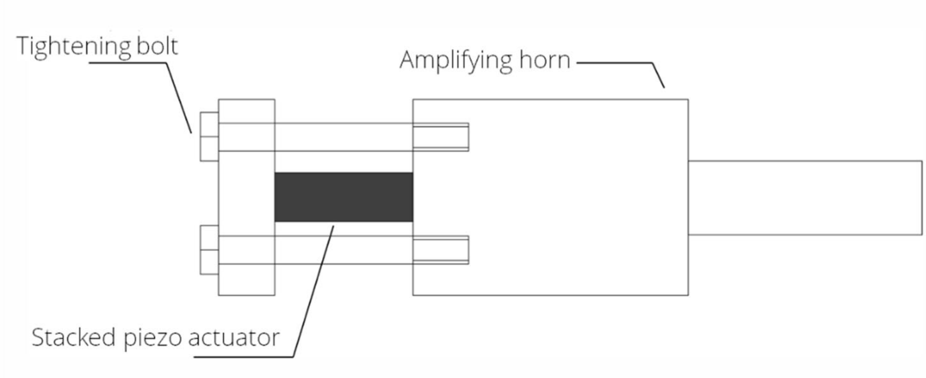


Figure 8. A sketch showing the DTI-DMRI ultrasonic knife for meat cutting testing. The PZ-actuator generates a longitudinal oscillation of the horn edge to the right with an amplitude depending on the horn geometry. *Image source*: DTI-DMRI.

Much more positive results have been made with oscillating knives, one pneumatic driven and one electronic driven. The advantage of the latter is the more attractive integration with any type of sensing device compared to a pneumatic counterpart. Both are however, evaluated positively on cutting of cold meat at DTI-DMRI as shown in Figure 9 below. The knives will be further tested at Animalias pilot plant. The idea is to test cutting off bones, tendons, and joints, and cutting soft tissue (fat and lean), both hot and cold.

(a)

(b)

(c)

(d)

Figure 9. Use of (a) an electrical oscillating knife and (b) and a pneumatic knife (EFA 805 power knife) for cold cutting of meat at DTI-DMRI. *Image source* (a,b): DTI-DMRI. (c) A double edged Ultrasonic cutter 1,25kg blade to be attached to a robot arm. *Image source: http://www.ultrasonic-metalwelding.com/.* (d) A blade from Ultrasonic Knives Technologies. *Image source: https://www.ultrasonicknives.com/.*

5.7 Summary – knife selection

The selection of knife is a difficult task. During the progress of the project the choice of which knife to use may change due to increased knowledge and requirements. The differences between human manual cutting and robotic cutting is essential.

At this early stage of the project, it is important to start trials with the robot and test knives with a prototype sensor. To start testing how knives behave on a robotic arm, handheld passive knives will be the first choice, using a bespoke adaptor for mounting to the robotic arm. At some point, sensors must be attached to the knife blade and it is therefore expected that we need a bespoke knife. A quote has been sent to the steel producer Uddeholm for production of six test knives, and these knives will be evaluated and further developed to fit the needs in the RoBUTCHER project.

A powered knife, potentially vibrating or sonic, could be a good option on a robot. However, this has not yet been studied well enough. This should be evaluated further, either by the project partners, or by an external specialist or manufacturer. The ultrasonic knife option will be pursued with an external specialist as a last attempt to investigate the technology.

6. Scissors

Scissors have been suggested to do the “Cut ribs” operations (Table 1**Table 1**, step 6). Scissors are used to cut joints (Figure 10b), and to cut the breastbone in a commercial abattoir in Denmark, using a combined clipping and cutting procedure (Figure 10c). The latter tool has a sharp edge and a blunt edge, the blunt edge positioned in the abdominal cavity. However, cutting the belly and ribs from the saddle using scissors is a process difficult to control as the cut is done horizontally in the MFC in contrast to conventional slaughtering, where a vertical cut is made. It would be difficult to precisely control the direction and make the desirable curved cut in the MFC. Another important issue is the principle of reducing the number of tools to a minimum, and scissors can be used for fewer cuts compared to knife and saw.

Poultry shears are scissors used to cut the thin, light bones of turkeys, chickens and other fowl. One edge is smooth, while the other has a serrated blade. It is unlikely that this type of scissor can cut through the ribs of a pig, as the bones of poultry are much more brittle, and there is also a chance that underlying soft tissue may be destroyed during the cutting. The use of a poultry shear may be investigated later in the project. Jarvis produces a powered/active scissor, as shown in Figure 10a.

(a)

(b)

(c)

Figure 10. (a) Poultry shears produced by Jarvis. Pneumatically powered hock and neck cutter for poultry. *Image source:* *http://www.jarvisproducts.com/Jarvis%20Poultry%20CPE.htm* (b) An example of a joint cutting scissor. (c) Picture from a Danish factory. The breastbone cutting knife blade is visible. The blunt counterpart is not visible as it is inserted in the abdominal cavity. *Image source* (b-c): DTI-DMRI.

7. Other cutting tools

There are also other types of cutting tools available. Laser cutting and water jet cutting (e.g. WARDjet, https://wardjet.com) been suggested in the RoBUTCHER project. However, these tools are not evaluated further as they are not considered suitable for our purpose: During laser cutting, the heat produced will cause burned edges and burnt odour. Water jet uses water force pressure (4000 bar and more) to cut without heating and deforming the cutting zone. However, the cutting can only take place on materials leaned against the cutting plane and not firmly fixed, which may affect accuracy, the water can contribute to bacterial growth, and the cutting technique is unpredictable because it is difficult to direct the depth of a cut.

Radiofrequency ablation has also been suggested as a possible method. This is a procedure mainly used to treat pain in humans where heat is generated from medium frequency alternating current to remove tissue. However, this method is unsuitable for the project as the use of heat can destroy the tissue.

Tools used in surgeries in veterinary medicine such as scalpel blades are also suggested, but they are too brittle and would have to be changed too often to be considered. The use of sonic knives in veterinary and human medicine has also been explored. Such knives are not used in surgical procedures or necropsies due to the cost and the inadequate precision ability of these knives. The top priority during surgeries is to prevent bleeding and this is managed with high frequency electrocautering. Mechanical cutting could theoretically be used in some specific applications to reduce the necrosis of the cell line along the cut, but such a device does not exist at this time.

8. Tongue/trachea cutting tool

The task addressed by the tongue/trachea cutting tool is given in Table 1 point 7. In opposite to knives and saws, no shelf ware tongue/trachea cutting tool is available. After the preparing operations, the tool will be used to cut around the diaphragm and separate organs from the belly. According to the table, a knife could alternatively be used. In that case, a butcher typically will hold the tissues (trachea etc) with one hand and blindly use the knife to loosen the relevant tissues. There is a wide variation of styles and precision. However, a bespoke tool is aimed for in the project. The only existing option known to the project is an earlier prototype produced by DMRI, doing a similar operation. A video and drawings are documentation available. Apparently from video, the machine removed both larynx, tongue and tonsils. It could perhaps be reproduced from drawings; however, it would have to be modified and simplified as the original machine was made for conventional lines and would be too bulky as is. This would be a complex and expensive task. The final option is to custom a tool in the RoBUTCHER project. This will be addressed in T5.5 *Internal gripper development*.

8.1 Technical criteria for the tongue/trachea cutting tool

It is expected that the criteria for the bespoke tool will be modified further while developing the bespoke tool. In an early phase, it is important to develop a tool able to perform the operations given in Table 1. Technical criteria for the tongue/trachea cutting tool are based on the criteria detailed in D1.1 section 4.3.3:

Tool material: Stainless steel should be used where possible; aluminium may be used for early prototypes.

Cutting mechanism: Circular or semi-spherical knife. Alternatively, an active scissor in combination with the trachea gripper. This alternative is a space-saver option leaving the remaining part of the visceral cuts to the knife robot.

Size: Normal width between mandibles (ca. 6 cm, range 0-10 cm).

Rotation direction: Direction of rotation is important to avoid jamming of blades with tissue in front of the blade.

Force applied: To be determined (estimated ca. 100 Newton)

8.2 Description of operations

The tongue/trachea cutting operations are given in Table 1 point 7, and the various operations are detailed below. The first operations listed, “Fixate belly, left and right” and “Begin lifting saddle of carcass to expose organs”, are preparing operations before cutting.

The first cut is “Separate organs from back”: The viscera are suspended in soft tissue from underneath the spine. This tissue can either be cut or teared bluntly with almost any tool – a knife is suggested for this cut. Then the bespoke tool will start its operations: After separating the organs from the back, a combination of trachea (cartilage), oesophagus, and other soft tissues are oriented towards the larynx and tongue. The trachea must be located and gripped by the bespoke tool. Subsequently, the gripper should glide towards the laryngeal bub (Figure 11) and stop. This is the fixation point.

After fixation of trachea, the bespoke tool must do its first cut, namely “Cut around the trachea”/laryngeal bulb: The tissue around and in front of larynx should be freed and loosened from the tongue and head. Ideally, the tongue and soft tissues including the tonsils of pharynx should be removed in one piece. Removing in one piece is however not considered in the first place, as it is a too complicated procedure.

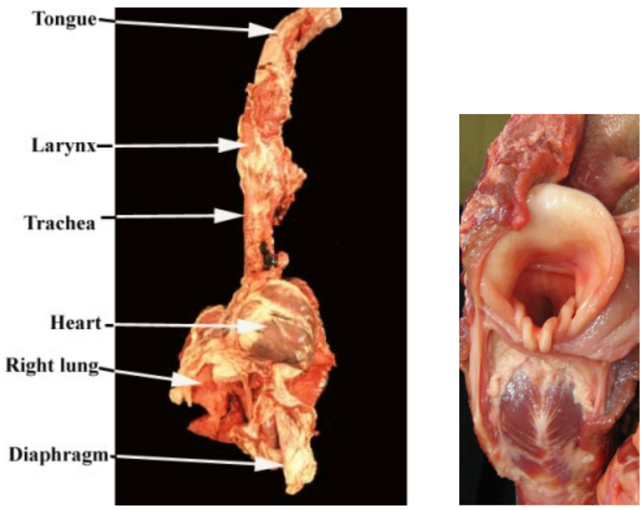


Figure 11. The picture shows a dissected pluck of the pig with the tongue, pharynx, larynx, oesophagus, heart and lungs. The bespoke tool should grip around trachea and oesophagus below the larynx, and then cut the tongue and other soft tissues through the root of the tongue. The picture to the right show larynx in detail. *Image source: http://www.carrsconsulting.com/thepig/disorders/chest/anatomy/anatomy%20of%20the%20Chest.htm.*

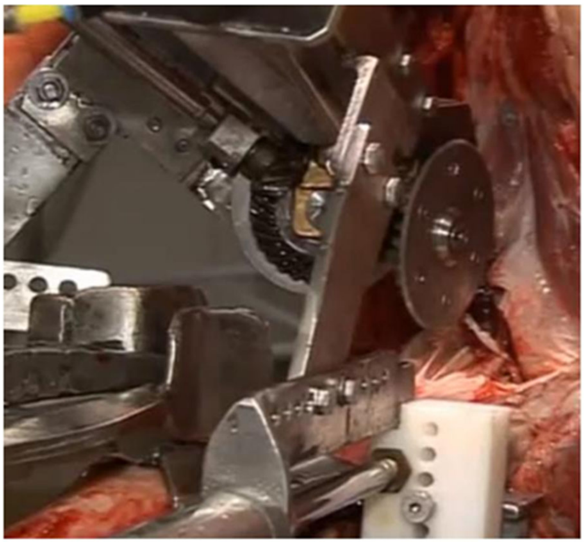
Next cut is “Cut around the diaphragm”: after loosening the trachea, the tissue is retracted. The heart is suspended with a fragile soft tissue towards the breast bone that can be torn by blunt traction. The lungs will follow gently after trachea until the diaphragm’s insertion into the ribbons are exposed (Figure 12b). By continuous retraction, there will be tension in the tissue and the diaphragm muscle can be loosened with a knife. The diaphragm is low value and precision is not very important.

The following operation is “Separate organs from belly”, which means to remove the viscera including the flare fat on top of the belly. It is assumed that the bespoke tool keep on gripping until the whole set of viscera is taken out and placed on the rack. Loosening of the flare fat will normally follow as the trachea is moved caudally without any cutting procedures, but tears have sometimes been registered. This operation needs some more attention before it is optimised.

During the “Remove organs from area” operation, the grip beneath the laryngeal bulb can remain until the viscera are removed from the carcass and deposited on the rack.

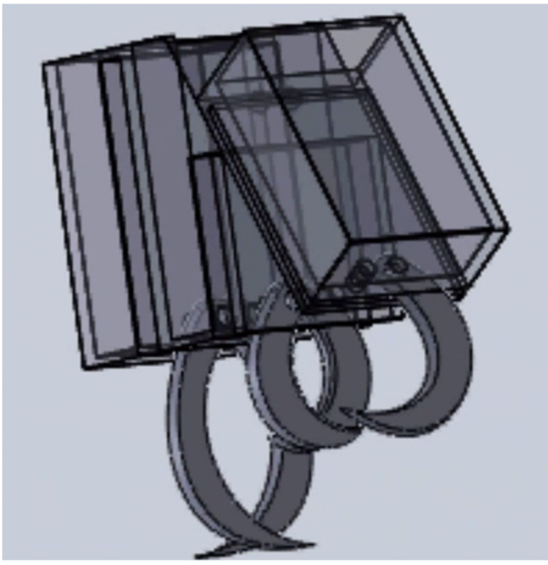
8.3 Bespoke tongue/trachea cutting tool

The trachea gripping and cutting must be performed in a rather confined space. Therefore, it is a potential advantage if the two operations can be performed by a single “combination” bespoke tool; a gripper combined with a coaxial scissor. DTI-DMRI has previously produced a bespoke tool for removal of the tongue, trachea, etc. (Figure 12a). The gripper part may seek inspiration in this specialty machine for the organ cutter, which is installed at Danish Crown in Blans, Denmark. The distance between the gripping position and the clip position may be taken as fixed as the only constraint is that the larynx must be positioned between the two tools. The larynx will establish a natural stop to avoid slipping for the grasp.



(a)

(b)



(c)

Figure 12. (a) An example of a DTI-DMRI-developed twin circular cutting tool (for cutting out the tongue). *Image source:* DTI-DMRI. (b) The sequence in the manual procedure in the MFC, where the butcher grips trachea with one hand and cuts in front of the larynx with the other. Snapshot from the MFC video. *Image source:* Alex Mason, NMBU. (c) A premature CAD model of the bespoke cutting/gripping tool. *Image source:* OBUDA University.

The DTI-DMRI bespoke tool for removal of the tongue, trachea, etc. was originally developed for mounting on a one-purpose (speciality) machine including several independent functions (arms) for gripping the trachea and cutting out the tongue. The tool is described in detail in D1.1 section 4.3.3.

The requirements for cutting the trachea when the pig reclines in horizontal position is quite different from the speciality machine where the carcass orientation is vertical. In the MFC, the carcass is much more open for gripping the trachea, as the back is loosened, see Figure 12b. But it may be advantageous to combine the gripping and cutting in one combined tool as the gripping and cutting positions are very close to each other.

A premature CAD model of a bespoke cutting/gripping tool under development in the RoBUTCHER project is shown in Figure 12c. The front scissor is cutting trachea in front of the larynx after the gripper fingers in the back has grasped the trachea. The gripper fingers may include a tactile sensor to start the cutting process when the grasp is secured.

9. Conclusion

To be able to demonstrate and evaluate a pilot prototype of an autonomous Meat Factory Cell (MFC), as is the aim of RoBUTCHER, having the proper cutting tools is essential. Various cutting tools with potential for adaptation to robotic tooling and use in the MFC in the RoBUTCHER project, are identified and evaluated against a set of selection criteria.

It has been stated that the number of tools should be reduced to a minimum to reduce costs and time for tool shifts. The project has revealed the need for three tools: a saw, a knife, and a bespoke tongue/trachea cutting tool. The number of tool changes is also dependent on how many operations one tool can complete.

At this early stage of the project, it is important to commence practical testing, and the choices made for the project do not need to be the optimal for a commercial solution. During the progress of the project and in a future commercial application, the tool choices may change due to increased knowledge and new requirements.

To be able to start the work in other work packages, the saw that met our criteria the best is the EFA SK 30/18. This is due to its light weight, sufficient cutting depth, potential for robotic adaption, reasonable delivery time, and affordable price. The choice of saw is expected to change during the project and a saw made for automation may be a better choice at a later point.

The choice of knife will develop through the project. To start testing how knives behave on a robotic arm, handheld passive knives will be the first choice, using a bespoke adaptor for mounting to the robotic arm. When sensors are to be attached to the knife blade, a bespoke knife will be needed. A quote has been sent to a steel producer for production of six bespoke test knives, and these knives will be evaluated and further developed to fit the needs in the RoBUTCHER project. The potential of a powered knife, potentially vibrating or sonic, should be evaluated further.

A commercial or shelf ware tool optimised for cutting the tongue/trachea does not exist and developing a bespoke tool for this operation is aimed for in the project. A combined gripping and cutting tool is suggested, as the gripping and cutting positions are very close to each other and the operations must be performed in a rather confined space.

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