Journal of Food Engineering 331 (2022) 111117

Contents lists available at ScienceDirect

Journal of Food Engineering

journal homepage: www.elsevier.com/locate/jfoodeng

Review

Towards human-robot collaboration in meat processing: Challenges and possibilities

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ARTICLE INFO

Keywords:
Human-robot collaboration
Human-robot interaction
Human-machine interaction
Meat industry
Meat processing

ABSTRACT

Background: Meat is one of the main sources of protein in human nutrition. During recent years meat production volume has been showing significant growth worldwide. The total growth of red meat production is expected to show an 80% increase by 2029, according to the Organisation for Economic Co-operation Development (OECD). Such growth indicates the necessity for existing production line modernisation to satisfy future increased demand for meat products.

Scope and approach: This article critically reviews automation challenges for robotic applications in the meat industry, among those are heterogeneity of meat pieces and inconsistency of cutting trajectories that must be overcome to achieve the final quality product. It specifically focuses on human-robot collaboration (HRC) that could be applied in the meat industry to address these challenges. The paper elaborates on possible adaptation of HRC in meat industry, based on its achievements in other industries.

Key finding and conclusions: With increased customisation for both hardware and software robots can offer a flexible, scalable, compact and cost-effective production line alternative to older machinery that require large floor space, are difficult to adapt and include higher maintenance costs.

However, in the case of red meat industry there are no off-the-shelf robotic solutions that can cover all the production steps in the secondary meat processing. Introducing collaborative robots into meat processing could help to promote higher standards in food safety and human-working conditions in the industry and make automation more affordable for smaller production plants.

1. Introduction

Meat is an important part of human nutrition and a core part of European and world culture (Klurfeld, 2018). It is a rich source of protein as well as necessary microelements and vitamins. According to Eurostat, in 2019 the EU member countries produced 22.8 million tonnes of pig meat, 6.9 million tonnes of bovine meat, 13.3 million tonnes of poultry meat, which is an increase of 2.1%, 1.7% and 4.8% respectively on the 2018 figures (European Union, 2019). This is not only a European trend – meat production has been constantly growing in Asia (Zhang et al., 2017) along with the South and North Americas (Food and Agriculture Organization, 2019).

In the first half of 2020, Norway produced more than 65 thousand tonnes (+0.8%) of pig meat and more than 53 thousand tonnes (+1.2%) of poultry meat (The National Statistical Institute of Norway, 2020). Compared with production in Europe, as noted earlier, this is considered small, mainly due to the small population of Norway in addition to its limited export of meat products.

The main meat producers in the world are Brazil, China, the European Union, and the United States, who collectively produce almost 60% of all red meat. According to the Organisation for Economic Co-operation Development (OECD) and the Food and Agriculture Organization of the United Nations, the total red meat production is projected to increase by nearly 40 million tonnes by 2029, which is an 80% increase compared to the production volume in 2019 (OECD Agriculture Statistics, 2019). This growth would have likely been even faster if

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https://doi.org/10.1016/j.jfoodeng.2022.111117
Received 10 January 2022; Received in revised form 10 April 2022; Accepted 23 April 2022
Available online 28 April 2022

recent African Swine Fewer (ASF) and Covid-19 outbreaks had not occurred.

The prevalence of meat-based products in society is clear and continues to grow. It is therefore important and necessary that the associated manufacturing processes are developed to improve sustainability and security. Furthermore, it is essential that those developments have relevance not only for large meat producing nations, but also for smaller players, such as Norway.

This work explores the potentially novel use of human-robot collaboration (HRC) in the meat processing context as a possibility to enable broad access to scalable automation for processors, thereby contributing to sustainability and security of supply in the sector. The paper provides a short overview of the automation solutions in meat processing today, and the key challenges it faces in regard of further intake of intelligent robotics. Key advances in automation that involves HRC are described and critically assessed for application in the meat sector. A specific example is proposed where HRC could be applied to so-called "pace lines", which are ubiquitous in meat processing plants.

1.1. Modern red meat processing in brief

Modern red meat processing can be divided into several main steps: animal handling, primary processing, secondary processing, packaging and labelling (Esper et al., 2021). In this paper, secondary processing is mainly discussed as this is the area today which involves the most manual labour, requiring highly dextrous operations, high-speed repetition and lifting/movement of meat pieces. Packaging and labelling are not discussed as they are often semi-or fully-automated, even at medium-scale production facilities (Caldwell, 2012).

According to McKinsey & Company, there are positive signs of increasing automation in European meat processing. The levels are:

- *Low automation* (level one): limited automation tools implemented. Examples include most cattle plants, where manual labour carries out major processes such as deboning and primal cutting.
- *Semi-automation* (level two): some processes automated, with manual labour needed during or in between. Examples include many of France's abattoirs, where humans use electric equipment.
- *Full automation* (level three): processes automated as far as possible, and robotics and data tools implemented. A good example of such automation can be Danish meat industry (Hinrichsen, 2010) which by utilising specialised machinery (including robotics) has been able to demonstrate a fully autonomous line for primary meat processing that offered better yield and reduced labour cost, making Denmark a country the most developed integrated pork meat production system in the EU (Marie-Laure).

As shown in the report by McKinsey&Company, the most technologically advanced regions in Europe are expected to reach about 25 percent level 3 automation by 2023, up from 10 percent in 2019 (Achieving optimal yields and efficiency in European meat processing, 2020). Although, there are positive signs of robotics involvement in the meat industry, according to one of the latest reports made by International Federation of Robotics (IFR), the degree of robotisation for food industry remained at the lowest level when compared to other industries (International Federation of Robotics, 2021a) (see Fig. 1). Typical operations performed by the butcher in the secondary meat processing are shown in Fig. 3. As can be seen from the figure, both butcher's hands are involved in the processing most of the time. Some of such operations, such as stretching or expanding require static force applied by the butcher's hand for quite a long period of time when processing 100–150 of pork hams/shoulders per shift. Application of collaborative robots to perform reorientation of limbs in case of hah/shoulder separation can ease physical stress the butcher is exposed to.

Primary processing concerns activities within a slaughterhouse, typically where a carcass is prepared for later cutting (secondary processing). In pork production for example, the carcass would be eviscerated after cleaning, and then split. All parts of the animal would be inspected by a qualified veterinarian, prior to further activities to "dress" the carcass, e.g., removal of excessive fat from edges of the cuts, or removal of the parts that are not intended for consumption, such as brain, internal fat or connective tissue. For primary meat processing there are strict regulations, in order to make an end-product safe to consumption. As an example, the number of primary carcass cuts is limited by three wholesale cuts (European Commission, 2004a). At the end of the primary processing stage the meat must be safe to consume, and only temperature regime both for the meat (3 °C for offal and 7 °C for other meat) and the environment (not more than 12 °C) must be maintained during the processing. The final product of primary processing, for example in pork, is typically half carcasses that proceed to a chilling room. At this stage the primary meat processing is finished, the meat is considered safe for consumption and the carcasses are ready to

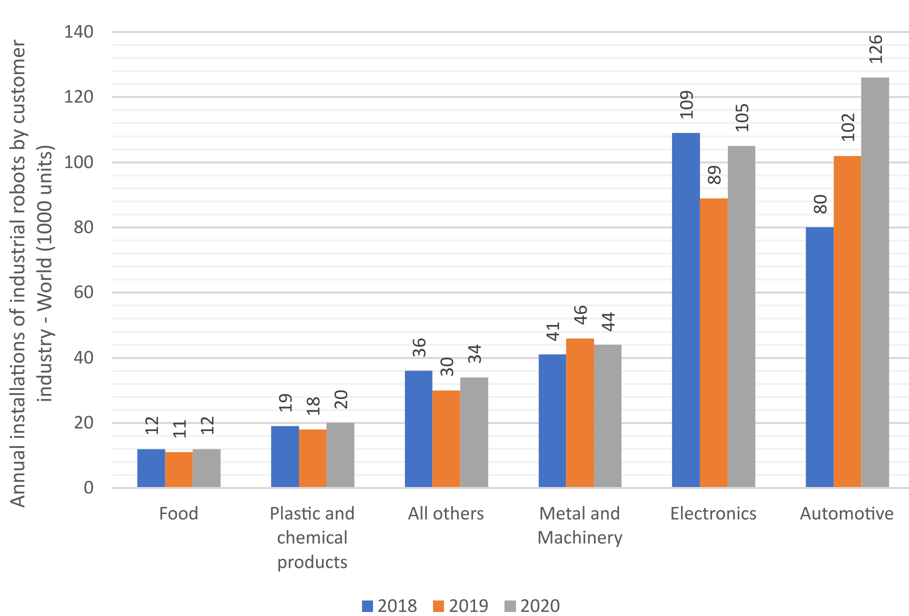

Fig. 1. Annual installations of industrial robots by customer industry from 2018 to 2020 according to IFR (International Federation of Robotics, 2021a).

go into secondary meat processing. The primary and secondary steps may take place in either two separate zones of one facility or at two different production plants. This configuration results from legislated hygiene requirements (Alvseike et al., 2019), in addition to the convention of payment based upon carcass grading at the end of primary processing. This tends to mean, therefore, that the output of primary processing is relatively standardised. Comparison between primary and secondary processing steps is shown in Fig. 2:

Secondary processing typically includes the following steps:

- *Primal cutting.* Cutting carcasses into smaller "primal" parts. In pork production, for example, this involves tri-sectioning a carcass into shoulder, belly and ham primals.
- *Deboning.* Separation of meat from the bones.
- *Slicing and portioning.* Forming the meat piece to a standard suited to customer specifications.
- *Trimming.* Removing extra tissues (fat, ligaments, etc.) from the meat piece. Weighing and preparing the meat piece for packaging.

The degree of automation for each of these steps across manufacturers depends on size, weight, structure and cost of raw material that goes into production. Thus, for example, the task of deboning chicken thighs or breasts is mostly automatic due to production volumes, size of primal meat cuts (or full carcasses) and unimportance of final product appearance. In this case, the automation is largely mechanised rather than robotised. The reason for that is the low price of chicken meat, its high demand on the market, and its broad use in other products (such as fast food or ready-to-cook products). In addition, legislative difference between poultry and red meat processing have favoured the former. However, for pork products, due to the size of primal cuts, these tasks cannot be solved in a similar manner, making it necessary to involve robotics. This adds cost, making it unaffordable to small producers. It should be noted that packaging is not considered to be part of the secondary processing; there exists a high level of automation for operations such as package sealing, palletising and labelling.

The same situation can be observed with slicing and fat trimming, where cut size is one of the main obstacles to cheap and robust automation. For example, the typical weight of a pork ham is 14 kg, whereas for a typical beef rear leg it is 76 kg. That in case of collaborative or fully autonomous processing, where there is a need in reorientation of meat parts (see Fig. 3) or other types of manipulation required to provide better reach to the butcher in collaborative operation, imposes additional requirements on the lifting capacity of robots and can easily increase the price of one robot by several times. On top of that, no existing systems are available on the market that can provide a robust robotic solution for any of the listed secondary processing tasks, with the exception of packaging. Even excluding cost of software development, the supplementary hardware necessary to setup the system in production (pedestals, conveyor belts, fences, tool changers, etc.) and expenses related to maintenance, buying 2–3 robots capable of lifting 30–40 kg loads makes such automation available only to big producers with high volume production.

In both primary and secondary production, the processes themselves are typically arranged as sequential steps, using overhead or belt driven conveyors to present the raw material to machines or human operators. In secondary processing, it is typical to see butchers stood alongside a conveyor, performing necessary operations on meat pieces. Configuration can vary from processor to processor, depending on requirements, volume of production and supplier of equipment. However, commonly this type of line in the red meat industry is often referred to as a "pace line" and requires each of the operators involved in the process to work at a constant (and usually relatively high) speed.

1.2. Social aspects in the meat industry

Effective production for most modern meat processing facilities fully depends on human butchers. This has been recently emphasised during the Covid-19 pandemic, where many factories around the globe suffered quarantine related closures prevent the spread of disease and to avoid contamination of products. Along with other risks, such as the distraction of the European meat and labour market as a result of the war in Ukraine, may also force the meat producers to consider new meat processing technologies that are more suited for local and flexible operation, and this is something that cobots can offer (Poultry meat export from Ukraine in 2021 grew to another highest, 2021).

High dependency on humans, high demand for meat products and high risks of injures on the factory floor all this put the industry in a difficult position when it comes to recruitment. As of now, the EU meat producers prefer to hire immigrant workers from countries with developing economies (Fassani et al.), that can allow them to increase

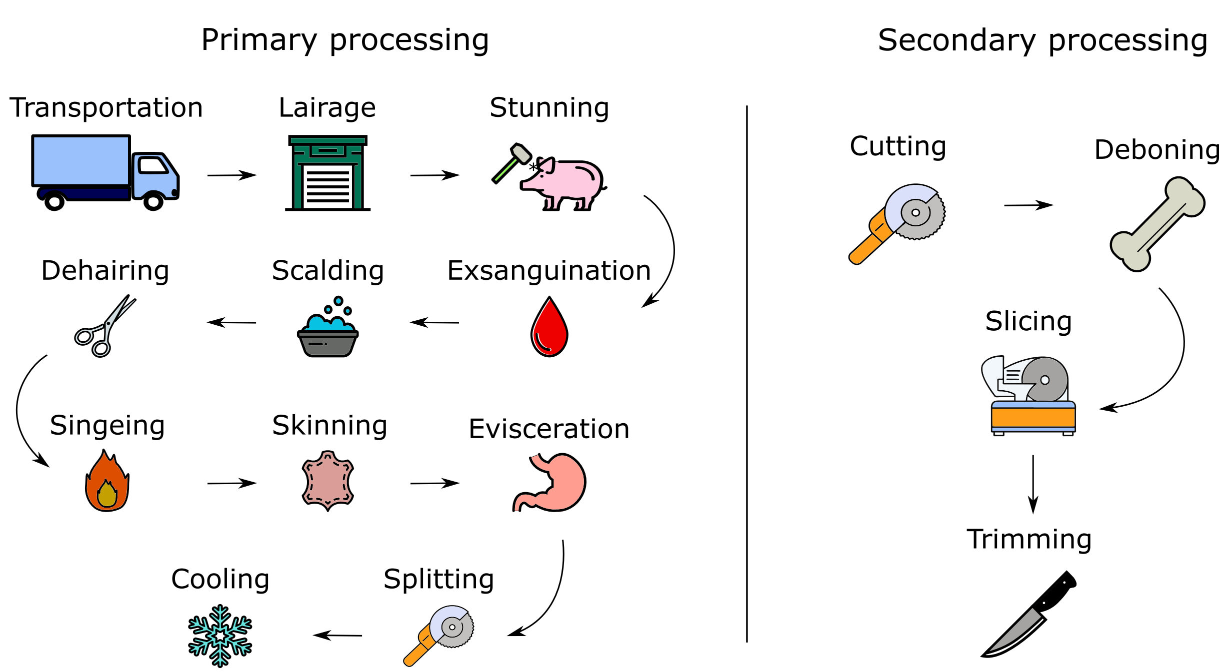

Fig. 2. A typical sequence for primary and secondary meat processing.

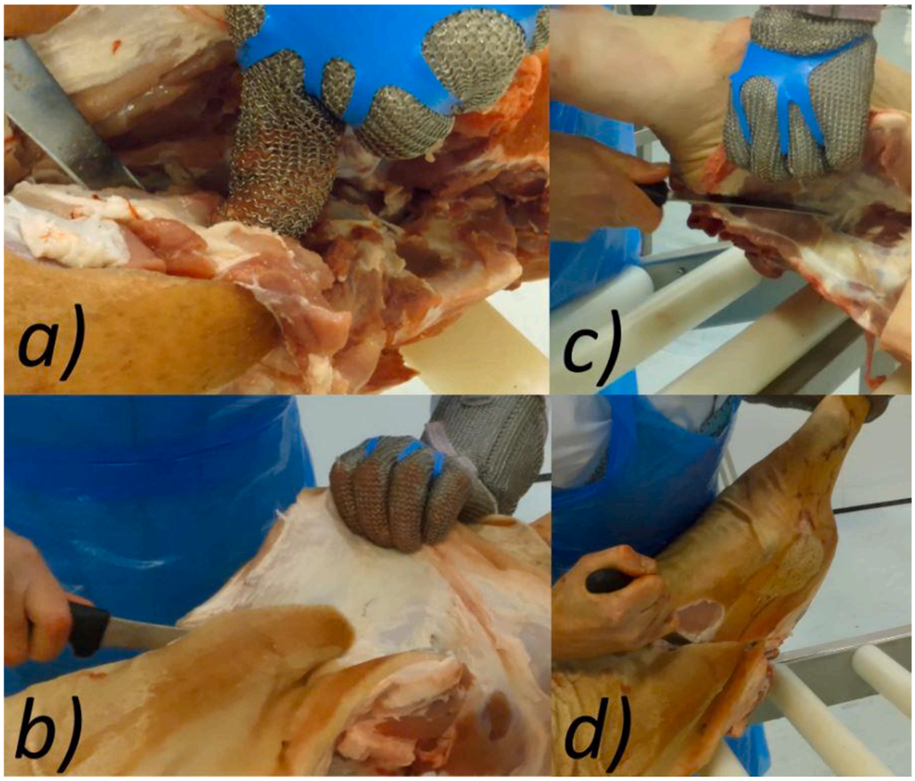

Fig. 3. Examples of processing steps in the secondary meat processing of pork: a - extending; b - fat trimming; c, d - stretching.

margins. There are some limitations with this approach, particularly in relation to retention of skilled workers, and the use of short-term contracts (e.g., seasonal work) is commonplace. This means that butchers may not have enough time to develop cutting skills. Experienced butchers often use, as they call it, the "just follow the knife" technique, that helps them to avoid muscle stress and further development of related musculoskeletal disorders (Dias et al., 2020).

According to Statistics Norway, an average monthly salary within the food industry (which include meat industry) in 2021 was NOK 46,300 (Earnings, 2022), or approximately EUR 4500. The number varies depending on country, but the main point is that actual annual expenses for employer and risks connected with employment (insurance, downtime in case of sick leaves, etc.) can easily be equivalent of a middle range collaborative robot.

Bringing cobots on the production floor could close the gap between experienced and newcomer butchers by introducing the last ones with step-by-step approach in processing, which means cobots can train new workers. Among technologies that can enable such training are virtual and augmented reality (3 Ways Augmented Reality Is Modernizing Employee Training, 2022; Bologna et al., 2020) in addition to the use of digital twins (Ren et al., 2022; Verdouw et al., 2021). These combined with the robotics can provide a person with step-by-step instructions visualised either in the virtual or real environment by projectors or lasers (Sato and Fujinami, 2014) This can be used, for example for providing the butcher with cutting trajectories projected with a laser onto a meat piece, or allow two-way communication between the butcher and the robot via pre-defined voice commands or messages displayed on a screen.

The International Federation of Robotics states that according to analysis by "PricewaterhouseCoopers" company (PwC) of data from the U.S. Bureau of Labour Statistics, the most robotics-intensive manufacturing sectors in the US as a proportion of the total workforce are automotive, electronics and metals. They employ about 20% more mechanical and industrial engineers and nearly twice the number of installation maintenance and repair workers than less robotics-intensive manufacturing sectors and pay higher wages than other manufacturing sectors (The Impact of Robots on Productivity and Employment and Jobs, 2017). This shows that despite common idea of "destructive influence" of robotics to job opportunities for unskilled workers, it also creates more workplaces for engineers who develop and maintain the robots.

1.3. *Key challenges in meat processing relevant to automation*

Prior to exploring the possibilities of human-robot collaboration in the meat sector, it is imperative to understand the key challenges faced by processors today. Those are:

- *Biological variation.* Each carcass, and subsequent part thereof, is subject to differences in size, shape, weight, constituent material, etc. This makes the interaction of the raw material with robotic systems more difficult than in other sectors (e.g., automotive) where materials have well defined and rigid shapes. Therefore, performing complex task analogous to expert butchers, including grasping (Ji et al., 2021), is often both difficult to achieve and very costly.
- *Working environment and job quality.* Workers in slaughterhouses (primary processing) and cutting halls (secondary processing) perform repetitive precision functions involving the preparation of meat – typically cutting, trimming, lifting and stretching. In addition to the environment being dangerous due to the proximity to cutting tools (blades, saws, etc.), it is often cold due to compliance with hygiene legislation, and workspaces are typically small for efficient use of space. The prevalence of repetitive tasks also leads to long-term injury, with a high proportion of workers suffering from muscular-skeletal disorders (Dias et al., 2020). Employee turnover is therefore often high and has led to the industry increasingly employing foreign migrant workers on temporary contracts (Lever and Milbourne, 2017).
- *Economic scalability.* Cost of automation is problematic for small- and medium-scale processors. There are automation solutions available

from globally renowned suppliers to the sector, including Frontmatec, Marel, Scott Automation and Mayakawa. Automation systems available for primary processing, particularly cutting, are also reviewed by Esper et al. (2021). Notably, the meat sector currently employs an “all or nothing” approach to automation, meaning that the processor cannot easily scale up automation, but must plan to have it all from the start. Likewise, scaling down (e.g., to suit seasonal variation) is not economical either. Technologies which enable a more predictable and scalable approach to automation are currently lacking but would nevertheless improve the accessibility of automation to the sector.
- *Constraints of the legislative environment.* Meat processing is regulated in the EU by several legislative documents (European Commission, 2004b, 2017a, 2017b, 2018; European Parliament, 2014). For the red meat processing, particularly in slaughterhouses, the legislation has been very restrictive in regard of innovation and has therefore stifled the ability of suppliers to provide highly-novel solutions which deviate significantly from existing manual processes. It is not the intention of this paper to elaborate significantly on legislative factors, but progress has been made by several groups to improve this situation (Ribmins, 2021). Most recently, the World Health Organisation (World Health Organization, 2021) has stated the following: *“In the past, food safety standards were often prescriptive in nature, unnecessarily limiting innovative methods of food production and processing, restricting cost-effective compliance, and not fully addressing new and emerging food safety risks. Drawing on science and risk-based knowledge, standards and guidelines in modern national food controls should be flexible in design and implementation, as long as they achieve intended food safety outcomes”.*

1.4. Need for advanced automation

Using flexible programmed and dextrous robot manipulators can help reduce the resources necessary to develop complex machinery that can only perform one specific task. Many industrial robotic arms have six degrees of freedom, meaning they can often replace or facilitate a human operator. This allows building flexible automation platforms with the possibility to redefine the production process in future by only changing the software, and without the need to rebuild the whole production line. This can facilitate product customisation for meat processors, which in the case of pork or beef can potentially increase the price of the final product, or improve visual appearance of mid- and low-range products.

Aside from quality, speed plays an important role in key performance indicators of production. It has been shown in other industries that involving HRC or HRI can positively affect production speed. In the automotive sector for example, application of cell-like approaches to automate parts assembly seems to be an effective solution. This concept is well described in a case study by Andronas et al. (2020); the authors point out benefits of fenceless HRC in terms of production efficiency. The work illuminates challenges in finding a balance between production speed and system’s compliance with safety requirements for two cell-layouts: using non-collaborative robot with workspaces separation (Mason et al., 2021a) and a collaborative one in a fenceless application. Nevertheless, according to the authors, due to built-in compliance with safety standards for HRC applications and a wide range of supported modes of operations in accordance to ISO/TS 15066 (including non-collaborative ones), the use of CoBots allows to decrease the cost of such a cell by approximately 21%.

Another important challenge that HRC can potentially solve when applied to the red meat industry is workspace ergonomics. When working with machinery, sharp tools and slicers, physical or mental stress of operators can lead to production related risks. An optimal layout can reduce the number of movements necessary to perform an operation by human, which can reduce error (e.g., prevent clamping and dangerous collisions with slicing machines, meat grinders, etc.) and serve as another passive layer in production safety.

The potential improvements that HRC can introduce into the red meat processing is, of course, not limited to those mentioned above. To summarise, HRC can:

- Improve working conditions (both physical and mental) by reducing the amount of physical stress butchers are exposed to. Collaboration can support butchers while doing exhausting repetitive tasks, such as lifting, hanging and reorientation of a meat piece. That in turn can reduce risks of injuries on the production floor.
- Reduce the cost of automation solutions by making it scalable. This can make it affordable to smaller producers.
- Allow higher customisation of meat products and improve their appearance that improve margins.

This section has provided a brief overview of meat processing, namely primary and secondary. As well as describing the steps involved, the key challenges regarding biological variation, working environment and economic scalability have been identified and discussed. Legislative barriers have also been noted, and although they are not the main focus of this paper, recent evidence shows a shift in thinking toward a more innovation friendly and open future. It is therefore evident that automation, via HRC, presents many opportunities, and this paper presents a timely discussion of such innovation pathways.

2. Methodology

Thus far this review has emphasised the key challenges in automating red meat processing. To progress further, the paper will explore the recent advancement of HRC/HRI technologies which are actively used in industries other than the meat sector. At present there are upraising interest to robotics in food sector, that also includes HRC for such tasks as packaging and palletising (Human-Robot Collaboration Is The Future of Food, 2019). Application of robots allows to decrease chance of product contamination in clean areas. Such trend can also be observed in agriculture that encourages new robotics tools development (Mason et al., 2021b) as well as control algorithms (Zhang et al., 2020). That indicates that there are existing examples of HRC/HRI that could be adopted for the meat sector needs, and therefore the approach of exploring other sectors is justified.

To narrow the search results and to find the most relevant articles an initial search was made. The search was carried out using the following scientific databases: Science Direct, Scopus, JSTOR and Web of Science. As every database uses different search algorithms and filters it is not possible to compare the results directly, but it gives a good starting point for the review process.

The following limitations were then applied to the search results:

- Years: All.
- Publication type: Review/Research Article/Book chapter.
- Keywords: “human-robot collaboration”, “HRC”, “human-robot interaction”, “HRI”, “human-machine collaboration”, “HMC”, “human-machine interaction”, “HMI”, “human-robot cooperation”, “human-robot integration”, “human-robot coexist”.
- Secondary keywords: “meat processing”, “red meat”, “food”, “agriculture”.

The primary keywords were searched in conjunction with the secondary keywords, such that the search string was *“<primary_keyword> AND < secondary keyword>”*. The number of the search results for HMC and HMI are represented in Table 1.

To be referenced in this review, articles had to describe or contain technologies that would implement HMC/HMI or refer to an impact of implementing such approaches. This approach was applied regardless of whether the article was related to the meat industry, due to the lack of specific articles where HMC or HMI intersected “meat processing” or

Table 1
Search result for keywords.

Primary keyword	Secondary keyword	Database/Search results			
		Science direct	Scopus	JSTOR	Web of Science
human-robot collaboration	<not present>	853	1603	11	1299
	meat processing	1	—	—	—
	red meat	—	—	—	—
	food	83	2	2	5
	agriculture	66	9	—	16
HRC	<not present>	18745	323	5895	7855
	meat processing	9	—	9	—
	red meat	8	—	15	1
	food	—	1	1335	251
	agriculture	73	—	915	33
human-robot interaction	<not present>	3825	16689	171	11683
	meat processing	2	—	—	—
	red meat	—	—	—	—
	food	314	21	53	29
	agriculture	187	19	10	33
HRI	<not present>	8655	2048	6933	7270
	meat processing	7	—	5	—
	red meat	17	—	9	1
	food	—	12	3124	290
	agriculture	758	4	1508	121
human-machine collaboration	<not present>	260	257	107	226
	meat processing	—	—	—	—
	red meat	—	—	—	—
	food	5	—	9	—
	agriculture	29	—	8	1
HMC	<not present>	10871	627	5726	6559
	meat processing	7	—	4	—
	red meat	19	—	1	—
	food	—	5	2312	344
	agriculture	607	—	707	91
human-machine interaction	<not present>	4863	4429	557	3810
	meat processing	1	—	—	—
	red meat	—	—	—	—
	food	369	8	82	12
	agriculture	258	13	37	12
HMI	<not present>	12172	1678	5670	6584
	meat processing	13	—	2	—
	red meat	5	—	8	—
	food	—	5	2807	92
	agriculture	634	7	1121	29
human-robot cooperation	<not present>	360	548	4315	484
	meat processing	—	—	257	—
	red meat	—	—	526	—
	food	27	—	1810	2
	agriculture	23	—	882	2
human-robot integration	<not present>	30	12	3684	18
	meat processing	—	—	220	—
	red meat	—	—	353	—
	food	4	—	1560	—
	agriculture	5	—	778	—
human-robot coexist	<not present>	15	—	426	94
	meat processing	—	—	30	—
	red meat	—	—	55	—
	food	—	—	187	—
	agriculture	—	—	85	—

"red meat".

The search results for acronyms of the primary keywords, for example, "HRC" or "HMI" included articles that were not related to the original search request. Among those were articles covered "histidine-rich calcium", "high-resolution chopper spectrometer", "human-machine interface", "hypnosis and music interventions".

Fig. 4 shows an approach to filter irrelevant search results.

As can be seen from Table 2 the number of papers that directly related to both HRC/HRI and red meat processing still remains low. According to the last report made by International Federation of Robotics (IFR), in 2020 annual global installation of industrial robots in the food industry was ten times smaller compared to the electronics industry, 12 thousand robots and 109 thousand robots respectively (International Federation of Robotics, 2021b). Among the reasons for this

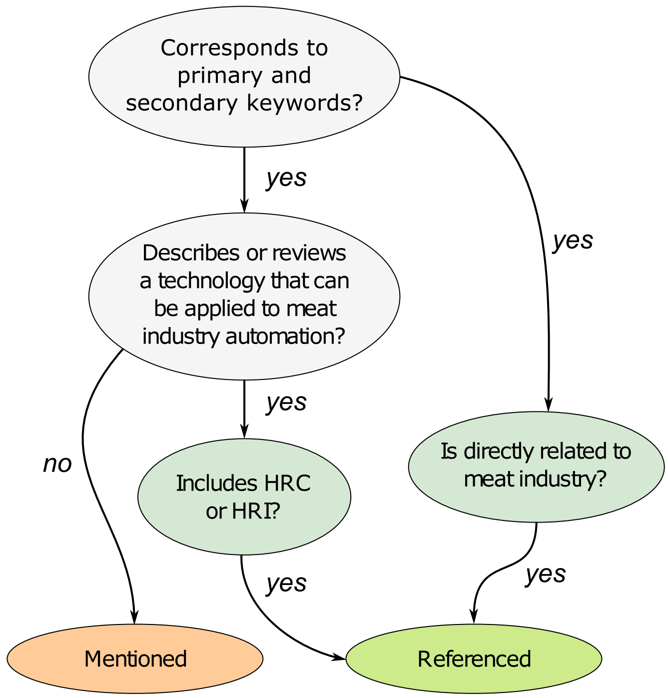

Fig. 4. Approach to search results validation.

are:

- Low marginality of meat production compared to other industries (oil and gas, automotive, medicine, etc.) that leads to smaller investments in this area.
- The availability of low-cost labour (in the EU) through migration from less developed countries is able to temporarily cover the gap in automation.
- High cost of research. Conducting experiments with real meat samples has limitation in time due to their organic nature, requires fresh meat samples, and must be well justified to follow the European Union policy on sustainable development and waste reduction.
- Lack of reference data. Even though there is published data (de Medeiros Esper et al., 2022), the number of samples in such datasets remain low due to challenges with research (availability of animal carcasses, time constrains, etc.).
- Legislation in robotics related to safety. For HRC these requirements are regulated by EN ISO 10218, and in general must be solved during the system design process. However, necessity to use sharp objects (e.g., knifes, saws, etc.) does not allow full implementation of HRC potential in secondary meat processing. A robot that operates with a knife is viewed as a source of constant danger, even when it is static.

Table 2
Interaction levels and safety features.

	Coexistence	Sequential operation	Parallel operation	Collaboration
Non-shared workspace	+	–	–	–
Shared workspace	–	+	+	+
Simultaneous manipulation	–	–	+	+
Hand-in-hand manipulation	–	–	–	+
Related safety feature	SRMS	PFL	SSM	HG

- Limited payload for collaborative robots, which is still remain low, even though high-payload collaborative robots are starting to enter the market (for example, Fanuc Cr-35iA, a collaborative robot, capable of lifting up to 35 kg (CR-35iA Heavy Payload Cobot by FANUC, 2021)).
- Low resolution of depth cameras and their sensitivity to external light sources, that increases error in object location determination.

3. Recent advancements in human-robot collaboration and interaction

When it comes to possible interfaces for interaction, a good example was given by Kildal et al. (2021) in a work on collaborative assembly of electrical cabinets by workers with cognitive disabilities, where the authors present multiple scenarios of HRI, based on human preferences. That allows human to decide on the process flow and request robot's help when it is necessary. Among the suggested interfaces are gestures, voice control, buttons and touch screens.

Finding a trade-off between production speed, its quality, ergonomic and safety in assembly operations, a work by Kofer et al. (2020) relies on the "keep it simple" approach to automation using collaborative robotics that according to the authors is getting more affordable compared to traditional robotic solutions, due to "off-the-shelf" compliance with current safety standards. The paper refers to HRC as to human-centred technology, and mentions that by implementing HRC it is possible to significantly reduce muscular tension (up to 90%) the workers are exposed to (Weidner et al., 2018).

More advanced examples of HRC were reviewed by Hjorth and Chrysostomou (2022) in work on non-destructive disassembly, where authors focus on tasks definition. According to the article, typical tasks performed by a CoBot, can be derived into a series of sub-tasks, such as "pick", "move" and "place". Among the approaches to task definition, there are several frameworks/architectures that authors refer to, such as: *CoSTAR* (Paxton et al., 2016) that creates natural abstractions that use perception to represent the world in a way users can both understand and utilize robust task plans. As well as to Skill-Based-System (SBS) framework (Schou et al., 2013) that allows none-expert users to intuitively define each specific tasks as consecutive series of robot's actions; and motion primitives described by Stenmark et al. (2018) that presents a prototype user interface, assisting kinaesthetic teaching of a collaborative industrial robot that allows for capturing semantic information while working with the robot in day-to-day use.

One of the key-challenges in finding an appropriate knowledge transferring path from robot to human for a specific application and building psychological trust described by Sullins (2020), where paper refers to trust as to "*a phenomena of perception*" of safety aspects not only by one human but by a group of individuals (Teacy et al., 2006). And it also worth to mention, that in the recent decade finding a way to transfer knowledge for automation became feasible due to the rapid development of neural networks and artificial intelligence (AI) (Ribeiro et al., 2021). Neural networks opened up endless possibilities for handling objects of undefined shape in production, including the meat industry (Xie et al., 2021).

Presentation of new collaborative robot series GoFa and SWIFTI made by ABB in February 2021 (ABB, 2021) shows that it is an area in which the manufacturers are ready to invest to. It increases the competition between ABB, Kuka and Universal Robots, and will make collaborative robots more affordable and easier to work with.

Nevertheless, nowadays automation goes beyond the production lines. CoBots also find application in tasks that aim to ind more efficient ways for musculoskeletal disorders treatment. The approach suggested by Prendergast et al. (2021) uses the Kuka iiwa 7 collaborative robot to define tendons strain maps in a human arm to identify the most suitable set of exercises for physiotherapy. Such novel approach to physical therapy allows to setup an individual-based exercise set, that can be automatically adjusted with respect to the patient's progress.

Using HRI in surgery (Haidegger, 2019) allows to achieve higher accuracy, reduce the stress level of a surgeon, move most of the personnel out of an operation theatre and reduce risk to contaminate the operating area and ensures sterility. Not less important is that it has allowed to perform scar-free surgeries. A good example of such systems could be ROBODOC, Zeus, ProBot, Da Vinci (Rao, 2018) and many others have already shown that there are many ways robotics can improve quality and lower the risks. A key-advantage they have is an ability for a constant force measuring between an attached to the robot tool and tissues that are being operate on. That provides a surgeon with a real sensation as if he would handle a tool in his hand.

A case of successful application of Senhance robotic platform by *TransEnterix* Surgical Inc. that was introduced in 2012 was presented by Siaulys et al. (2021), the system tested on more than 100 patients who had a robotic gynaecological surgery. The system consists of four robotic arms and a control centre, that provides surgeon with haptic feedback, and located outside of the surgery theatre.

But yet, all of these solutions are intended for use only inside a specific scope and there are no low-cost solutions that would allow to transfer all of the listed advantages to the meat industry. Mainly because there will be no significant profit from investment in rebuilding them for the meat industry purposes.

4. Human-robot collaboration

Cobotics is a term introduced in the 1990's by Professors Edward Colgate and Michael Peshkin of Northwestern University (Edward et al., 1999). A cobot is defined to be a "*robot for direct physical interaction with a human operator, within a shared workspace.*"

In late 1980s, growing production volumes led to the need for automation in manufacturing. Since then, using robots and machines in production lines became a reality for many industries. In the automotive industry, for example, robots have been extensively used for tasks such as assembly, welding and painting, revolutionising vehicle production. However, the pace of uptake of new technologies has not been equal for all industrial sectors (Barbut, 2014, 2020). Even though Industry 4.0 technologies are becoming more attractive to red meat producers, the level of automation in the red meat sector is still significantly lower compared to the poultry or fish industries. One of the reasons for this is that quadruped livestock carcass size has greater variation compared to that of poultry or fish, which adds to automation complexity. Also, such complication includes the fact that consumption of the red meat industry products is much lower, and its processing quality is more dependent on butchers' experience.

In the meat sector, wide divisions have developed between large-, medium and small-scale producers, and it tends to be only large-scale production that can economically implement robotics and machinery on its production lines. This leaves the majority of producers without access to advanced automation systems. Recently however several actors consider ways to resolve this issue, particularly in light of food security concerns during the global Covid-19 outbreak.

Traditionally, robotics and machinery excelled in performing repetitive tasks. There are examples of such equipment used in the meat sector over the past decades – these include, but are not limited to, Scott Automated Boning Room (Scott, 2021), Hamdas-RX (MAYEKAWA Americas, 2021) and Frontmatec AiRA Robots (AiRA dressing line robots). It is notable however that the nature of the raw material (i.e., biological variation) has restricted the extent of automation in the red-meat sector. This has contributed to the high costs of systems which overcome those challenges.

Nowadays however, automation goes beyond only performing repetitive tasks, and human-robot collaboration is increasingly seen as a key feature in future factory automation (Demir et al., 2019). In the meat sector, where almost all processors rely heavily on manual labour, human-robot collaboration could offer an attractive opportunity to improve sustainability and security, regardless of production scale. Briefly, HRC can be described as the *"ability of robots to work jointly with others or together, especially in an intellectual endeavour"* (Green et al., 2008) and by "others" it implies both humans and robots. It is also important to distinguish HRC from human-robot interaction (HRI), as the former implies robot autonomy, as described in ISO 8373: *"an ability to perform intended tasks based on current state and sensing, without human intervention"*, but not imply performing tasks autonomously in a shared space.

It is important to understand that HRC is a general term, which can describe *interaction levels* between human and robot; *Co-existence* (non-shared workspace); *Sequential operation* (shared workspace); *Parallel operation* (simultaneous manipulation); and *Collaboration* (hand-in-hand manipulation) see Fig. 5. Those interaction levels are ordered in relation to the proximity of human and robot, with the latter being with the closest working proximity, and are derived from the need for safety when bringing any automation system into a real production environment (Rysz and Mehta, 2021). Such transition is often a subject of an independent safety assessment at the production line, that requires time to be conducted, experts, and adjustments of production facility as well as production process. One of the recent research EU Horizon 2020 projects "COVR" (Safearoundrobots, 2020) indicates that there is an actual need for more transparent and human-oriented approach to understanding of industrial safety in robotics.

There are international standards that regulate robotic applications, among those are: ISO 8373 (*Robots and robotic devices*), ISO/TS 15066 (*Robots and robotic devices — Collaborative robots*), ISO 10218-1 and ISO 10218-2 (*Robots and robotic devices — Safety requirements for industrial robots — Part 1: Robots and Part 2: Robot systems and integration*, respectively). They describe safety measures and limitations that must be applied to reduce or avoid potential hazards in applications that involve industrial robotics. ISO 10218-2 includes a set of requirements (so-called "collaborative safety features") that prescribes robot manipulators behaviour in relation to chosen human-robot interaction model and type of operating workspace, based on production specific risks. The features are:

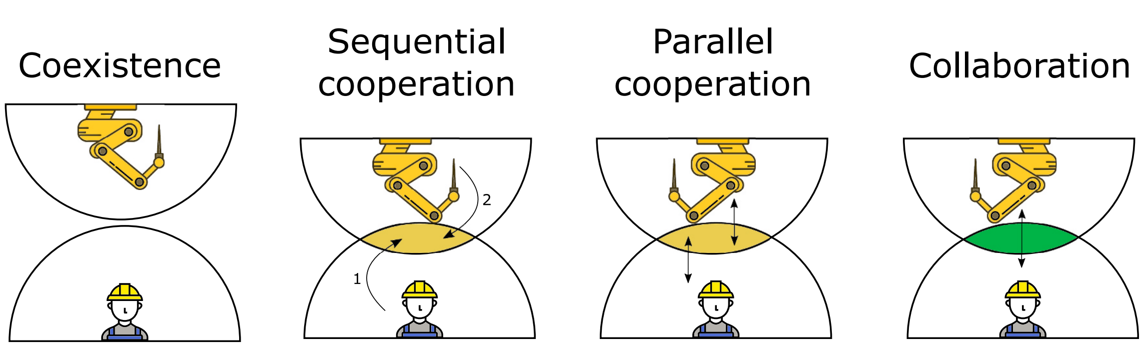

Fig. 5. Types of collaborative applications.

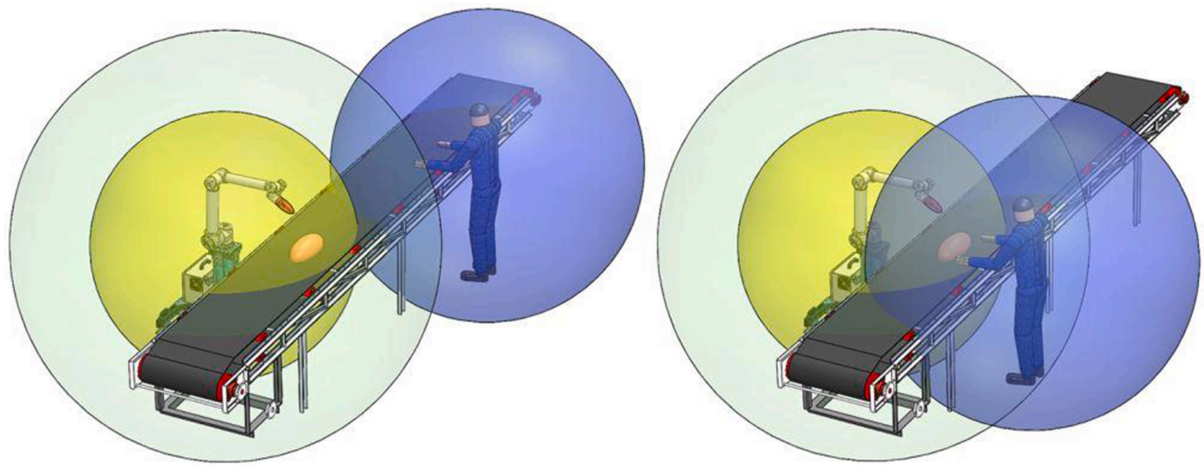

Fig. 6. Operational spaces for coexistence (left) and collaboration (right). Red: area of a tool, green: cobot's operating space, yellow: collaborative workspace, blue: operator workspace.

- Safety rated monitored stop (SRMS).
- Hand guiding (HG).
- Speed and separation monitoring (SSM).
- Power and force limiting (PFL).

Relations between safety features and interaction levels are represented in Table 2. An example which shows the difference between *coexistence* and *collaboration* is shown in Fig. 6, with a simplified example relevant to the meat sector. There are several examples of collaborative robotic arms, for example, available commercially which can be adapted to various industrial applications. Those include offerings from Universal Robots, Omron, KUKA, ABB, as well as high payload collaborative robots, capable of lifting up to 35 kg (CR-35iA Heavy Payload Cobot by FANUC, 2021).

It is important to understand these different interaction levels and the associated safety requirements (Robla-Gomez et al., 2017); this is particularly relevant to the meat sector where it is likely that robots will operate with tools such as knives or grippers. Nevertheless, HRC provides opportunities to assist, complement or replace human operators in today's processing facilities.

5. Future implementation of human-robot cooperation in pacelines

According to studies from The Future of Manufacturing in Europe project (Hansen, 2018), meat industry worker tasks can be divided into three main groups:

- *Physical (manual tasks).* Tasks that require physical strength or/and dexterity, such as, cutting, deboning, wrapping, labelling and cleaning of processing areas.
- *Intellectual tasks.* Monitoring of product quality and compliance, training on safety at work.
- *Social tasks.* Coordination with other workers, mentoring and coaching colleagues and newly recruited staff.

Repetitive movements can cause different types of musculoskeletal disorders (Dias et al., 2020; Reis et al., 2012), as physical tasks can be not only exhausting, but can cause a significant harm to human health.

Physical and intellectual tasks are more likely to be solved in foreseeable future as the ones that can be divided into smaller parts that can be described as a sequence of actions and can be implemented by robot's program. Social tasks are vaguer and performed at a higher level of mental activity, so it is difficult to separate each specific task from the big picture.

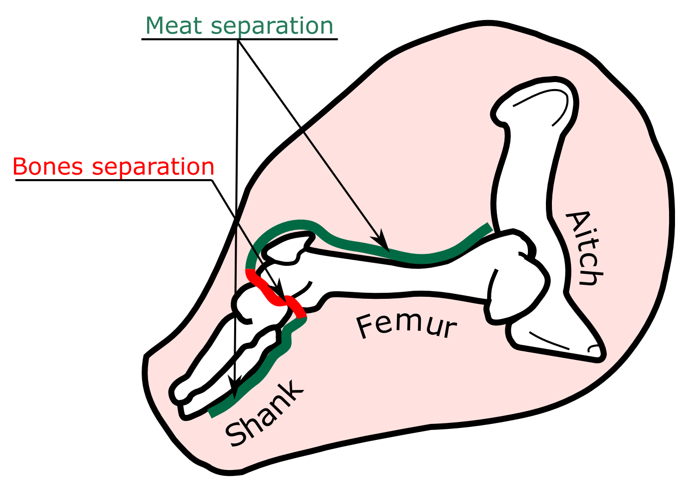

Fig. 7. An example of trajectory required to separate meat from pork ham.

As an opposite to the primary meat processing, where physical tasks do not consist of complex movement and do not require much intelligence to be done in a simple and effective way, in the secondary meat processing similar tasks can cause several challenges when trying to implement them using robots:

1. Meat piece is an object of undefined shape. Unlike parts in the car assembly line, the shapes of which are determined, while processing a meat piece by a robot it is not enough to have its approximated 3D model, since there is no catalogue to find a similar piece of meat.
2. Meat piece is heterogeneous. Meaning that different types of tissue (fat, ligaments, muscles, bones etc.) effect its form and elastic properties, though despite the detailed model of the piece itself, it should be updated in real time.
3. To perform more complex manipulations with a meat piece, than just moving it from one surface to another, the robot must be equipped with a gripper which would be similar to and as dextrous as a human hand. Vacuum suction caps require direct contact with the surface to provide a good grip and could reduce amount of water in the meat piece, that imposes restrictions on caps material to be food safe and also their life span, mainly because of chemicals, significant temperature difference in storage and working areas, natural wear and tear, etc. That makes robotic grippers more preferable.

4. Some meat pieces contain ligaments and tendons that complicate the cutting process and impose additional requirement on the quality of materials a cutting tool is made of and on its sharpness.

For example, pork ham deboning requires high precision from the butcher to reduce meat waste and avoid unnecessary knife blade damage. An example of one trajectory within this task is shown in Fig. 7.

Some of the studies suggest using cell-like approach in meat processing. For example, meat cutting robotic cell suggested by Long et al. (2013). It has many advancements in terms of production hygiene compared to inline meat processing, mainly because of reducing the risk to contaminate the meat by physiological fluids that left from the processing the previous animal. A detailed review of possible risks and advancements of cell-approach in meat processing is given by Alvseike et al. (2018).

In case of collaborative scenario in cell meat processing, most of operations performed by the butcher will require hand-in-hand manipulation on meat pieces, which means that on a part of built-in force and torque limiting features, cobot must have feedback from the attached tool, to provide robot with additional information on tool position in the meat piece. As for the meat industry, especially in the secondary meat processing, where one of the main tools are knives, more strict requirements for robot response time must be applied.

However, taking into account that the force applied to the cutting edge is small and that it cannot be sensed by a robot due to low resistance of soft tissues to the blade, using cobots built-in force limiting feature is not enough as it cannot guarantee an adequate level of safety to humans. In Maithani et al. (2021) was given an overview and an example of force and torque sensor application with KUKA LWR 4+, that uses a knife as a controller for hand guiding. The article indicates that force applied to the knife's handle is significant (up to 50N) which is enough for the blade to cut through the skin.

In order to let robots to operate in collaborative space, avoiding safety stops, they must be equipped with tools that could distinguish between human body and work object while cutting. And such feedback cannot rely on force nor torque alone.

Following from the above and taking into account difficult working conditions and physically demanding tasks a butcher has to perform, as opposite to the cell-like approach, another option involving robotics can be considered. The solution for the described challenges could be a gradual replacement of human operators working on such pacelines with robots (see Fig. 8).

Introducing HRC can be a good starting point in building fully autonomous pacelines. In order to interest meat producers in a new approach and make them ready to introduce it to their facilities, a developed system must be low-cost, adjustable, scalable and require a minimum operator training.

This task can be solved by using technologies already available on the market, and there are many examples of low-cost solutions for each of its parts. These are Robots, 3D-cameras (Mu et al., 2020), augmented-reality interfaces (Khatib et al., 2021) and software. Software part is the most challenging one, and there are many unsolved challenges when it comes to implementation of a system that would be robust enough, among those are human goals prediction algorithms (Pulikottil et al., 2021) and (Al-Yacoub et al., 2021), computer-vision systems (Terreran et al., 2020), human to robot skill transferring algorithms (Liu et al., 2020), etc.

Further implementation and adaptation of these technologies and approaches can allow HRC in secondary meat processing. An example of a solution using cell-like approach is presented in Fig. 9.

The solution implies using butcher's knowledge to find the most efficient way to process a meat piece fed by conveyor belt. To build a two-way communication interface between the butcher and the robot, the system can rely on voice and gesture recognition of commands to be executed by the robot, on one side, and on laser projection of cutting trajectories to be confirmed by the human, on another.

Such cell consists of:

- conveyor belt;
- rotary table, to ease reach to the meat piece for the robot, and provide meat piece fixation by suction cups;
- protective barrier, to prevent the butcher bending over the table and blocking the 3D-vision and laser projector systems;
- collaborative workspace within which robot has freedom of move, if it does not go against safety precautions;

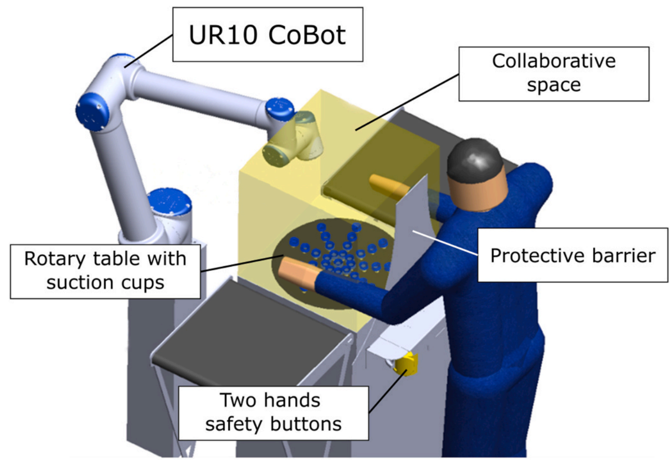

Fig. 9. An example of a cell based on HRC approach, for secondary meat processing in collaborative space (yellow cube).

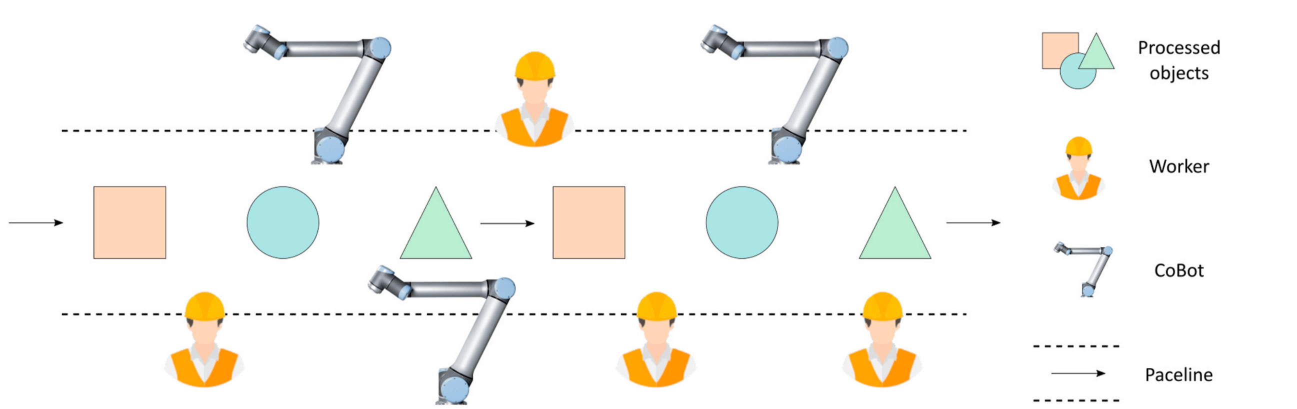

Fig. 8. People on a paceline in meat factory will work side-by-side with robots, and there should be no fences between them for safety – other smart approaches are required.

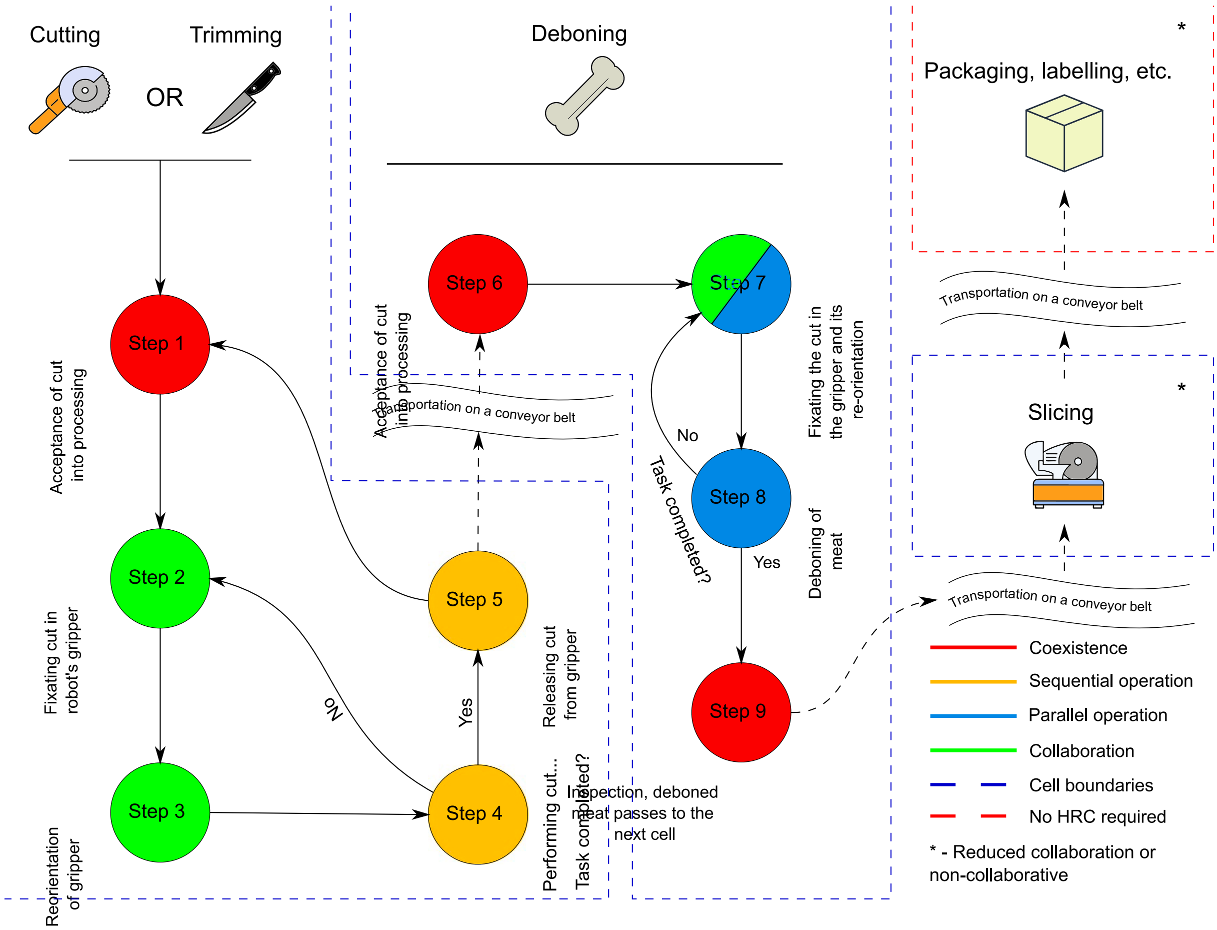

Fig. 10. Possible allocation of tasks within cells in the secondary meat processing utilising HRC.

Table 3
Manual processing time per step required to debone a pork ham and shoulder.

	Time required, s	
	Pork Ham	Pork Shoulder
Skin removal	31	8
Tail-bone removal	18	–
Aitch removal	27	–
Femur and shank removal	36	–
Scapula removal	–	34
Humerus removal	–	11
Ribs and spine segments removal	–	17
Fat trimming and small muscle separation	10	10
Total time required	122	80

- two-hands safety buttons, to add an additional layer of protection when robot operates with a cutting tool.

At least two different scenarios are seemed to be feasible in case of hand-in-hand HRC:

a) *human operates with a knife when the robot helps to hold a meat piece and provides easy access to the cut, and the system suggests an optimal cutting trajectory to the butcher, by projecting it onto the meat piece surface;*
b) *the butcher suggests cutting trajectory to the robot, while robot operates with the knife, by pointing it on the surface of meat piece. The last scenario requires an additional confirmation for each of the cuts from human, by giving a voice command or a gesture, as well as holding two hands safety buttons, allowing the robot to proceed the operation.*

Utilising these scenarios for tasks such as cutting, trimming or deboning as well as allocation of cells, in the processing chain is shown in Fig. 10.

Both aforementioned scenarios must put safety first, especially, when robots operate with a knife. However, improvement of computer-based vision systems, sensorised robotic tools (Mason et al., 2022), and other systems, ensure a safe environment for human workers which can allow implementation of collaborative meat processing on real meat processing plant in near future.

The application of a cell-like approach when in use with affordable collaborative robots will most likely require sequential or parallel operation in a shared workspace for tasks when the robot is not operating with a knife, to maintain pace of production. Among these tasks can be deboning and fat trimming of relatively big parts that go into production (for pork industry these are hams and shoulders). In this case a cobot can serve as a "third hand" for the butcher, positioning the meat piece and providing support in its lifting.

Some of operations, such as following a path with a knife, can be performed in non-collaborative mode, to increase processing speed. An estimated time required to debone a pork ham for a professional butcher is approximately 122 s for ham and 80 s correspondingly.

A table with time durations of each step required to debone a pork ham and shoulder is listed below (Table 3). The values shown in the table indicate the high pace of production that the cobots will have to maintain, when operating in collaborative mode.

It should be noted that, aside from processing speed, an important parameter for meat processing is meat appearance (Valous et al., 2016). To get good cuts quality and maintain the same processing speed, a butcher requires years of experience. That also can be addressed with HRC introduction into the processing as a form of guidance as was

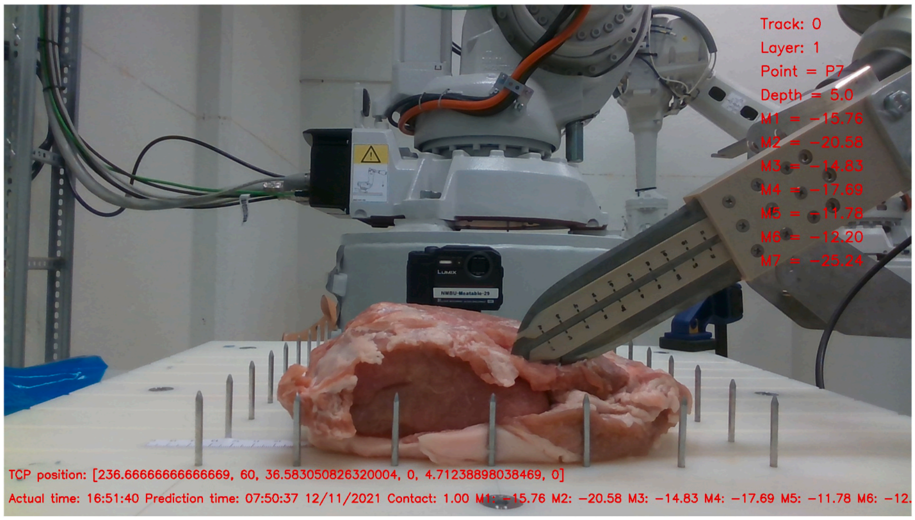

Fig. 11. Parameters read from the sensorised knife described in Mason et al. (2022) overlayed with image from camera.

previously suggested by Kildal et al. (2021). A higher degree of automation can enable use of the Internet of Things (IoT) in the industry, collecting such data as cutting paths, weight of cuts, appearance of cut, as well as readings from sensorised tools (Mason et al., 2022; Romanov et al., 2021) (Fig. 11).

6. Conclusion and future needs

Introducing a new technology always requires much time and efforts, and most small and medium scale meat producers are not ready to take potential risks of implementing new approach into production process. Though, there is no way in easy transferring specific processing techniques or cross-replacing industrial equipment between industries, but at the same time, it is possible to find some similarities to use them as a reference point in this transition.

As far as there is no suitable solution to cover current needs of small meat producers, compact collaborative robots could replace humans at some steps of the secondary meat production, such as packaging, deboning, trimming, etc. However, it cannot be done without feedback from a cutting tool that rely only on force, in order to not cause harm to a human.

The paper reviewed current approach for automation in the red meat industry. It showed that even with high level of automation, there are many tasks that are still being performed by human butchers. Nevertheless, there is upraising interest for collaborative robotics in agriculture sector, that indirectly indicated by increased number of products by key robotic manufacturers, that offer HRC as more flexible and more human-oriented approach to industrial automation. In this review paper main obstacles on the way to apply HRC were assessed, among those are: undefined meat piece shape, complex cutting trajectory, reduced field of vision for cameras while operating on a meat piece and lack of sensorised robotic tools that would be capable to eliminate it.

Further development of HRC applied in meat processing is seen as an absolute necessity for many meat producers. Such a system could provide butchers with additional assist at the early development stages and could narrow the scope of research to specific tasks in the secondary meat processing. To make automation process more smooth collaborative robots can be used to assist butchers in the pacelines. That would allow to use the accumulated data and knowledge to create fully autonomous pacelines in future.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This work was supported by the EC H2020 project "RoBUTCHER", with grant agreement no. 871631.

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