Meat and Muscle Biology™

Less But Better—Pork Meat Will Become One of the Luxury Foods of the Future

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Abstract: The global demand for meat is projected to rise, necessitating a transformative shift in the meat industry towards sustainable and emission-neutral production models. For decades, price competition has driven intense rivalry among meat packers, with a focus on cost control and product differentiation. However, anticipated increases in input costs and challenges to meat supply present a unique opportunity for innovation. Meat production faces mounting pressures, particularly in Northern Europe, to transition from traditional industrialized systems to sustainable practices that address climate impacts. Despite substantial investments in alternative proteins, livestock remains an efficient converter of low-value inputs into high-value human nutrition. As meat becomes scarcer, its historical status as a luxury food is poised to resurface, offering a business opportunity for meat packers while prompting Western consumers to adopt more plant-rich diets. Technological advancements such as automation and AI have revolutionized meat production, enabling efficient processes, enhanced meat quality, and reduced environmental impacts. The future of meat production hinges on adopting circular and emission-neutral practices. The industry's sustainability will depend on balancing efficiency with ecological harmony, transforming meat from a ubiquitous commodity to a luxury symbol of quality. Through technological innovation and a paradigm shift in production philosophy, the meat industry can meet the nutritional needs of a growing global population while adhering to stringent environmental standards.

Key words: production technology, meat quality, AI, sustainability, pork, global consumption
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Introduction

For decades, global price competition has driven intense rivalry among meat packing companies. Successful firms within this sector have focused on rigorous cost control to meet the international pricing benchmark while striving to differentiate themselves and add value to their products. However, the industry is on the cusp of significant change. Anticipated increases in the cost of inputs for meat production (Tillman et al., 2011), coupled with expected challenges in meat supply, present a unique opportunity for meat packers, albeit one that requires a departure from traditional strategies.

Meat production is perceived to be linked to climate change due to methane emissions and excessive land use. Likewise, climate change and the significant variability in climate pose considerable challenges to livestock production. Therefore, it is necessary to develop greater resilience in the production systems (Godde et al., 2021; Thornton et al., 2021).

In Europe, emissions from meat production are increasingly being compared to those from fossil fuels, leading to a polarized political debate, especially in Northern Europe and transition from an animal-based to a plant-based food production is discussed (Prag and Henriksen, 2020). This has resulted in passionate discourse between meat enthusiasts and advocates of plant-based meat alternatives over the true impact of meat on the climate. Denmark is likely to become the first country in the world to introduce a CO_2 tax on biological systems, aiming to reduce the consumption of CO_2-intensive foods, including meat and meat products. Despite these measures, a recent Organization for Economic Co-operation and Development – Food and Agriculture Organization project estimates a significant increase in global meat consumption over the next decade and towards 2050, a period by which many Western nations aim to achieve climate neutrality (FAO, 2023). Notably, only a small fraction of this increase is expected in developed countries, with the majority occurring in the developing world, driven primarily by demand for poultry and pork. This growth is fueled by a growing world population and rising affluence, pushing meat demand upward, though not necessarily to Western levels, but significantly beyond current consumption rates. The meat production system faces challenges, and the debate, particularly in Northern Europe, perhaps ought to shift towards how we can equitably distribute the meat that our planet can sustainably support, rather than pursuing a linear expansion of industrialized production systems. This debate is increasingly about global sharing rather than merely increasing production.

Undoubtedly, meat possesses complex and substantial nutritional value. It is well-documented that humans can thrive on considerably less meat than what is currently consumed in the Western world (Blomhoff et al., 2023). As such, we must transition towards a more distributed meat production system that can nourish people globally, not just in the Western world. Despite billions of USD invested in alternative meat production methods and alternative products, livestock remains an efficient and robust means of converting low-value inputs (forage, grass) that humans cannot digest into high-value nutrition for humans. Livestock is an efficient bioconverter of low-value residues into nutritious food (Wilkinson, 2011).

In the rush for food in the Western world, the special status of meat and meat products is often overlooked. Unlimited access to these products is not an inherent right; it is a habit we have developed. Historically, meat was not a daily menu item but a luxury, reflecting its relative expense and limited portion sizes. In earlier times, meat featured on the menu only weekly, highlighting its value in terms of nutritional content, taste, and convenience. Thus, the looming scarcity of meat should be seen as a significant business opportunity for meat packers and a wake-up call for Western households that need to re-balance the diets with less meat and more plant-rich components, although the complexity of the environmental footprint of the meal is high (Siegrist and Hartmann, 2023). Meat is poised to become a luxury food of the future, a symbol of quality of life.

A Tight Supply Chain Made It Happen

How did the meat industry evolve into its current state, characterized by highly consolidated companies with global market access and extremely complex supply chains? One might logically argue that industrialized countries with high salary costs should not be able to compete on a global scale when compared to low salary countries. Yet, much like the bumblebee, which theoretically should not be able to fly, operators in the supply chain have heavily invested in technology and knowledge as means to drive down costs. At the pork slaughterhouse level, the automation of main operations has enabled highly efficient production processes, with an almost fully automated pen area, dirty end of the slaughter-line, and clean end of the slaughter-line as well. Only a few operations are not automated yet, and at this stage, there are already promising solutions underway for automating these remaining manual operations. For the remainder of this paper, the focus is on pork production.

Operating a production line with up to 1200 pigs per hour proves to be very cost-effective, although it appears the technology is now at its maximum performance capacity. With such line speeds, it becomes clear that the entities need to be large to realize economies of scale. A significant number of carcasses provides the basis for costly investments in new technology and encourages the consolidation of meat packers. High-capacity utilization enhances the business case even further, making meat packers very reliant on a large and steady supply of animals. Consolidated companies can generate stronger cash flow and utilize the benefits from economies of scale. In this context, big is beautiful and creates an attractive business case for automation. However, it is not just the supply of any animals but the supply of animals with the right weight and the requested carcass and meat quality that is crucial.

Market Access

A vital factor in the historical success of meat packers is market access. The meat business has become a truly global business with free and open trade in many places around the world. Market access is not only about expanding an existing market but also about diversifying to meet the needs of various markets, which can be quite different. As seasons change and shift demand around the world, it is crucial that companies can follow the demand from one export market to another. Obtaining market access is certainly not straightforward; it takes years of effort to qualify for each market. Of course, the products must be adequate, but perhaps even more crucial is food safety and compliance with quality assurance schedules. Food safety is the crankshaft of the supply chain, as it is a prerequisite to enter a market, and companies that excel in this discipline have a significant advantage over their less capable competitors. It is all about finding the right level of security to fulfill the needs of the market and maintain the profitability of the operation. Many big meat packers have spent decades building this capability, which is difficult to copy and expensive to build *de novo*, providing a true competitive advantage. The Danish meat industry is, however, sharing their research, e.g., by the comprehensive collection of predictive models for food safety and shelf life (Meinert et al., 2021). The models are used as an integral part of the meatpackers self-inspection systems and the hazard analysis of critical control points (Figure 1). This approach has proven very efficient as basic documentation is available for the entire sector rather than a few proprietary partners. Customers and authorities accept this kind of documentation, which makes the dialogue related to food safety and shelf life very transparent and efficient. It is important, however, that predictive models as shown in Figure 1 are kept updated and constantly expanded with new products, microorganisms, and processes.

Meat Quality as a Value Driver

Genetics

The breeding efforts have been astonishing and probably the main driver of profitability in the entire supply chain. Animals are optimized for subsequent processing, with ever-increasing feed efficiency. Litter size is also continuously increasing, contributing further to the profitability of the supply chain. The trend is that the same genetic companies provide breeding material globally, leading to animals that become more and more alike worldwide. Traditionally, feed conversion, growth rate, litter size, and lean meat percentage (LMP) have been the main traits included in breeding programs. However, quality and welfare issues like drip loss and boar taint (skatole and androstenone) and characteristics like bone strength and temperament could also be part of breeding parameters.

New methods within gene technology allow for a more targeted development of breeds. To prioritize a new trait in the breeding goal, that particular trait needs to be measurable and heritable. Moreover, the choice of breeding goals is a trade-off among the different selected traits, in other words, how much effort one would like to put into a single trait. It is likely that pig breeding organizations must put more attention to societally important traits like welfare, animal health, and ecological effects of meat production in the future (Kanis et al., 2005).

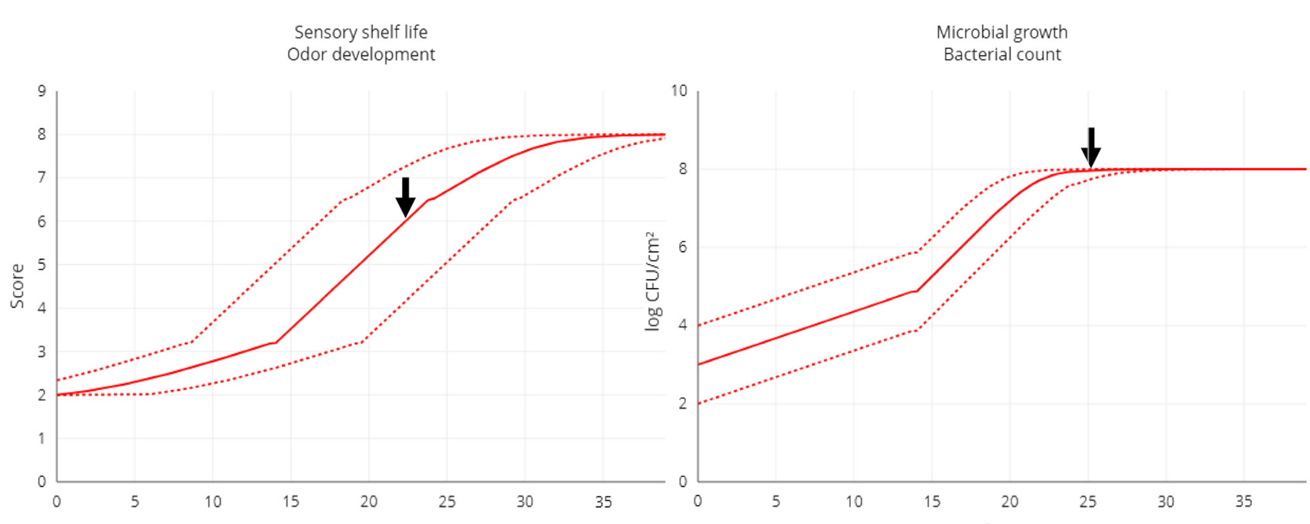

Figure 1. A sample from the extensive collection of predictive models used for managing shelf life and food safety (www.dmripredict.dk). The sample shows a pork cut in a simulated cold chain with 14 d at 2°C, 10 d at 7°C, and 15 d at 5°C in vacuum. The model estimates that the sensory score is unsatisfactory after 22 d and the microbial load will reach 10^8 cfu/cm^2 after 25 d.

Animal welfare

Animal welfare is to a certain extent driven by authorities, non-governmental organizations, and the meat industry itself. Pre-slaughter handling is not only an animal welfare issue but also an influence on the quality and yield of the carcass (Støier et al., 2016). For instance, inappropriate and stressful pre-slaughter handling can cause higher drip loss, pale, soft and exudative conditions, and injuries like hemorrhages and skin lesions, thereby reducing the value of the carcass due to cut-off and reduced use of cuts for high-value products. Therefore, besides animal welfare, animal handling has always been an important theme for the meat industry to obtain the best possible meat quality, subsequently.

The group-based stunning principle, where pigs are kept in the same group during transport, lairage, and stunning, is an example of a concept contributing to a higher level of animal welfare (Gade & Christensen, 1999). Furthermore, partly automated systems based on the knowledge of animal behavior support gentle handling of the pigs during transfer to holding pens and to the stunner (Gade, 2004).

Today, market demands for animal welfare have become an even more significant driver. The market sets animal welfare requirements to comply with, including demand for surveillance, e.g., during the unloading of animals and in the lairage area at the abattoir. Surveillance of animal welfare could be an effective tool to identify and register problems in primary production, during transport, and at the slaughterhouse. Monitoring animal welfare parameters provides the possibility of changing inappropriate procedures and operations. Vision technology and digitization offer the possibility for onsite and online measurement of animal welfare. Lesions can be recorded by vision technology. Furthermore, automated image analysis, including the development of algorithms by which movement patterns of the animals can be analyzed, is a useful tool to identify deviating movement patterns and thereby possible animal welfare issues (Gronskyte et al., 2015; Matthews et al., 2016). The use of artificial intelligence (AI) makes the algorithms for detecting lesions and assessing movement patterns more robust and the speed of analyzing the images even faster. Vision technology allows for surveillance and documentation of animal welfare.

Castration of entire male pigs has been a subject of debate for years. The benefits in primary production are related to avoiding the intervention point at higher feed efficiency and higher meat percentage, thereby resulting in less climate impact compared to castrates, and this would certainly be in favor of stopping castration. However, the challenges related to handling the more aggressive boars and to the risk of boar taint, changes in carcass composition, lower fat content, and more unsaturated fat make the decision much more complex. All these aspects should be considered if the cost of producing entire males is to be calculated (Kristensen, 2024). The carcasses must be controlled to decrease the risk of a bad consumer experience due to boar taint (Aaslyng et al., 2019). Therefore, an increase in the number of slaughtered male pigs has led to demands for a rapid, reliable, and inexpensive instrumental method for measuring androstenone and skatole. An accurate method for measuring boar taint components in backfat from uncastrated male pigs, matching industrial demands for speed of operation and robustness, has been introduced and is used at-line today (Lund et al., 2021).

Grading

At slaughterhouses, carcasses are graded according to a variety of criteria. The total LMP content in pig carcasses serves as the standard metric for expressing carcass value within the European Union, and deployment of objective methods for estimating LMP directly on the slaughter-line is mandatory (Official Journal of the European Union, 2008). Globally, online classification equipment, such as AutoFom, is employed to assess the LMP in pig carcasses, but these indirect methods must be calibrated regularly. Traditionally, the primary reference method for calibrating these online classification instruments has been based on the dissections of a representative sample of carcasses. However, the advent of technology now allows for the use of computed tomography (CT) scanning and virtual dissection as alternative instrumental reference methods (Olsen et al., 2017).

In several countries, the classification process fulfills 2 critical functions: 1) ensuring fair compensation for the producers for the animals they deliver, and 2) facilitating the sorting of carcasses into different categories (Polkinghorne and Thompson, 2010). For example, payments to pig producers are calculated based on both the weight and lean meat content of the delivered pigs. This payment system is designed to incentivize farmers to supply pigs that not only meet a specified meat quantity but also exhibit a more consistent weight. Moreover, the data collected on weight and classification are leveraged for sorting carcasses efficiently. Once the data from online measurements and CT scanning have been analyzed, it becomes feasible to accurately estimate reference parameters, such as the weight and lean meat content of the ham, middle piece, and fore-end.

Additionally, customer-defined quality characteristics and product yields can be determined, allowing for the development of calibration models for these parameters specifically aimed at enhancing sorting and/or production control. Consequently, the utilization of carcass variability can be optimized.

Advancements in grading and measuring systems now enable the inclusion of additional traits within the payment model. A fundamental condition for integrating new parameters into the payment system is their measurability and the ability of the primary producer to influence and control these parameters effectively. It is imperative that the payment system remains robust and accurately promotes the desired qualities (i.e., providing the correct incentives as described by Hocquette et al., 2020). Therefore, there are practical limits to the level of differentiation the system can accommodate and the number of parameters it can incorporate. The payment system must maintain transparency and should not be perceived as a 'black box'.

Carcass balance as the profit engine

The globalization of the meat industry has unveiled opportunities to allocate various parts of the carcass to specific markets, even those overseas. What might be considered low-grade products or even inedible locally can be highly valued elsewhere (e.g., China). For example, organs such as hearts, livers, and tongues, which are not highly prized in the Western world, are sought-after commodities in other markets. All parts of the carcass should be utilized to optimize profit and assure as much as possible for consumption (Figure 2). However, an even more critical aspect during the cutting and deboning process is the precise knowledge of customer specifications. A deviation of just a few millimeters can significantly impact the profitability of specific cuts. This is particularly true for the middles, where there are numerous options for cutting bellies, ribs, backs, deciding on bone-in/out, rinds on/off, and so forth. The implications of these decisions are often underestimated by many companies (Cisneros et al. 1996).

A perennial topic of debate is the optimal carcass weight. Typically, the LMP and feed efficiency dictate the ideal carcass weight, but it is frequently observed that carcasses are excessively large, rendering them suboptimal for further processing (Latorre et al., 2008). Most markets adhere to detailed customer specifications, and an oversized carcass in this context often results in more trimmings of lower value. An optimal scenario would involve a lower carcass weight, fewer low-value trimmings, and products that precisely meet customer specifications (Lebret and Candek-Potokar, 2022).

Figure 2. Using more of the carcass as food reduces the carbon footprint. It also maximizes the profit in the supply chain. The carcass has many nonedible uses too.

Indeed, carcass balance represents a domain where digitalization is set to make a significant impact in the forthcoming years. Algorithms powered by AI are poised to predict the most advantageous manner to cut a carcass, reflecting a real-time snapshot of customer orders. Moreover, computer vision systems will monitor operators to ensure optimal cutting yields and quality are achieved.

This evolution underscores the meat industry's shift towards a more technologically integrated approach, where precision and efficiency are paramount. By leveraging digital tools and AI, the industry can better align its operations with market demands, ensuring maximum profitability and minimized waste.

Slaughter and chilling process

The slaughter and chilling process plays a crucial role in determining the final meat quality and the microbial status of the carcass. It is well understood that the chilling rate significantly influences meat tenderness and water-holding capacity (WHC) due to the pH/temperature decline in the muscle tissue. In pig abattoirs, quick chilling tunnels are widely utilized, where moisture is evaporated from the carcass surface and removed by circulating air around the carcass. This process delays the pH decrease, leading to reduced chill and drip loss. However, it is notable that the energy consumption of this technology increases exponentially with the rate of chilling. Therefore, the faster the chilling rates, the higher the energy consumption, cost, and environmental impact. Moreover, very fast chilling heightens the risk of cold shortening, which results in less tender meat (Rosenvold & Andersen, 2003). Consequently, there is a compelling case for exploring alternative chilling concepts.

Previously, the concept of stepwise chilling was introduced with the aim of improving pork tenderness without compromising the WHC of the meat (Rosenvold et al., 2010). By implementing gentler handling on the day of slaughter (including groupwise transport, lairage, and stunning), the carcass temperature at the time of slaughter is reduced. This reduction in temperature decreases the risk of PSE and maintaining the temperature interval of 10 to 15°C *pre rigor* results in maximal tenderness (Tornberg, 1996). Additionally, it has been observed that glycogen breakdown at 15°C and 4°C occurs at an identical rate (Kylä-Puhju et al., 2005). The stepwise chilling regimen tested by Rosenvold et al. (2010) entailed a rapid temperature reduction to an average carcass temperature of 10°C or 15°C (via a quick chill tunnel), followed by a 6-h holding period at 10°C or 15°C, respectively, and then concluding with tunnel chilling to 4°C. This study concluded that the tenderness of *M. longissimus dorsi* could be significantly improved without compromising the WHC of the meat. Subsequent research has demonstrated that stepwise chilling can be feasibly implemented under commercial conditions (Rosenvold & Borup, 2011), but no companies have yet made the investment. This may be because the meat industry is conservative compared to other industries (Troy and Kerry, 2010). Figure 3 is an example of a recently built quick chill tunnel with an updated design and engineering.

A challenge that remains is designing a chilling system that can provide all carcasses with an equal rate of chilling while also utilizing less energy. The considerable variation in weight and meat content across carcasses complicates the task of ensuring uniform chilling of individual carcasses using traditional air or spray chilling methods. The pad chilling concept offers a potential alternative. In this approach, heat is removed from the carcass through direct contact with a cold surface, a principle that is well established in the poultry industry's spin chiller. Heat removal by conduction, rather than by evaporation, is significantly more efficient and is the fundamental principle behind the pad chilling concept (Damgaard & Borup, 2007). However, this process necessitates a complete transformation in the chilling systems currently in use. As of now, for example, issues related to the cleaning of the contact media have been a significant deterrent to widespread adoption.

Figure 3. New installation of a contemporary quick chill tunnel for effective chilling of pork carcasses with minimal power use. Cooling relies on direct expansion ammonia and the cooling space has been diminished by a horizontal deck in the cooling tunnel. This will lower energy consumption by up to 30% and make cleaning and maintenance easier. An efficient quick chill tunnel should have a chill loss of 1.0% or less.

Traceability

The importance of traceability from farm to fork is increasing, and the reality is that no company currently has full, individual traceability from animal to meat cut. Today's systems are built on comprehensive quality assurance schemes underpinned by rigorous audits. Batch sizes are generally determined by time slots and can vary in size based on the production volume and time intervals. From a food safety perspective, this approach represents the best possible strategy for managing recalls. However, in the event of a recall, the costs can be substantial because an excessive amount of product may be recalled. Typically, a recall situation employs a top-down logistic approach where the flawed product is traced downstream in the process. The more contained the recall can be executed, the less costly it will be. High levels of traceability improve the precision of this containment and, as a result, reduce costs.

Moreover, traceability is crucial for other reasons as well. The top-down approach is insufficient for the appraisal of consumer products. Often, a product's premium market position cannot be visually discerned from the meat itself. It is challenging to determine whether a piece of meat is organic, has been produced under high animal welfare standards, originates from a specific terroir, or comes from a particular country. These distinctions all depend on the quality assurance system and the frequency of audits conducted. As a result, several companies have experimented with bulletproof traceability systems based on blockchain technology. While blockchain technology itself is mature enough for industrial use, there is still no traceability system capable of ensuring full transparency upstream in the supply chain. The primary obstacle is the difficulty of easily identifying a meat cut.

Meat packers invariably aim for a premium position for their products to secure a unique standing in the market. New systems are being developed to address this need, and in this context, computer vision is enabling significant improvements in traceability systems. There is typically full traceability when the carcass is on the gambrel. However, once it passes through the carcass splitter and enters the packaging line, maintaining traceability becomes more challenging. Nonetheless, developments in camera tracking systems aim to ensure traceability is maintained all the way to the transport boxes (equipped with radio frequency identification tags) or until the final dispatch (Figure 4). Some countries utilize "christmas trees" as an internal transport system, which further complicates traceability. It has been demonstrated that solutions based on computer vision can track meat cuts on and off the christmas trees, although these have not yet been implemented in the industry.

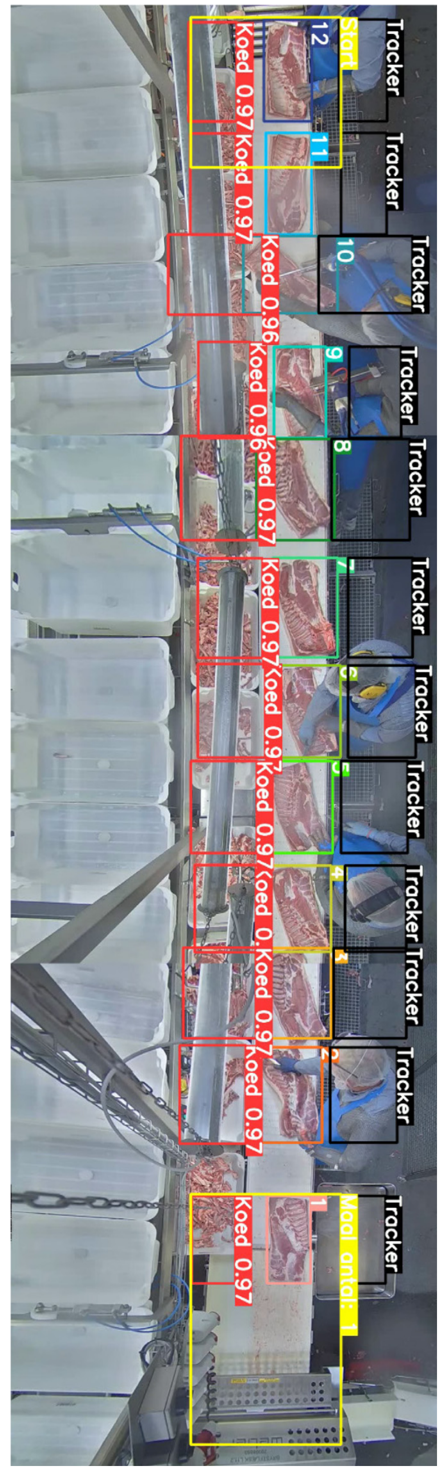

Figure 4. A vision-based tracking system can enhance the traceability from lairage to dispatch. It can track the objects from gambrels to transport boxes along, e.g., pacelines, and detect whether the object on the conveyor is meat or an artefact. The system is in the process of implementation at a Danish meat packing company.

For a traceability system to be viable, it must be cost-efficient and not negatively impact the meat. There are commercially available systems that can document the journey from meat cut back to the original animal through genetic fingerprinting (Merck, 2024). Although this technology is highly effective, it primarily serves to augment the existing audit system due to the costs and speed of analysis involved. In the past, there have been experiments with bar codes printed with laser beams directly onto meat cuts, but no system has yet been introduced to the market.

Diversifying the product range and offering premium products is an important strategy for meat packers, and an efficient traceability system is essential to realize the added value of the products as increased profit. For large companies with highly complex supply chains, traceability is a top priority, underscoring the need for robust and innovative solutions.

Technology

As in most other industries, the technological development within the meat processing sector has propelled improvements in production efficiency and facilitated a continuous decrease in unit costs. Slaughterhouses that have embraced a high level of automation can function with just a fraction of the workforce required for manual operations while remaining competitive in the market. Various technology providers offer comprehensive turnkey solutions that span the entirety of the production process, including areas such as lairage, stunning, kill lines, packaging, and dispatch. The cutting and deboning area presents much more complexity, but in the subsequent packaging area numerous companies offer well-proven automated solutions for packaging and dispatch.

The production technology and philosophy utilized today, especially in the cutting and deboning sectors, may soon find themselves outdated. The conventional line production principle is approaching its limits in terms of efficiency, and it needs to be rethought. A complete redesign is likely needed to achieve profitable automation, as previously suggested by Mason et al. (2023) and Hinrichsen et al. (2022). Robotic production cells in parallel would replace the traditional line production, which would introduce a new innovation trajectory with many interesting perspectives. This new model is predicated on executing a longer series of operations within a single cell, with several such cells operating in parallel. This arrangement not only accommodates more complex operations but also leverages the capabilities of modern robotics, controlled by sophisticated algorithms rooted in AI. While the requisite technology for such an advancement is available, the barrier to entry remains the substantial initial capital investment required, which may deter slaughterhouses from adopting this innovation prematurely.

The future of production technologies is anticipated to lean more heavily on software advancements rather than hardware. This trend mirrors observations across various industries where robots have become commoditized and widely accessible. In contrast, the specialized algorithms that control these robots are becoming the proprietary advantage of pioneering companies. This evolution presents a significant challenge for technology providers, necessitating a reevaluation of their business models.

Further into the future, it is envisioned that algorithms will evolve to become self-learning, thereby continuously enhancing their performance in optimizing product yields and quality. Such algorithms could not only improve operations within a single factory but might also facilitate the collective progression of manufacturing practices across multiple production sites, optimizing the allocation of production activities. The concept of self-improving algorithms (Mnih et al., 2013), such as those based on reinforcement learning, is especially appealing in the meat industry due to the inherent biological variability of the raw materials. The more precisely this variability can be accommodated in the production system, the greater the alignment of products with specifications, thereby maximizing profitability.

One of the primary challenges in advancing automation lies in the domain of sensor input. Robotic systems struggle to achieve optimal performance without adequate sensor data. While advancements in computer vision have significantly enhanced sensor capabilities, they are limited to identifying only exposed surfaces. Despite rapid developments in camera technology, differentiating among fat, bone, and cartilage remains a challenge. As a result, alternative sensing technologies, particularly various forms of X-ray systems, have been explored for their applicability (Nielsen et al., 2018).

A particularly promising application is the use of CT based on X-rays, a technique well established in the medical field. An X-ray CT scanner can offer a comprehensive 3-dimensional description of the carcass, accurately delineating the locations of meat, fat, and bone. This precise mapping is ideal for guiding subsequent robotic cutting operations. Efforts to develop an online CT scanner as a sensor for cutting robots have encountered several challenges, with scanning speed being a critical factor for success. The trade-off between scanning speed and image resolution presents a delicate balance; medical scanners, which provide high-resolution images, operate relatively slowly compared to the needs of a pork middle scanner, which would need to process at least 600 pieces per hour. Design considerations for the scanner also include ensuring it is suitable for the rigorous cleaning protocols of slaughterhouses and safe for operators to work alongside without risk of X-ray exposure. A prototype has been developed, but reducing capital investment remains a goal. The latest innovation in this area involves simplifying the scanner by reducing the number of X-ray projections and replacing the rotating X-ray source and detector panel with a fixed setup with only a few projection points. This approach could provide a cost-efficient alternative to full-scale CT scanning while still offering sufficient sensor input for cutting robots. Figure 5 shows a prototype of an online CT scanner for scanning pork middles. Advancements in camera technology continue to make it more affordable and powerful, with vision cameras now ubiquitous throughout processing facilities, providing vast amounts of data for a myriad of applications. These range from controlling gambrels and inspecting R2 boxes to machine surveillance, product identification, and more.

The automation or augmentation of visual meat inspection is garnering increasing attention due to its crucial role in ensuring food safety, animal welfare, and disease control (Sandberg et al., 2023). Currently performed entirely by manual labor, experimental equipment has been installed in Denmark to automate this process. This setup involves towers equipped with multispectral cameras and LED lights that record all carcasses passing through, aiming to detect common and less frequent flaws (Figure 6). Initially, the system has been successful in identifying fecal contamination, bile, and pleural effusion, supplementing the meat inspection process with the potential to automate parts of it in the future. Beyond flaw detection, the system aids operators in correcting identified issues by pinpointing the specific area on the carcass that requires attention, streamlining the correction process compared to situations where operators must search for flaws without initial guidance.

The potential of this inspection system is vast, as it provides high-resolution, multispectral images of all carcasses, which can be utilized for a variety of analyses. These include checking tails, assessing the color of meat and fat, evaluating surface quality and processing quality, and identifying animal welfare indicators such as bruises and bleedings. Moreover, the system holds promise for estimating and advising on the optimal use of carcass parts, such as hams and middles, potentially supplanting existing grading solutions. Ultimately, this technology could provide a comprehensive digital documentation of each carcass, supporting further processing and possibly extending to

Figure 5. A prototype for online CT scanning. The prototype works at a line speed that matches 600 middles per hour and produces complete 3D images of each slice with enough resolution to distinguish the different tissues.

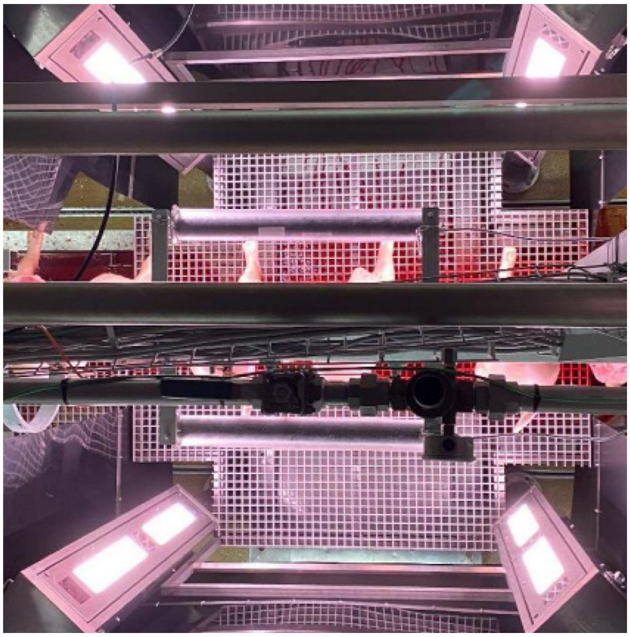

Figure 6. A system being developed for digital veterinary inspection. The system is constituted by 12 multispectral cameras in 4 towers with LED light. The entire carcass is covered, and it is presently possible to detect fecal contamination, bile residues, and pleural effusion with very high certainty in a resolution at least down to 4 mm^2. The system is viewed from above the slaughter line, and the carcasses move from right to left.

customer-level interactions. The success of such a system hinges on the ability to extract meaningful information from the data it generates, with AI already playing a crucial role in current applications. The volume of data generated is immense, as is the economic potential harnessed within it.

Speculation abounds regarding how the accelerating development of AI will impact the food system, particularly the meat industry. AI is already making inroads into the industry through new production technologies that have hit the market. The increasing application of vision technology, for example, generates vast amounts of data that necessitate some form of data reduction and interpretation. Controlling algorithms for processing equipment and the general adoption of enterprise resource planning systems for tasks such as scheduling, cost control, and inventory management are becoming increasingly powered by AI. Overall, AI is expected to enable even more efficient resource use, thereby minimizing waste throughout the supply chain. In the future, AI could play a significant role in developing consumer products and detecting early trends in consumption and demand. The emergence of advanced language models in recent years is likely to further enhance these solutions. However, beyond the initial excitement surrounding advanced chatbots, there is potential for language models to also make meat production more efficient. Imagine a training robot, real-time language translation, and seamless advanced voice communication with systems and production technology. Augmented reality, once empowered by AI, could significantly boost operator performance in areas such as yields, work environment, robot controls, preventive maintenance, and more, showcasing the vast potential of AI in transforming meat production.

Meat in a Sustainable Future

In the discourse on sustainable agriculture and the future of our food system, these authors firmly believe that meat possesses an indispensable role. The challenge of feeding the global population without the involvement of livestock is formidable, underscoring the critical importance of meat in our diets. However, it is imperative to highlight that the sustainability of some highly efficient production systems is currently in question. These systems, while super-efficient, often fall short in terms of sustainability and fail to maintain a harmonious balance with the surrounding environment (Olesen et al., 2021).

The environmental impact of meat production, particularly its contribution to CO_2 emissions, is well-documented and significant, but not well understood by the general population. As other sectors progress in reducing their carbon footprints, the meat industry's share of global emissions could disproportionately increase if it does not adapt and implement emission reduction measures at a similar pace. Advocates for sustainable agriculture have put forth strong arguments in favor of regenerative production systems and conservation agriculture. These innovative approaches are posited to have considerably lower emissions, with the potential to achieve a CO_2-negative status. Despite the potential these systems hold for mitigating climate impact, their adoption remains limited. This situation presents a valuable opportunity to lower emissions across the board and is expected to penetrate agricultural practices in the future. The ongoing heated debate should, therefore, pivot towards critiquing and improving the production systems rather than critiquing the livestock themselves. The path forward necessitates a reinvention of the highly efficient production models we rely on today. The goal should be not only to minimize CO_2 emissions but also to enhance biodiversity and reduce overall arable land use. The escalating threat of global warming makes the preservation of fertile soil a priority. This precious resource must be allocated judiciously to cultivate crops that are vital for our sustenance while carefully managing the competition for resources among food, feed, materials, and energy production.

Conclusion

The meat industry is poised for significant transformation driven by evolving consumer demands, sustainability concerns, and technological advancements. As meat becomes a luxury commodity, optimizing production efficiency and carcass utilization will be paramount. Automation and digitalization, powered by AI and computer vision, offer promising solutions for enhancing traceability, quality control, and yield optimization.

Innovations like online CT scanning and multispectral carcass inspection systems exemplify the potential of emerging technologies to revolutionize meat processing. Moreover, the integration of AI algorithms and self-learning systems could enable real-time adaptation to biological variability, aligning products with customer specifications and minimizing waste. However, the industry must confront the environmental impact of meat production by embracing sustainable practices and exploring regenerative production models. Striking a balance between efficiency and sustainability will be crucial for the long-term viability of the meat sector.

As the industry navigates these challenges, interdisciplinary collaboration and knowledge sharing will be essential. By leveraging cutting-edge technologies, embracing sustainable practices, and fostering innovation, the meat industry can adapt to the evolving landscape and secure its role in a sustainable food future.

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