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Killing them softly

Pig and cattle welfare at slaughter and its economic relevance

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Cover: the creative masterpieces by Albert & Benjamin, and my mum, were put together by my talented friend Liudmyla Ivanova

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Killing them softly - pig and cattle welfare at slaughter and its economic relevance

Abstract

The time spent at the slaughterhouse represents a relatively short period in an animal's life, yet it holds substantial relevance for animal welfare. Thereto, slaughterhouse businesses are profit-driven and must maintain an efficient process flow whilst producing high-quality products that meet societal expectations. The overall aim of this thesis was to map animal welfare-related aspects during the slaughter of pigs and cattle and assess the economic relevance of animal welfare improvements for slaughterhouse businesses. This research is primarily conducted from a Swedish perspective, but it also holds international relevance. Using an interdisciplinary approach that combines animal science and production economics, the work develops a theoretical economic model for animal welfare at slaughter, includes on-site slaughterhouse observations, analyses post-mortem meat inspection data, and simulates the economic effects of improved animal welfare at slaughter. The results show that process flow and personnel-related aspects are key factors for slaughterhouses in the decision-making process of investing in animal welfare improvements. Stunning efficiency in both pigs and cattle varied widely between slaughterhouses, and longer stun-to-stick intervals were associated with inadequate stun quality and the likelihood of re-stunning. The occurrence of traumatic injuries was linked to higher condemnation rates, resulting in both direct and indirect economic effects on slaughterhouse operations. Economic simulations revealed that the prevalence of stun failures had implications for both animal welfare and economic outcomes. These simulations demonstrated that the primary drivers of net benefit change for improving stunning efficiency were costs related to labour and investments in new stunning equipment in both pig and cattle slaughterhouses. This thesis concludes that animal welfare and economic outcomes at slaughter are interconnected, often favourable, indicating that animal welfare should not be solely treated as a cost. The results provide an empirical basis for understanding the complex connections between animal welfare and economic outcomes, offering insights for decisions on slaughterhouse, authority and policy level.

Keywords: abattoir, animal protection, animal welfare, commercial slaughter, condemnation, economic modelling, humane slaughter, profitability, stun quality, traumatic injuries

Killing them softly - djurvälfärd och dess ekonomiska relevans vid slakt av grisar och nötkreatur

Sammanfattning

Tiden som djuren tillbringar på slakteriet utgör en relativt kort period av deras liv, men har ändå stor betydelse för djurvälfärden. Samtidigt verkar slakterierna på en konkurrensutsatt marknad, där kraven på effektivitet och lönsamhet måste balanseras mot högt ställda krav på djurskydd och produktkvalitet. Det övergripande syftet med den här avhandlingen var att kartlägga djurvälfärdsrelaterade aspekter vid slakt av grisar och nötkreatur samt att undersöka den ekonomiska relevansen av djurvälfärdsförbättrande åtgärder för slakteriföretagen. Forskningen bedrevs ur ett svenskt, men internationellt relevant, perspektiv och baserades på ett tvärvetenskapligt angreppssätt som kombinerade husdjursvetenskap och produktionsekonomi. Arbetet inkluderade utveckling av en teoretisk, ekonomisk modell för djurvälfärd vid slakt, analyser av nationell slaktdata, bedömning av bedövningskvalitet, och ekonomiska simuleringar av scenarier för förbättrad djurvälfärd vid slakt. Resultaten visar att processflöde och personalrelaterade aspekter är nyckelfaktorer för slakterier i beslutsprocessen kring investeringar i djurvälfärdsförbättrande åtgärder. Längre sticktider, dvs. tiden mellan bedövning och avblodning, ökade risken för att både grisar och nötkreatur blivit antingen initialt dåligt bedövade, eller uppvisade tecken på dålig bedövningskvalitet. Även sannolikheten för att djuren behövde ombedövas ökade med längre sticktider. Förekomsten av traumatiska skador var kopplade till ökad kassation av kött och därmed även till både direkta och indirekta kostnader för slakteriföretagen. De ekonomiska simuleringarna visade att investeringar i ny bedövningsutrustning och regelbunden service hade positiva effekter på både djurvälfärd och lönsamhet, men att utfallet berodde på slakteriets storlek, arbetskostnader och nuvarande effektivitet. Sammantaget visar resultaten att djurvälfärd och ekonomi vid slakt är tätt sammanflätade, ofta på ett fördelaktigt sätt, och att investeringar i djurvälfärd inte enbart kan ses som en kostnad. Avhandlingen bidrar med ny kunskap om sambanden mellan djurvälfärd och ekonomiska konsekvenser och ger ett vetenskapligt underlag för beslutsfattande på såväl slakteri-, myndighets- som politisk nivå.

Keywords: bedövningskvalitet, djurskydd, ekonomisk modellering, human slakt, köttkassation, kommersiell slakt, lönsamhet, slakteri, traumatiska skador

Preface

How does someone become so curious, so deeply immersed, in the act of killing animals? It's a question I'm often asked, and one I've asked myself many times.

The truth is, it doesn't make complete sense. Not when thinking about who I was before I first entered a slaughterhouse. I couldn't imagine watching an animal die, let alone being the one to end its life. But something shifted the moment I stepped inside a slaughterhouse, and definitely when I was handed the captive bolt. This animal must die, and it was up to me, the person holding the gun, to make sure it happened in the best possible way.

That moment marked the beginning of the bloody path I'm still walking. Since then, I've held on to one belief: if animals are going to die because of us, we owe them the best possible end. There are better and worse ways to do this, and once we know the difference, there's no excuse not to choose the better one.

Working in, and later with, the slaughterhouses, I began to see how financial considerations shaped everyday decisions on the floor. I saw a need for bridging the gap between economic reasoning and animal welfare, so that decisions could be made with both in mind. I'm so thankful for the people who saw the same need, believed in me and my idea and made this possible.

This work is done with the people in mind who do what few of us are willing to do, but most of all, it is for the animals who, without a choice, will enter a slaughterhouse for the first and last time in their lives.

Prince Edward Island, July 2025

"Thine is a task of blood –
Discharge that task with mercy,
Let thy victim know no pain
But let the sudden blow bring death,
Such death as thou thyself would ask."

Pistol versus Poleaxe, 1932

Dedication

Albert och Benjamin
ni är allt

Contents

List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I. Jerlström, J., Berg, C., Karlsson, A.H., Wallenbeck, A., Hansson, H. (2022). A formal model for assessing the economic impact of animal welfare improvements at bovine and porcine slaughter. Animal Welfare, 31 (3), 361-371. doi:10.7120/09627286.31.4.004

II. Jerlström, J., Berg, C., Wallenbeck, A. (2025). Unnecessary suffering during the slaughter of cattle and pigs: mapping stun quality and associations to stun-to-stick intervals. Frontiers in Animal Science, vol (6), doi:10.3389/fanim.2025.1633616

III. Jerlström, J., Lind, A-K., Lindahl, C., Berg, C., Wallenbeck, A. (2025). Traumatic injuries detected at slaughter in cattle: impact of production system and season on animal welfare and meat condemnation in Sweden. Acta Veterinaria Scandinavica 67 (18). https://doi.org/10.1186/s13028-025-00804-x

IV. Jerlström, J., Wallgren, T., Westin, R., Olsson, M., Karlsson, A.H., Wallenbeck, A. Traumatic injuries detected at slaughter of pigs at Swedish slaughterhouses and their implications on meat condemnation and animal welfare (manuscript)

V. Jerlström, J., Hansson, H., Wallenbeck, A., Wei H. V. Assessing slaughterhouses' economic outcomes of stun failures in pigs and cattle (submitted)

Papers I, II and III are published with open access.

The contributions of Josefine Jerlström to the papers included in this thesis were as follows:

I. Main author. Planned and designed the study, collected data, analysed and interpreted results, produced tables and figures, and drafted and led the writing of the manuscript.

II. Main author. Planned and designed the study, collected and cleaned data, performed statistical analyses and visualisation, and drafted and led the writing of the manuscript.

III. Main author. Planned and designed the study, retrieved and processed slaughter data from Växa, assisted in data cleaning, statistical analysis and visualisation, and drafted and led the manuscript with co-authors.

IV. Main author. Planned the study, retrieved and processed slaughter data from Farm and Animal Health, performed data cleaning, statistical analysis and visualisation, and drafted and led the manuscript.

V. Main author. Planned and designed the study, collected data, analysed data, and drafted and led the manuscript.

All studies were planned, designed, and written in collaboration with the co-authors. Jerlström was the corresponding author for all papers. The results from Papers I, IV, and V were presented at international scientific conferences, while the results from Papers II and III were presented at national scientific conferences. In addition, findings from all five studies were shared with the industry through various meetings and conferences.

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Abbreviations, terms and definitions

Abbreviations

ATI	Acute Traumatic Injuries
CO_2	Carbon dioxide
CTI	Chronic Traumatic Injuries
FBO	Food Business Operators
SOP	Standard Operating Procedures
WOAH	World Organisation for Animal Health

The definitions in this thesis aim to clarify important terms and expressions frequently used for a better understanding of the subject.

Acute traumatic injuries (ATI): defined as recent musculoskeletal traumatic injury, for example, wounds, hematomas, bruises and fractures, and should reflect injuries occurring during transport or at the slaughterhouse.

Anoxia: An essentially oxygen-free atmosphere (the extreme end of hypoxia). Operationally, an anoxic atmosphere could be described as <1% O2.

Animal welfare: The physical and mental state of an animal concerning the condition in which it lives and dies. This includes not only positive experiences but also the animal's state in relation to pain, fear, distress and other types of suffering.

Chest stick: Severing the aorta, brachiocephalic trunk, and carotid arteries and other blood vessels in the animal's chest to cause bleeding. In cattle, two cuts are made: the first to remove the hide on the brisket and the second to open the blood vessels. In pigs, only one stick is made to open the blood vessels.

Chronic traumatic injuries (CTI): Older musculoskeletal traumatic injury, for example, wounds, hematomas, bruises and fractures, and should reflect injuries occurring on-farm. In practice, this could be wounds secondary to hernias, shoulder ulcers or hematomas that have turned yellow

Consciousness and sensibility: A state in which an animal is awake and capable of perceiving, processing, and responding to sensory

information from its environment. A conscious and sensible animal can experience sensations, including pain, and show coordinated voluntary movements and purposeful responses to external stimuli.

Death: The death of an animal at the time of slaughter is defined as the physiological state in which respiration and circulation have ceased due to failure of the respiratory and circulatory centres in the medulla oblongata. Death is considered to occur when both brain and heart activity have ceased.

Exsanguination (bleeding): The process of cutting the central or carotid arteries to bleed the animal. Due to the loss of oxygen and nutrients to the brain, it will eventually cause the animals' death.

Food Business Operators (FBOs): The natural or legal persons responsible for ensuring that the requirements of food law are met within the food business under their control (Regulation (EC) 178/2002). In the context of this thesis, the FBOs are also directly responsible for ensuring animal welfare at slaughter and compliance with the laws (Regulation (EC) 1099/2009).

Humane slaughter: When the handling, stunning and killing procedure results in insensibility to pain within a short period of time, without causing unnecessary pain and suffering to the animal.

Hypoxia: Exposure to a low-oxygen atmosphere that deprives tissues of oxygen; in pig stunning, this is usually created with inert gases (argon or nitrogen) or mixed-gas systems. Operationally, a hypoxic atmosphere is commonly described as <2% O_2 by volume.

Hypercapnia: Exposure to very high carbon dioxide atmospheres (typically means ≥80–90% CO_2) that elevate CO_2 in the animal's blood and tissues.

Investment: An expense made today with the expectation of future return or benefit.

Killing: The deliberate process (e.g. stunning and bleeding) which causes the death of an animal.

Neck cut: Severing the carotid arteries and other blood vessels in the animal's neck to cause bleeding.

Slaughter: The deliberate process of killing an animal with the purpose of using its meat for human consumption.

Slaughterhouse business: An enterprise that operates facilities for the slaughter of farmed animals and the initial processing of carcases into meat for human consumption.

Standard operating procedure (SOP): The individual slaughterhouse's standards to achieve uniformity of the performance of a specific function, i.e., regulates stun-to-stick intervals, according to EU regulation 1099/2009.

Stun failures: Situations where the stun depth is insufficient and the animal either maintains or recovers and regains some level of consciousness

Stunning: The intentional procedure that makes an animal unconscious and incapable of sensory capacity without causing unnecessary pain, fear and suffering of the animal. The stunning method must result in loss of consciousness and sensibility.

Stunning efficiency: The percentage of animals rendered unconscious on the first stunning attempt.

Stun quality: How effectively an animal is rendered unconscious by the stunning process, based on observable indicators of unconsciousness and insensibility.

Stun-to-stick interval: The time from achievement of effective stunning to the start of exsanguination. The maximum time for this is regulated in the slaughterhouses' SOPs.

Tangible/intangible asset: A tangible asset is a physical resource with a measurable value, such as buildings or equipment, whereas an intangible asset is a non-physical resource that provides future economic benefits, such as trademarks or goodwill.

Unconsciousness and insensibility: A state in which the brain's ability to perceive, process, and respond to sensory stimuli is temporarily or permanently abolished by the stunning method. An unconscious and insensible animal shows no awareness, voluntary motor control, or response to external stimuli such as sound, light, or infliction of pain.

1. Introduction

Public concern about animal welfare has grown over the past decades (European Commission, 2016; 2023), particularly regarding welfare at slaughter, with mounting expectations that animals must be treated humanely during the final stages of their lives. Although the time spent at the slaughterhouse represents a relatively short period in an animal's life, it has a major influence on their welfare. At the same time, slaughterhouse businesses are profit-driven (Broek et al., 2006) and thus they must also maintain efficient process flow, produce high-quality products, and ensure worker safety and well-being whilst meeting societal expectations. Together, this creates a complex balance between animal welfare and economic outcomes for slaughterhouse businesses.

A central measure that protects animals from unnecessary suffering at slaughter is to render them unconscious and insensible prior to bleeding, a process referred to as stunning (McKinstry & Anil, 2004; Woolridge, 1922). This unconscious state must persist until death from blood loss occurs. Within the EU, stunning is mandatory, but exemptions, such as those related to religious slaughter, may be permitted (Council Regulation (EC) No. 1099/2009). In Sweden, however, the regulations are stricter and do not allow any exemptions (SFS 2018:1192). The most common stunning method for cattle (*Bos taurus*) is mechanical stunning using captive bolts (EFSA, 2020b). For pigs (*Sus scrofa domesticus*), group gas stunning with high concentrations of carbon dioxide (CO_2) or electrical stunning are the preferred methods (EFSA 2020a). These are all technically complex procedures that require functional equipment, clear standard operating procedures (SOPs), and trained personnel capable of recognising signs of consciousness or recovery (Grandin, 2013).

The relationship between pre-slaughter stress, animal handling, and meat quality is well described (Chulayo & Muchenje, 2016; Costa et al., 2006; Grandin, 1980; Warner et al., 2007). Factors such as personnel skills, slaughterhouse design, stunning procedures, and equipment maintenance influence both animal welfare and process efficiency (Grandin, 2000; Hultgren et al., 2014). One indicator of compromised welfare is the occurrence of traumatic injuries, which may arise from on-farm incidents, transport, or handling at the slaughterhouse (Valkova et al., 2021). These injuries signal reduced animal welfare (Broom, 2000; Comin et al., 2023),

but can also lead to condemnations and food waste, resulting in economic losses for both farmers and slaughterhouses.

Previous research suggests that animal welfare can be an important component of slaughterhouse economic outcomes (Gallo & Huertas, 2016; Gibson & Jackson, 2017; Grandin, 1995; Wigham et al., 2018). Indeed, humane handling practices can yield economic benefits by reducing production costs, improving carcase and meat quality, and minimising disruptions in the workflow. Notably, inadequate stunning not only risks exposing animals to unnecessary suffering but can also disrupt workflow, require re-stunning, and negatively affect operational efficiency (Grandin, 1995). Despite these connections, scientific studies on the economic outcomes of animal welfare at slaughter are lacking.

Whilst investments in animal welfare-improving practices, such as redesigned facilities, upgraded stunning systems, or training of personnel, are often associated with significant costs, their economic benefits are difficult to quantify. As a result, animal welfare may be undervalued in strategic decision-making, particularly when the benefits are long-term or indirect. From a societal perspective, this uncertainty challenges policymakers, who must determine whether existing economic incentives are sufficient in ensuring high animal welfare standards and whether additional measures are needed to encourage industry investment in welfare improvements.

Considering the immense number of animals slaughtered globally each year, preventing unnecessary suffering at any stage of the process is crucial for maintaining both animal welfare and public trust in animal production (WOAH, 2024). At the same time, efficiency and sustainability must also be addressed, as condemnations due to traumatic injuries highlight both economic losses and food waste (Strid et al., 2023), which affects the farmer, the slaughterhouse, and the environment. In Sweden alone, nearly 2.6 million pigs and 420,000 cattle are annually slaughtered (Swedish Board of Agriculture, 2025). Thus, the implementation of slaughter operations that safeguard animal welfare, ensure carcase quality, maintain economic stability, and operate with transparency and legitimacy in the eyes of society has become increasingly urgent.

In light of these challenges, this thesis is grounded in the need to assess incentives for the slaughterhouse industry to invest in animal welfare improvements. By applying both animal science and production economics

approaches, this work provides novel insights into the economic relevance of animal welfare at slaughter, thereby supporting more informed decision-making by policymakers and slaughterhouse businesses.

1.1 Scope of the thesis

This section describes the scope of the thesis, outlines its aims and objectives, and explains how the work is structured. The research within this thesis is based on the general acceptance of killing animals for human consumption and therefore does not compare killing with not killing animals, although ethical aspects are touched upon. Furthermore, this thesis adopts an anthropocentric perspective, recognising animal welfare as a human responsibility that holds ethical, economic, and societal importance within sustainable food production.

1.1.1 Overall aim and specific objectives

The overall aim of this thesis is to map animal welfare-related aspects during the slaughter of pigs and cattle and assess the economic relevance of animal welfare improvements for slaughterhouse businesses.

Specific objectives are to:

- Develop and introduce an economic model that maps the possible economic outcome for slaughterhouse businesses by improving the welfare of pigs and cattle at slaughter (Paper I).
- Assess the stunning efficiency of CO_2 stunned pigs and mechanically stunned cattle under commercial slaughter conditions in relation to animal welfare (Paper II).
- Map the prevalence of chronic traumatic injuries (CTI) and acute traumatic injuries (ATI) among pigs and cattle at slaughter and quantify condemnations related to these injuries (Papers III & IV).
- Develop realistic and relevant slaughterhouse-based strategies that improve the welfare of pigs and cattle at slaughter and assess the economic effects of their adoption (Paper V).

1.1.2 Structure of the work and thesis

This interdisciplinary thesis is based on five papers (I–V), which together address how improvements in animal welfare during the slaughter of pigs

and cattle can influence the economics of slaughterhouse businesses and provide incentives for investments in animal welfare. This research is primarily conducted from a Swedish perspective but holds international relevance (Figure 1).

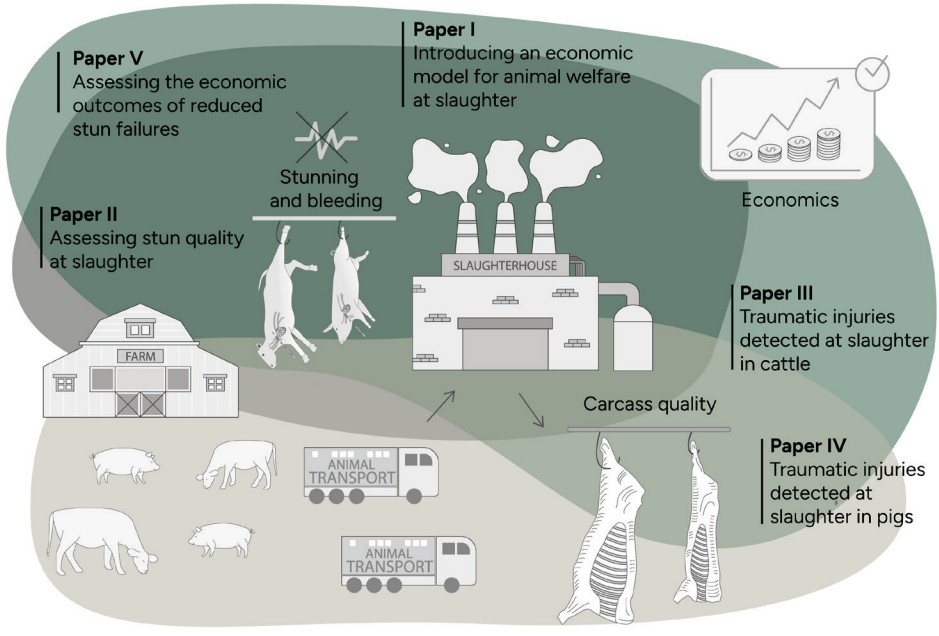

Figure 1. Schematic illustration of the work performed in Papers I-V and the links between the papers.

In Paper I, a conceptual framework describing the role of animal welfare in relation to the economic performance of the slaughterhouse businesses is developed. This study has three specific aims: to highlight the possible economic effect of animal welfare improvements, to develop an economic model demonstrating the theoretical contribution of animal welfare to slaughterhouse profitability, and to validate the model through focus group interviews with slaughterhouse personnel.

Paper II provides empirical data on animal welfare at slaughter by assessing the stunning efficiency of pigs stunned with CO_2 in five slaughterhouses and cattle stunned mechanically in six slaughterhouses. It also investigates how stun-to-stick intervals are associated with the risk of

animals regaining consciousness, which could potentially lead to compromised welfare and unnecessary suffering.

In Papers III and IV, observational studies analysing the prevalence of traumatic injuries detected during the slaughter of nearly 7.1 million finishing pigs (slaughtered between 2019-2021) and around 336,000 cattle (slaughtered between 2020-2022) are performed using routinely recorded slaughter data. For pigs, data was retrieved from the Swedish Farm and Animal Health (national livestock health organisation) and for cattle from Växa Sverige (national advisory cooperative for cattle). Additionally, the associated condemnations are quantified to illustrate the extent of meat loss resulting from such injuries.

The final study, Paper V, develops realistic and relevant strategies for slaughterhouses aimed at reducing stun failures, thereby improving stunning efficiency and animal welfare, for pigs and cattle at slaughter. To achieve this, the results from Paper II, combined with expert elicitation from slaughterhouses and manufacturers, are used to model baseline scenarios and alternative scenarios. Additionally, the results from Papers III and IV are used to contribute to the modelled scenarios. Subsequently, the economic outcomes of transitioning from the baseline to the alternative scenarios are assessed by applying a stochastic partial budgeting framework.

2. Theoretical and conceptual framework

The slaughter of animals constitutes a central component of the food production chain. It commences on the farm with rearing and management, continues through transport, handling in lairage and in relation to slaughter, processing, storage, and the distribution of meat and by-products to food manufacturers, retailers, and consumers. This thesis is primarily centred around the sections of the production chain that link to the procedures in the slaughterhouse, particularly in relation to animal welfare and the relevance it holds for the economic outcomes of slaughterhouse businesses. However, two of the five papers also include aspects of on-farm management to highlight the importance of rearing conditions for slaughterhouse practices, in terms of e.g. handling and labour.

In this chapter, key aspects of the theoretical and conceptual framework of this thesis are described. The first section addresses the concepts of humane slaughter and animal welfare, as well as the regulatory framework for the protection of animals at the time of killing. The second section briefly discusses meat production and slaughter practices for pigs and cattle, and how stunning efficiency is assessed. The third section addresses the economic dimensions and relevance of animal welfare at slaughter, and the possible incentives for slaughterhouses to invest in animal welfare improvements.

2.1 Humane slaughter and animal welfare

Death is a subject that most people avoid talking about, possibly because of the uncertainty of when it will occur. For livestock, however, it is principally humans who determine the moment of death. This is usually carried out through a procedure known as slaughter, which is defined as the killing of animals intended for human consumption, including all related operations such as handling, lairage, restraining, stunning, and bleeding, conducted within the context and location of slaughter (Council Regulation (EC) No. 1099/2009). Animal welfare during slaughter is considered highly important by consumers (European Commission, 2023), and upholding these standards is central to maintaining the slaughter industry's social license to operate. Regardless of where in the world slaughter takes place, the intended

outcome is always the same: the animal should arrive at the slaughterhouse alive and leave it dead.

2.1.1 The concept of humane slaughter

Historically, the concept of humane slaughter emerged at the end of the 19th century (Slade, 1879) with the rise of industrialisation, when the slaughter industry began to expand and become a central component of the modern animal production system (Fitzgerald, 2010). Driven by growing public concern about animal suffering and the efforts of early animal protection movements within Europe (e.g., RSPCA), campaigns by animal protectionists advocating for more humane slaughter practices spread (Macnaughten, 1932). Since then, various methods for humanely killing animals have been developed and debated, reflecting differences in technology, tradition, and religion across countries.

The concept of humane slaughter has been defined in several ways. At the international level, the World Organisation for Animal Health (WOAH) emphasises that slaughter is not a single act, but a process comprised of careful handling, restraint, stunning, and bleeding such that the welfare of the animal is protected throughout, meaning that there is minimal pain, distress, and suffering at each stage (WOAH, 2024). Similarly, the American Veterinary Medical Association (AVMA) describes humane slaughter as the application of scientifically supported techniques at every stage from handling to inducing death to cause a rapid loss of consciousness and, ultimately, a complete loss of brain function to avoid suffering (AVMA, 2024). Together, these definitions have a common principle: that humane slaughter meets both an ethical and technical standard. The process encompasses the use of methods designed to minimise suffering, ensure rapid loss of consciousness, and maintain respect for the animal throughout.

The most well-known method to carry out this task is stunning, an intentional process that induces a loss of consciousness and sensibility until death occurs through exsanguination (bleeding) or cardiac arrest (Terlouw & Le Neindre, 2024). The primary purpose of stunning is to prevent pain and suffering by interrupting the normal neuronal and neurotransmitter functions in the brain (EFSA, 2004; Holst, 2001). Importantly, the stunning method itself should not cause stress or pain (Steiner et al., 2019). Nevertheless, it is well established that pain, fear, and stress can occur in association with certain stunning methods, arising from either the induction process itself or

the handling of animals immediately prior to stunning (Brandt & Aaslyng, 2015).

According to WOAH (2024), humane slaughter, therefore, requires that animals are rendered unconscious and insensible before death, and that this state is maintained until death occurs. To ensure good welfare, bleeding must be initiated before consciousness can be regained (Atkinson et al., 2012). Bleeding, or exsanguination, involves severing major blood vessels in the neck or chest, which prevents oxygen and nutrients from reaching the brain, leading to irreversible loss of consciousness and death (Mota-Rojas et al., 2012; Terlouw et al., 2016a). If bleeding is delayed or performed improperly, slow exsanguination may occur, increasing the risk of recovery and inflicting pain or distress if not promptly detected and re-stunned. An essential factor that influences the efficiency of bleeding is the design and handling of the sticking knife. A precise incision at the correct anatomical location with a well-sharpened knife enhances rapid exsanguination. Furthermore, using a 20 cm double-edged knife has been shown to reduce poor sticking and incomplete bleeding in pigs (Wotton & Gregory, 1986). Conversely, inaccurate or insufficient incisions may delay exsanguination and increase the likelihood of animals regaining consciousness during slaughter (Anil et al., 2000).

2.1.2 Regulatory framework

Today, under European Union (EU) legislation, pre-slaughter stunning is mandatory to minimise unnecessary suffering, fear, anxiety, pain, and stress (Council Regulation (EC) No. 1099/2009). Exemptions may be granted for religious slaughter or, in certain cases, for economic reasons. In Sweden, however, all animals must be stunned prior to bleeding.

Council Regulation (EC) No. 1099/2009 regulates the protection of animals during the killing and slaughter process. This legislation applies to all member states of the EU and thus sets the standard for Sweden as well. However, Swedish legislation has historically contained stricter animal welfare regulations than those required by the EU directive. The current Swedish Animal Welfare Act (SFS 2018:1192) and the Animal Welfare Ordinance (SFS 2019:66) are complemented by the Swedish Board of Agriculture's Regulations and General Advice on the Slaughter and Killing of Animals (SJVFS, 2019:8 (L22)). This states that animals must be spared from unnecessary suffering and discomfort during slaughter and be rendered

unconscious prior to bleeding and until death has occurred. In Sweden, death is considered to occur when both brain and heart activity have ceased (Jerlström, 2014; SCAW, 2017). Together, these legislative frameworks include provisions that require stunning before slaughter, without exemptions for e.g. religious slaughter.

All personnel handling live animals at slaughter must hold a certificate of competence, involving both theoretical and practical training. The Food Business Operators (FBOs) must ensure that only certified personnel perform key tasks such as movement, stunning, and slaughter, and that equipment and facilities comply with regulatory standards (Council Regulation (EC) No. 1099/2009). Moreover, there are international welfare standards for the slaughter and killing of animals, which underscore that stunning methods should minimise distress and ensure non-recovery (WOAH, 2024; FAWC, 2017).

According to current EU legislation, FBOs are required to implement slaughterhouse-specific procedures, SOPs. These should be risk-based and established for all stages of the production process to ensure consistent outcomes in animal welfare and food safety. They should include, for example, stun-to-stick intervals that are suited to their stunning equipment and indicators to monitor signs of unconsciousness versus consciousness. In Sweden, the Swedish Food Agency, together with the County Administrative Boards, is responsible for overseeing that slaughterhouses operate in accordance with their SOPs and for enforcing animal protection and welfare at slaughter. Additionally, the Swedish Food Agency is responsible for ensuring food safety through ante- and post-mortem inspections in slaughterhouses, in accordance with EU Regulation (EU) 2017/625 on official control.

2.1.3 Physiological aspects relevant to humane slaughter

Animals can only feel pain, fear, or distress when they are conscious (Broom, 2022; Terlouw et al., 2016a). Thus, consciousness is not directly an animal welfare issue but a necessary condition for suffering. Humane slaughter, therefore, requires the induction of unconsciousness and insensibility that persist until death (Verhoeven et al., 2015). Although definitions may vary, it is widely accepted that an unconscious animal is insensible and unable to perceive or respond to sensory stimuli, as its brain

no longer processes sensory information (Blood and Studdert, 1988). As a result, it cannot experience pain or discomfort (Broom, 2022).

Considering that the state of unconsciousness and insensibility can be reversible, meaning that the animal can recover, continuous monitoring of the animal after stunning and bleeding is essential until death has occurred through blood loss (Gregory & Shaw, 2000). The death of an animal at the time of slaughter is defined as the physiological state in which respiration and circulation have ceased due to failure of the respiratory and circulatory centres in the medulla oblongata (EFSA, 2004; EFSA 2020a, 2020h), i.e. when brain activity has ceased and the heart activity has stopped (Jerlström, 2014).

The interval between stunning and bleeding, or stun-to-stick interval, is critical to prevent the recovery of consciousness (WOAH, 2024). European Union legislation requires slaughterhouses to define maximum intervals in their SOPs (Council Regulation (EC) No. 1099/2009), with 60 s generally accepted for both stunning pigs with CO_2 and mechanically stunning cattle (EFSA, 2004; European Commission, 2017; Holst, 2001). In practice, however, many slaughterhouses struggle to meet this standard due to equipment layout or slaughter process speed (County Administrative Boards, 2023). When stunning and sticking are performed properly, longer intervals, i.e. over 60 s, do not necessarily compromise welfare (Atkinson & Algers, 2007), but few studies have examined this aspect in detail.

2.1.4 Animal welfare at slaughter: from concept to practice

Historically, the scientific understanding of animal welfare has developed through several phases. However, it gained broader international recognition in 1965 through the introduction of the Five Freedoms: freedom from hunger and thirst, freedom from discomfort, freedom from pain, injury, and disease, freedom to express normal behaviour, and freedom from fear and distress (FAWC, 2009, 2011). Subsequently, the concept was expanded to encompass three essential components: the animal's subjective experience of its situation, its biological functioning, and its ability to adapt to the environment in which it lives (Fraser, 2008; Fraser et al., 1997). Attention later shifted toward the idea that animals should have "lives worth living", meaning that their negative experiences should be minimised whilst opportunities for positive experiences are promoted (Mellor, 2016).

Building on this broader perspective, frameworks such as One Health and One Welfare have emerged, recognising that the welfare of animals, the well-being of humans, and the integrity of ecosystems are interdependent (Garcia Pinillos et al., 2016; OHHLEP, 2022). These integrative approaches reflect a growing understanding that improving animal welfare not only contributes to ethical animal production but also to public health and environmental sustainability.

Assessing animal welfare is, however, rather complex because the concept of welfare includes the animal's subjective experience, which is difficult to measure directly (Browning, 2022). Therefore, a combination of measures is usually the most feasible option. Within the slaughterhouse, it is especially tricky, as animals spend a relatively short period of their lives there, but it can have a major impact on their experience of a "life worth living" due to exposure to other animals, people, design of drive races, sounds, smells, etc. (Miranda-de la Lama et al., 2012).

The main welfare concerns during slaughter are when animals are initially inadequately stunned, when the induction of unconsciousness is delayed, or when consciousness returns before death. Animal welfare at slaughter is determined by the interaction between animal behaviour, competence of personnel, design and infrastructure of the slaughterhouse, and management. Calm handling (Grandin, 1997; Hemsworth et al., 2011; Hultgren et al., 2014), well-trained personnel (Atkinson et al., 2013; Gallo et al., 2003; Grandin, 2013), and well-designed infrastructure can improve welfare, worker satisfaction, product quality, and the overall efficiency of slaughter operations. As an example, when animals are transferred into stunning areas, it is important that they can move in a species-appropriate and natural manner, and that the handling systems are designed to facilitate this (Gallo et al., 2003).

Information from several different aspects must therefore be considered, including resource-based indicators (e.g., the design of drive races and the handling of animals) and animal-based indicators (e.g., animals' physiological and behavioural responses) (Blokhuis et al., 2013; Grandin, 1997; Huanca-Marca et al., 2025). Observing behavioural indicators such as vocalisation or slipping is a common strategy to assess if an animal is stressed or negatively affected by their environment. New environments, such as the slaughterhouse or the stunning box, can themselves be stress-

inducing. In relation to stun boxes, the use of head restraint can cause stress in cattle (Ewbank et al., 1992) and should therefore be kept to a minimum.

The human component is one of, if not the most, important factors for animal welfare (Hemsworth et al., 1994). Indeed, job satisfaction, worker motivation to learn, and technical skills and knowledge can have a direct impact on welfare. Improving the attitudes and handling skills of personnel through training reduces stress among animals on farm as well as in slaughterhouses and enhances welfare outcomes (Breuer et al., 2000; Coleman et al., 2012). Better welfare can also improve efficiency, as calm animals move more willingly through the system (Grandin, 1995).

The scientific understanding of the relationship between pre-slaughter stress, animal handling, and meat quality is well established (Chulayo & Muchenje, 2016; Costa et al., 2006; Grandin, 1980). Stress-related defects include pale, soft, exudative (PSE) meat and dark, firm, dry (DFD) meat. Among these, PSE meat is particularly common in pigs and results from acute stress shortly before slaughter. This accelerates the normal post-mortem glycogen breakdown and acidification when the muscle is transformed into the raw material meat (pH 7 to 5.5), producing pale meat with poor water-holding capacity (Grandin, 2000; Warriss et al., 2010). In contrast, DFD meat arises from prolonged stress or exertion that depletes muscle glycogen, resulting in a high ultimate pH and dark, dry meat that is prone to spoilage (Holdstock et al., 2014). In both cases, meat must be downgraded or condemned (European Commission, 2007).

Carcase quality is closely linked to animal welfare during the pre-slaughter and slaughter process. Physical defects, such as bruises, hematomas, fractures, or cuts, are common indicators of poor handling or facility design, which also directly decrease a carcase's value through trimming and condemnation (Comin et al., 2023; Faucitano, 2010; Strappini et al., 2009). Bruising is one of the most common injuries observed at slaughter (Grandin, 2018) and can provide insights about when injuries occurred. Bright red lesions typically reflect trauma near the time of slaughter, such as bruises on the side where cattle collapse after stunning (Meischke & Horder, 1976). In contrast, darker lesions often indicate earlier events which frequently occur during transport or on the farm, and are related to, for example, the design of boxes (Strappini et al., 2009). High levels of fresh, red bruising have been linked to rough handling and incorrect use of

equipment in the period immediately prior to stunning (Strappini et al., 2013).

Skin lesions have been shown to serve as indicators of meat quality, as higher lesion scores correlate with elevated muscle pH 24 hours post-slaughter and an increased incidence of DFD meat (Guardia et al., 2009). Furthermore, transportation conditions, notably driving behaviour and vehicle design, have a major influence on carcase damage. Even with identical vehicles, differences in driving style accounted for 8–17% more carcases without injuries, suggesting that rough driving increases the risk of bruising and related welfare impairments (Driessen et al., 2020).

Recording the type of injuries at slaughter not only contributes to public health surveillance but also to monitoring animal welfare across the entire production chain (Comin et al., 2023). So far, however, its systematic use for animal welfare assessment is limited (Brandt et al., 2015; Grandin, 2017).

2.2 Meat production and slaughter practices for pigs and cattle in Europe and Sweden

Slaughterhouse businesses are industrial facilities that process animals into meat products within a regulated environment (Fitzgerald, 2010). The economics of slaughterhouse businesses are driven by the scale (Broek et al., 2006), efficiency, labour, and processing of by-products. Revenues typically come from meat and by-products (and sometimes slaughter fees, e.g., contract slaughtering, which is described below), whilst costs are dominated by animals (usually purchased from farmers), labour, energy, compliance, and waste handling (Hagberg et al., 2024). Generally speaking, many slaughterhouse businesses struggle with profitability, rendering both operational efficiency and full utilisation of the animal as the main contributors to profit maximisation.

2.2.1 Overview of the meat production industry

In 2024, the EU produced a provisional 21.1 million tonnes of pig meat and 6.6 million tonnes of bovine meat (including both beef and veal carcases). The predominant beef-producing countries were France, Germany, and Spain, which together accounted for approximately 46% of the total beef and veal production. The leading producers of pig meat were

Spain, Germany, and France, jointly responsible for nearly 54% of total pig meat production (Eurostat, 2025).

In Sweden, almost 250,000 tonnes of pig meat and 159,000 tonnes cattle was produced in 2024 (Swedish Board of Agriculture, 2025). The Swedish slaughter industry is characterised by a few large, dominant operators alongside a growing number of medium- and small-scale specialised facilities (Swedish Board of Agriculture, 2015). In 2024, a total of 82 pig and cattle slaughterhouses were active, 42 of which processed pigs and 63 processed cattle, with 23 facilities handling both species (Swedish Board of Agriculture, 2025).

No official classification system exists for slaughterhouse size in relation to red-meat species; therefore this thesis applies a categorisation developed within a project by the Swedish County Administrative Board (2023). Slaughterhouses were defined as small-scale when fewer than 3,000 animals of a given species are processed per year, medium-scale at 3,000–15,000, and large-scale at more than 15,000 animals annually.

Applying this classification, 46 cattle slaughterhouses were identified as small-scale (processing approximately 4% of the national total), ten as medium-scale (≈ 20%), and seven as large-scale (≈ 76%) (Figure 2). For pigs, no medium-scale facilities were identified; instead, 30 small-scale slaughterhouses accounted for 0.5% of total slaughter, whilst 12 large-scale facilities processed 99.5% of all pigs. A smaller number of Swedish slaughterhouses operate through contract slaughtering, where animals are processed on behalf of farmers who then retain ownership of the meat. This practice, which has become increasingly common, supports small-scale farming and maintains access to local slaughter services in an industry that is consolidating.

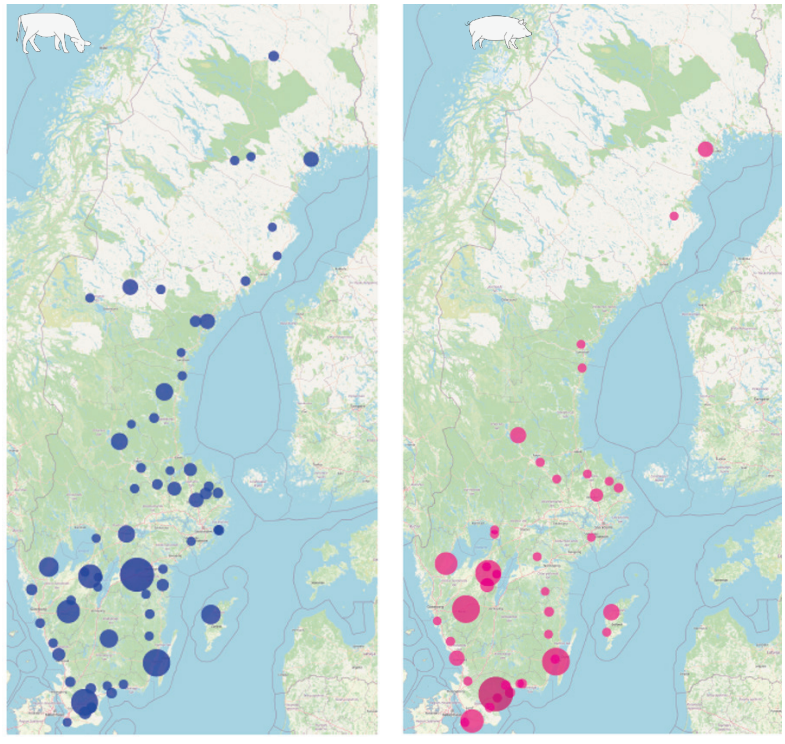

Figure 2. Geographic distribution of pig slaughterhouses (right, n = 42) and cattle slaughterhouses (left, n = 63) in Sweden during 2024, based on data from the Swedish Board of Agriculture (2025). Each circle represents one slaughterhouse; larger and darker circles indicate higher slaughter volumes (number of animals slaughtered per year).

2.2.2 Slaughter practices for pigs

In the EU, the legally approved stunning methods for pigs include CO_2, electrical and mechanical stunning (Council Regulation (EC) No. 1099/2009). Most pigs are stunned using high concentrations of CO_2 (≈ 67%), whilst about 28% are electrically stunned; the method used for the remaining 5% is not specified (PigStun, 2024a). Large-scale slaughterhouses predominantly use CO_2 systems; therefore this is the method that this thesis primarily focuses on, with electrical stunning briefly described.

Both CO_2 and electrical stunning are reversible, meaning that animals can regain consciousness if parameters such as gas concentration, exposure time, or electrical current are insufficient (Becerril-Herrera et al., 2009). However, in gas stunning, the potential for irreversible stunning, in contrast to reversible, is related to the gas concentration and duration of gas exposure.

CO_2 stunning was introduced in the 1970s as an alternative to electrical methods, which improved line efficiency and meat quality by reducing blood splash and PSE meat (Terlouw et al., 2008; Velarde et al., 2001). Modern group-based systems such as the Butina® dip-lift and paternoster designs generate less handling stress compared with earlier individual systems (Grandin, 2003). One additional advantage is that CO_2 is a colourless and odourless gas with a slightly acidic taste and anaesthetic properties. It does not leave residues in meat, occurs naturally in living organisms, and is relatively cheap to produce (Wallgren et al., 2020).

According to Regulation (EC) No. 1099/2009, a minimum of 80% CO_2 must be used at the highest concentration level of the system, and pigs must be exposed for a duration that is long enough to induce unconsciousness. This physiological mechanism involves hypercapnia and acidification of brain cells, causing loss of consciousness and eventually death (Atkinson et al., 2020; Llonch et al., 2012; Rodríguez et al., 2008). Higher CO_2 concentrations shorten an induction time (Terlouw et al., 2016a), but the process is not instantaneous and will cause aversive behaviours such as gasping, escape attempts, and possibly vocalisation (Atkinson et al., 2012). After stunning, bleeding commences through chest sticking, in which the major thoracic blood vessels are severed. The interval between stunning and sticking should be kept as short as possible to prevent recovery of consciousness. A maximum of about 60 s is generally accepted (EFSA, 2004; European Commission, 2017), although longer intervals may be acceptable when both stunning and bleeding are effective (Atkinson & Algers, 2007).

In the dip-lift system, a gondola containing up to eight pigs is lowered into a pit at a depth of two to four metres, where pigs are exposed to the highest CO_2 concentration at the bottom, as CO_2 is a heavy gas (Figure 3).

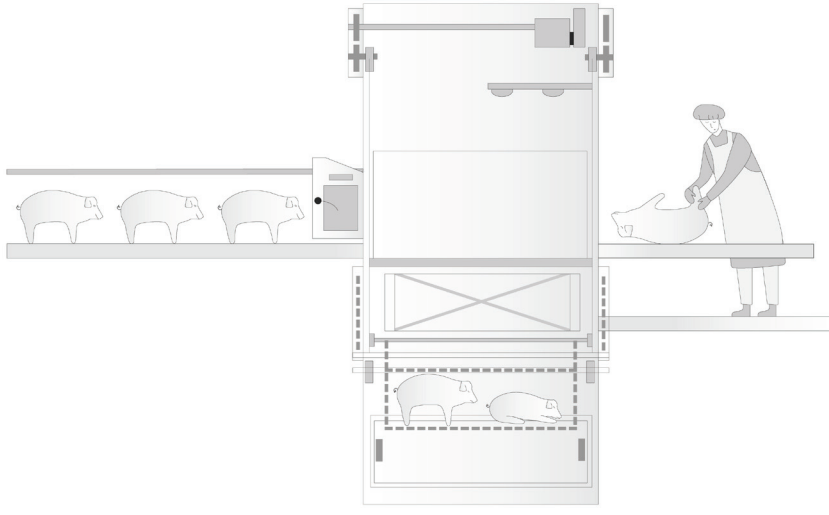

Figure 3. Illustration of a dip-lift system for stunning pigs with CO_2. The system contains one gondola, with a capacity of between two and eight finishing pigs.

In the paternoster system, up to seven rotating gondolas, each carrying two to seven pigs depending on the model, move through a CO_2 gradient in a pit three to eight metres deep (Figure 4). Live pigs are loaded at one end of the system, whilst unconscious pigs are unloaded for sticking at the other end.

In Sweden, group CO_2 stunning is the standard practice in large facilities, whilst electrical and captive-bolt methods are predominantly used in small-scale slaughterhouses (SJVFS 2019:8). After chest sticking, carcases are hung for approximately 3–4 minutes to ensure death before further processing (Jerlström, 2014; SCAW, 2017).

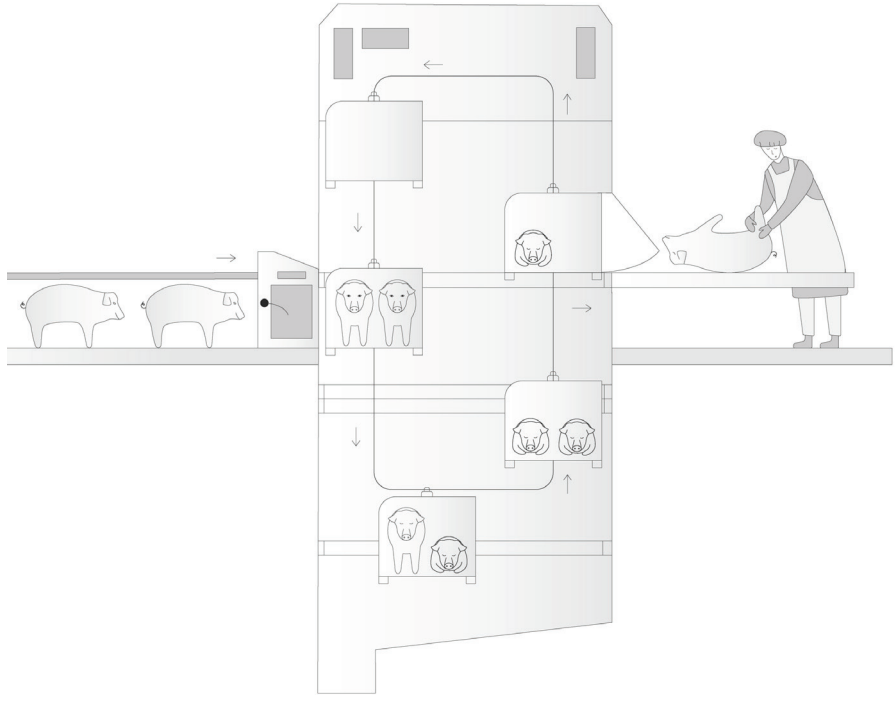

Figure 4. Illustration of a paternoster system for stunning pigs with CO_2. The system usually contains between four and seven gondolas, each with a capacity of between four and eight finishing pigs.

Electrical stunning, first introduced in Europe in the 1920s, remains a widely used method worldwide (EFSA, 2020a; Wotton & Gregory, 1986) and can be effective when applied correctly, but requires individual handling restraint, which can be very stressful (Grandin, 2013). There are primarily two types of electrical stunning methods: head-only stunning, which induces reversible unconsciousness, and head-to-body stunning, which induces both unconsciousness and death, i.e. an irreversible method (EFSA, 2020a). The purpose of electrical stunning is to induce a generalised epileptiform seizure by passing an electric current through the animal's brain, thereby causing an immediate loss of consciousness (McKinstry & Anil, 2004).

The recently finalised PigStun project aimed to develop and evaluate practical alternatives to high-concentration CO_2 stunning. The project identified and tested several promising systems, including optimised electrical methods and inert gases such as helium. The results demonstrated that certain alternative gases and optimised electrical systems could reduce

aversive responses from pigs compared to conventional CO_2 stunning. However, further development and cost assessment are needed before large-scale commercial implementation (PigStun, 2025). Studies on alternative stunning methods are an increasingly researched area that, in addition to stunning efficiency, also examines aspects of meat quality (Gelhausen et al., 2025).

2.2.3 Slaughter practices for cattle

The legally accepted stunning methods for cattle in Europe are mechanical stunning with captive-bolt, free-bullet rifles and shotguns, and also electrical stunning (Council Regulation (EC) No. 1099/2009). Mechanical stunning has been used since the late 19th century, evolving from early designs such as the Bruneau Mask (1872) and Greener's Humane Cattle Killer (1895) to the first captive-bolt pistol, the Behr Flash Cattle Killer (1904). This would later be developed into the modern Cash Captive Bolt Stunner (1913), which remains the basis of modern equipment (Hughes, 2011).

Two main types of captive-bolt systems are used: cartridge-driven and pneumatic. Pneumatic devices use compressed air instead of gunpowder and are typically heavier, often requiring a head-restrainer in the stun box (Figure 5). Nevertheless, both systems drive a retractable bolt up to 15 cm in length into the skull, causing extensive brain damage and concussion that immediately abolishes consciousness (Kamenik et al., 2019; Terlouw & Le Neindre, 2024). Stun quality depends on correct shot placement, bolt characteristics (length, diameter, velocity, cartridge strength), restraint efficiency, and operator competence (Shaw, 2002; Wagner et al., 2019). Proper equipment maintenance, well-designed stunning boxes, and skilled operators are essential for consistent performance and good stunning outcomes (EFSA, 2004). Under optimal conditions, 100% of the animals can be rendered insensible with one shot (Gregory & Shaw, 2000), however this level of consistency is difficult to achieve in practice (Atkinson et al., 2013; von Wenzlawowicz et al., 2012).

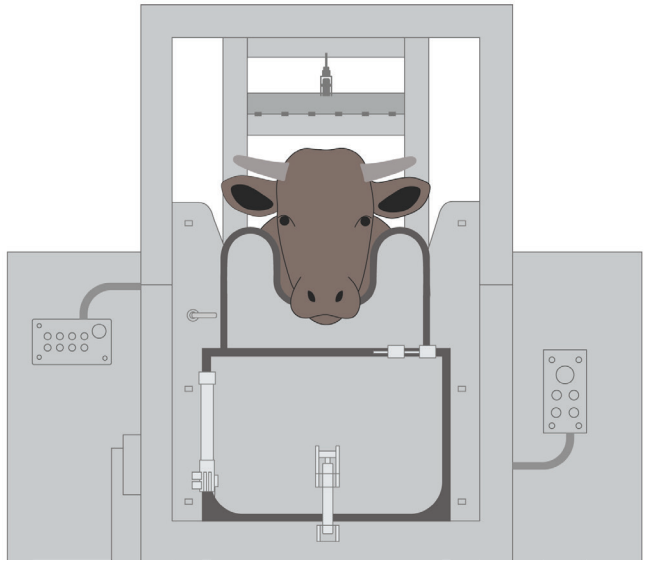

Figure 5. Illustration of a stun box with head-restrainer for cattle.

In Sweden, cattle are stunned individually using penetrating captive-bolt stunners, free-bullet rifles, shotguns, or safety rifles with free bullets, followed by chest sticking. Carcases are typically hung for 3–4 minutes to ensure that death has occurred by cardiac arrest before further processing (Jerlström, 2014; SCAW, 2017).

2.2.4 Monitoring and assessment of stun quality

Regular monitoring of indicators of consciousness, unconsciousness, and the risk of recovery is vital to ensure that stunning renders animals insensible until death (Council Regulation (EC) No. 1099/2009). Such assessments are critical for maintaining high welfare standards and preventing pain, distress, or prolonged discomfort as a result of ineffective stunning (Gregory & Shaw, 2000). Furthermore, several factors should be taken into account, including equipment maintenance, cutting and bleeding efficiency, and the occurrence of cardiac arrest (Lambooij, 2024).

Under commercial slaughter conditions, direct measurement of brain activity (e.g., EEG) or heart activity (e.g., ECG) is not practically feasible. Stun quality is therefore evaluated through several behavioural and physiological indicators that reflect the animal's level of consciousness (Levitis et al., 2009). Commonly used behavioural, or visual, signs of a

successful stun include collapsing, and absence of rhythmic breathing, righting attempts, eye movements, and vocalisation (Terlouw et al., 2016b; Verhoeven et al., 2015), as well as absence of reflexes such as corneal and palpebral reflexes (EFSA, 2004, 2020a, 2020b). The absence of these indicators (except for loss of posture, which must occur) suggests insensibility, whereas their presence indicates incomplete stunning and potential pain perception. Although mechanical stunning induces a concussion, it can, under less optimal circumstances, be partly reversible depending on shot accuracy and bolt parameters (Gibson et al., 2015; Gibson et al., 2012). Thus, the stun-to-stick interval represents a critical control point both for pigs and cattle.

Physiological parameters such as blood glucose, lactate, haematocrit, and body temperature can provide supplementary information on stress and welfare(Brandt & Aaslyng, 2015). However, visual indicators remain the most practical and reliable measures under commercial conditions (Verhoeven et al., 2015; EFSA, 2020a, 202b). Any signal of residual sensibility necessitates immediate corrective actions, typically re-stunning (Algers & Berg, 2022; Terlouw et al., 2024).

Assessing stun quality in pigs

Under commercial conditions, the assessment of stun quality in pigs relies on behavioural and reflex indicators. However, CO_2 stunning presents challenges with assessments, as the induction phase is gradual and pigs are stunned in groups, while not accessible to the observer. Moreover, direct testing of reflexes at the onset of unconsciousness is rarely feasible, since the pigs are in the bottom of the gas system. Instead, signs such as the absence of rhythmic breathing, spontaneous movements, regular gasping, and righting attempts are observed directly after exiting the stunning system, during shackling and bleeding (EFSA, 2020a). Additionally, the corneal reflex, tested by lightly touching the eye, and the pain reflex, tested by pricking the snout, are frequently used measures of sensibility. A blink or withdrawal response indicates that consciousness or partial sensibility may persist, whereas their absence confirms insensibility (EFSA, 2004; Lambooij et al., 2012).

Considering that the duration of insensibility depends on exposure time, CO_2 concentration, and the stun-to-stick interval, these parameters must be carefully controlled to prevent recovery before death (Holst et al., 2011; Atkinson et al., 2012). Regular calibration of the stunning systems,

verification of CO_2 levels and exposure times, and continuous operator training are essential to ensure effective stunning and minimise variation between groups (Grandin, 2000).

Assessing stun quality in cattle

Effective mechanical stunning of cattle relies on the immediate and sufficient disruption of brain activity. During mechanical stunning, direct damage to key brain regions, such as the thalamus, midbrain, and pons, is necessary to induce an irreversible loss of consciousness (Fletcher et al., 2025; Gibson et al., 2012; Terlouw et al., 2016a). Inadequate stunning or poor shot placement can lead to partial sensibility, causing significant pain or fear before or during bleeding (Terlouw et al., 2016a).

Stun quality is immediately assessed after the shot. The absence of rhythmic breathing, righting attempts, eyeball rotation, and corneal reflexes are the primary indicators of insensibility (Gregory & Shaw, 2000; EFSA, 2020a, 2020b). Animals should collapse instantaneously, exhibit tonic (rigid) muscle contractions followed by clonic (involuntary kicking) movements, and make no coordinated attempts to rise or make vocalisations (Algers & Berg, 2022). A fixed, glazed eye with dilated pupils and no blink response further confirms effective stunning (Verhoeven et al., 2015).

Additionally, regular inspection of equipment, cartridge strength, bolt condition, and the restraint boxes is essential to maintain stunning outcomes (Grandin, 2010).

2.3 The economic dimensions of animal welfare during slaughter

Animal welfare has ethical and economic dimensions that both ultimately relate to human welfare. From an economic perspective, improvements in animal welfare can influence human utility through both use values, linked to efficiency, product quality, and profitability, and non-use values (Hansson et al., 2018), which reflect the ethical and societal satisfaction that people receive from knowing that animals are treated humanely, independent of market transactions (Gibson & Jackson, 2017). Within this framework, animal welfare can be conceptualised as a resource that consumers are willing to pay for, but it must be balanced against production costs (Lusk & Norwood, 2011; McInerney, 1993).

Traditional economic theory focuses on efficient resource allocation and profit maximisation, but such a framework only manages to capture part of the welfare–economy relationship (Vetter et al., 2014). Animal welfare may also influence consumer behaviour, regulatory compliance, and the societal perception of the food sector, all of which have economic implications (Gibson & Jackson, 2017). This creates a tension between purely monetary values and broader ethical or societal values, as animal welfare concerns the well-being of the individual animal, whereas economics traditionally centres on human needs and material outcomes.

The relationship between animal welfare and productivity is often described as a balance, where increasing productivity can reduce welfare and vice versa (McInerney, 1993, 2004). Although these models illustrate the inherent trade-offs, they are difficult to implement in practice because animal welfare lacks a standardised unit of measurement (Tuyttens et al., 2025), and societal preferences vary over time.

Lusk (2011) identified a gap in production economics regarding animal welfare and proposed various approaches to quantify and trade units of animal welfare. Subsequently, research has demonstrated that improved farm animal welfare can yield economic advantages, including higher productivity (Telldahl et al., 2019), competitive differentiation, and access to market premiums (Fernandes et al., 2021), but also contribute to more non-use values for farmers (Hansson & Lagerkvist, 2015). More recent research has explored how production factors interact with welfare and profitability. For example, Estevez (2007) identified an optimal stocking density for broilers where productivity and welfare were jointly maximised, whilst Ahmed (2021) reported that increased space for cow–calf pairs reduced short-term profits but improved long-term performance. Similarly, Jerlström and co-workers (2022) demonstrated that two strategies aimed at reducing respiratory diseases in finishing pigs at slaughter were economically sustainable under simulated conditions. However, findings are not consistent, as some studies show that improving animal welfare comes at a cost (Olsen et al., 2023; Peden et al., 2021).

Taken together, the literature emphasises that the optimal balance between welfare and productivity is extremely context-dependent: welfare improvements can enhance efficiency, product quality, and societal acceptance, but they may also require investments. To approach this, context-specific economic modelling, supported by demand analyses and

cost–benefit assessments, is needed to guide decisions that align production, profitability, and animal welfare objectives.

In the context of slaughter, recognising both the tangible and intangible contributions of animal welfare therefore provides a broader understanding of how welfare improvements can generate value for farmers, consumers, and society. Compromised animal welfare can result in carcase damage, downgraded meat quality, and reduced consumer trust (Gibson & Jackson, 2017), whereas high welfare standards can enhance product value, societal acceptance, and long-term business performance. Consequently, economic methods play a key role in clarifying the incentives for slaughterhouses to invest in improved animal welfare practices.

2.3.1 Economic implications of animal welfare

At the slaughter stage, animal welfare and economics have been suggested to be closely intertwined, where humane handling and effective stunning can generate both measurable and intangible benefits (Gallo & Huertas, 2016; Grandin, 1995; Wigham et al., 2018). These benefits are often difficult to quantify but can be seen as improved productivity, smoother workflows, enhanced competitiveness, and market premiums (Fernandes et al., 2021; Telldahl et al., 2019).

Investments in better infrastructure, such as well-designed drive races, stunning boxes, and restraining equipment, can reduce pre-slaughter stress and meat damage, thereby improving product yield and profitability (Grandin, 1995). Stunning efficiency also has important operational implications, as effective stunning reduces bruising and carcase defects, improves meat quality, and contributes to smoother process flow on the slaughter line (European Commission, 2007). Alongside the welfare implications, physical injuries such as skin lesions (bruising, hematomas, haemorrhages) represent a source of economic loss in pig meat (Ciui et al., 2025) and beef (Huertas et al., 2015) production and processing. These lesions reduce carcase value through price deductions, partial or total carcase condemnations, and generate losses caused by trimming of damaged areas (Driessen et al., 2020; Faucitano, 2010; Harley et al., 2012).

Consumer awareness of animal welfare continues to grow across Europe (EU Barometer, 2023), and several studies have shown a general willingness to pay for products associated with higher welfare standards (Lagerkvist & Hess, 2010; Leonardsson et al., 2011). Providing information about welfare

conditions further strengthens this effect (Napolitano et al., 2008), and animal-friendly products are often perceived to be higher quality, healthier, and safer (Alonso et al., 2020). However, consumer interest in the slaughter process itself remains limited (Abrams et al., 2015), possibly reflecting ambivalence towards the killing of animals for food (Algers & Berg, 2017; Gori et al., 2017). Nevertheless, by aligning with consumer preferences and differentiating their products accordingly, slaughterhouses could enhance competitiveness and simultaneously improve welfare outcomes. Moreover, maintaining high welfare standards lessens the risk of regulatory non-compliance and protects the reputation (European Commission, 2007; Läpple & Osawe, 2022).

2.3.2 Economic implications of meat loss and condemnation

Losses of meat due to animal deaths, condemnations, and carcase trimming pose significant economic and environmental challenges for the livestock sector (Strid et al., 2023). In Sweden, approximately 8% of total beef production and 3% of pig production, measured through slaughter weight, were lost between the farm and slaughterhouse in 2020 (Swedish Board of Agriculture, 2022). The greatest losses occurred among culled dairy cows and calves, with nearly 18% of them not entering the food chain. For pigs, the corresponding figure was 16%, rising to 25% when stillborn piglets were included.

The annual economic loss from pig meat alone is estimated at 134–144 million SEK, depending on whether transport losses and condemnations at slaughter are included, and 500 million SEK for beef lost on farm (Swedish Board of Agriculture, 2024). Beyond their financial impact, these losses also carry substantial environmental costs. Considering that livestock production is resource-intensive, every kilogram of wasted meat therefore also represents wasted feed, water, energy, and land. Consequently, animal losses either prior to or during slaughter not only affect animal welfare and farm profitability but also Sweden's commitments to reducing greenhouse gas emissions and food waste under the National Food Strategy (National Food Strategy, 2025).

The economic implications of meat condemnations have also been estimated in several other countries, although these studies are based on study populations rather than on a national scale. In a study in Ireland, condemnations were estimated to decrease the net margin in pig production

by more than 5% (Boyle, 2012). In Germany and Italy, losses were valued at approximately 392,744 EUR (in one slaughterhouse) and 1.2 million EUR, respectively (in one slaughterhouse, over two years) (Ciui et al., 2025; Rosamilia et al., 2023). These figures illustrate that condemnations represent a notable source of inefficiency in meat production, emphasising the need to identify their causes and develop preventive strategies that limit both food waste and economic loss.

Beyond direct economic effects, poor welfare and condemnations contribute to food waste, thereby undermining sustainability within a One Health framework. Condemned meat and by-products not only represent a loss of nutritional value and higher waste-management costs but may also pose food-safety risks (Cruz-Monterrosa et al., 2017). Thus, reducing these losses through better handling, improved stunning efficiency, and stronger health management is not solely a welfare and economic priority but also an environmental one.

2.3.3 Incentives and challenges for improving animal welfare

Recognising the connection between animal welfare outcomes and overall business performance is central to improving welfare standards at slaughter (Gibson & Jackson, 2017). Decision tools that translate outcomes, such as fewer failed stuns, smoother workflow, or reduced carcase condemnations, into measurable economic terms are therefore essential.

The incentives for farmers are shaped by both use values (linked to productivity and efficiency) and non-use values (linked to ethical and societal expectations) (Hansson et al., 2018), and similar mechanisms are likely to also influence slaughterhouses' decision-making. Despite this, barriers remain, including the cost of new infrastructure, potential downtime during implementation, and difficulties in quantifying economic returns. At the same time, external drivers such as audits, regulatory requirements, and public scrutiny reinforce the need for robust stunning practices and well-trained personnel (Grandin, 2000).

Measuring animal welfare itself presents additional challenges (Browning, 2022). Welfare indices that integrate animal-, resource-, and management-based indicators face both methodological and ethical limitations (Blokhuis et al., 2013). For instance, whether poor outcomes for some individuals can be offset by better outcomes for others (Botreau et al., 2007). From an economic perspective, valuation frameworks often rely on

marginal analyses using consumers' willingness to pay (WTP) or willingness to accept (WTA) compensation to express welfare improvements in monetary terms (Bennett, 1995; Bennett et al., 2012). In practice, achieving welfare levels beyond the legal minimum typically requires either demonstrable economic benefits or external incentives, such as policy support or market differentiation (Ingenbleek et al., 2012; Owusu-Sekyere et al., 2023). Furthermore, initiatives in the supply chain, such as welfare auditing (Grandin, 2010) and standards set by retailers, play a crucial role in enhancing animal welfare throughout the production and slaughter processes (Harvey & Hubbard, 2013).

Slaughterhouses are most likely to invest in welfare improvements when they:

1) Enhance operational efficiency and product quality – for example, by reducing line stoppages, re-stuns, and carcase defects such as PSE or DFD (Grandin, 1995; Wigham et al., 2018).
2) Protect or increase market value – as consumers often perceive higher-welfare products as being healthier and safer, and are willing to pay a premium for such attributes (Alonso et al., 2020; Lagerkvist & Hess, 2010; Napolitano et al., 2008)
3) Ensure regulatory compliance and safeguard reputation – because legislation such as Council Regulation (EC) No. 1099/2009 mandates compliance with welfare standards, whilst public scrutiny poses reputational risks (Fernandes et al., 2021).

The main challenge is that many of these benefits are intangible or only seen in the long term, making it difficult for slaughter managers to demonstrate clear economic returns. This underscores the importance of economic models and decision-support tools that can help visualise and quantify the business case for animal welfare improvements (Gibson & Jackson, 2017; McInerney, 1993, 2004).

3. Research design and methods

This chapter presents an overview of the methods used in this thesis. To address the overall aim, the work combined several approaches: the development of an economic model, qualitative data collection through focus group interviews with slaughterhouse personnel, on-site slaughterhouse observations during stunning and bleeding, analysis of routinely registered meat inspection data, and economic simulations (Figure 1). More detailed information can be found in Papers I-V.

3.1 Ethical considerations

This work involved observations and assessments of stunning efficiency during the slaughterhouses' normal operational routines, i.e., the regulated stun-to-stick intervals in each slaughterhouse's SOPs. Ethical approval for animal experiments in accordance with Swedish legislation (2018:1192; SJVFS 2019:8) was therefore necessary. The ethical approval number is Idnr 005587, Dnr 5.8.18-07913/2023. Moreover, the research was conducted in line with the legislation and institutional requirements.

Although this thesis includes focus group interviews with slaughterhouse personnel, it did not collect any sensitive personal data. Thus, an ethical review for research involving humans was not required under Swedish law (SFS 2003:460). All participants were informed of confidentiality, anonymity, voluntary participation, and GDPR.

3.2 Paper I – Introducing an economic model for animal welfare

In the first study, a mixed-methods approach was applied, in which a theoretical framework was used to highlight the economic effects of animal welfare improvements on slaughterhouse businesses, and a theoretical economic model was developed and subsequently validated through interviews with slaughterhouse personnel (Figure 6).

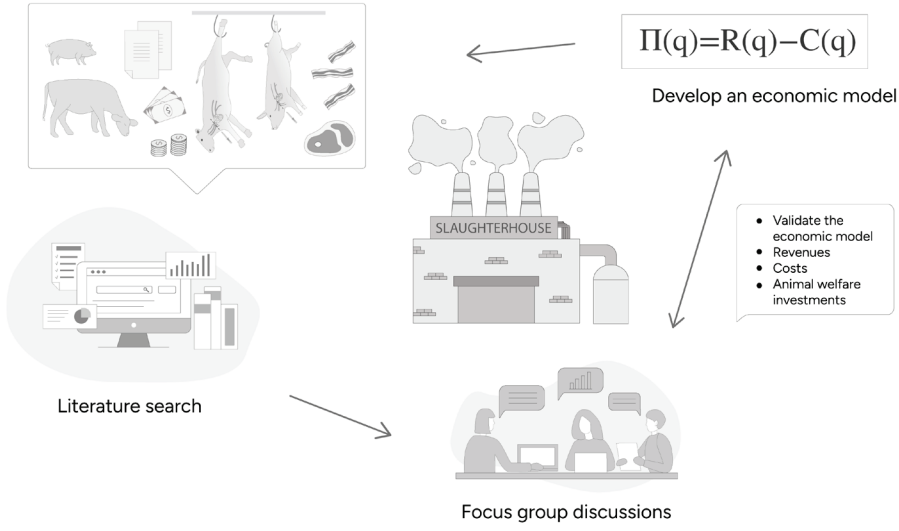

Figure 6. The approach of the study: combining scientific literature, development of an economic model, and validation in focus groups.

The approach is based on scientific evidence that animal welfare plays a key role in the economics of slaughterhouse businesses, including evidence that humane animal treatment can lead to several economic benefits (Grandin, 1995; Gallo & Huertas, 2015; Wigham et al, 2018). By investing in animal welfare improvements, slaughterhouses could potentially improve the slaughter process flow, lower production costs, and enhance the quality of their outputs (carcases, meat, and byproducts). The animal welfare factors related to slaughter and their expected effect on the economic outcome for the slaughterhouse businesses, based on the scientific literature, are summarised in Table S1 in Paper I.

A formal economic model was developed under the assumption that slaughterhouse businesses are driven by profit maximisation (Den Ouden et al., 1997). This model was based on a profit function that describes the costs and revenues of the slaughterhouse businesses to identify the optimal level of output. Moreover, animal welfare was presented as an intangible asset within the production function alongside capital, labour, materials, and energy.

To validate the model and explore the possible relationship between animal welfare investments and economic outcomes, two focus group interviews were conducted with Swedish slaughterhouse personnel. Focus group interviews represent a quantitative method to derive valuable, in-depth

data from specific people of interest (Coyne et al., 2014; van Staaveren et al., 2019).

The first focus group consisted of four female employees who work with the quality assurance schemes and animal welfare in their respective slaughterhouses. The second focus group consisted of three male employees who work as slaughter managers at different slaughterhouses. All seven participants had received a formal education in animal welfare in accordance with EC 2009/1099. The interviews were conducted online in November 2019 and April 2021, lasted approximately three hours each, and all participants received preparatory material in advance.

The discussions were moderated by facilitators with expertise in animal science and agricultural economics and covered three main themes:

1) The most important animal welfare factors influencing the economic outcome for the slaughterhouse,
2) The economic model and slaughterhouse economics in general, i.e. the most important costs and revenues,
3) Previous and planned investments in animal welfare improvements at the slaughterhouse.

The qualitative data derived from the interviews were anonymised, summarised, and subjected to thematic analysis to determine certain themes or concepts across the qualitative data (Braun & Clarke, 2006).

3.3 Paper II – Assessing stun quality at slaughter

Data collection was conducted between May 2023 and November 2024 during routine slaughter operations at medium- and large-scale Swedish slaughterhouses (Table 1). All observations were performed by the same experienced assessor to ensure consistency

Table 1. Descriptive summary of the observations performed on pigs and cattle.

Variables	Finishing pigs	Cattle
Number of studied animals	2,795	330
Number of slaughterhouses (and visits)	Five slaughterhouses, seven visits	Six slaughterhouses, six visits
Number of observation days per visit	One to two	One to three
Stunning method	CO_2 group stunning (dip-lift or paternoster)	Captive bolt (cartridge-driven or pneumatic)
Stun-to-stick interval	From when the pigs left <80% CO_2 until they were stuck	From when the first shot was fired until they were stuck
Stun quality	Four levels: good, doubt, shallow, and poor	Four levels: good, doubt, shallow, and poor
Number of observed animals out of the total number of slaughtered animals (daily)	17–93%	8–94%

3.3.1 Data collection for pigs

The pigs were commercial hybrids that were stunned in groups using either dip-lift or paternoster CO_2 systems. Information on system parameters, such as gas concentration, exposure time, temperature, and size of gondolas, was obtained from the slaughterhouses, whilst group sizes were recorded directly.

Stun-to-stick intervals were measured individually with a stopwatch, commencing when the gondola reached the level of <80% CO_2 and ceasing when chest sticking was performed.

Stun quality was assessed using a modified version of the Atkinson et al. (2012) protocol, with inspiration from Welfare Quality® and EFSA (2020a) which was categorised into four levels: good, doubt, shallow, and poor (Appendix I). In addition to behavioural indicators of consciousness, the corneal reflex was tested on most pigs, and pain reflexes were evaluated in a subset of animals by pricking their snout. Stun quality was monitored until two minutes after sticking.

3.3.2 Data collection for cattle

For cattle, observations were made during routine stunning with both cartridge-driven and pneumatic captive bolt devices. Shot accuracy (placement and angle) was documented after decapitation or, if possible, when the animals were hanging on the rail.

Stun-to-stick intervals were measured from the moment of shooting until chest sticking, and information on animal sex, age, breed, and number of shots was collected.

Stun quality was evaluated according to Atkinson et al. (2013) with inspiration from Welfare Quality® and EFSA (2020b), using the same four-level classification that was applied to pigs (Appendix II). Indicators of consciousness included corneal and pain reflexes, attempts to regain posture, rhythmic breathing, and vocalisation. Assessments continued until two minutes after sticking.

3.3.3 Statistical analysis

Data editing, descriptive statistics, and statistical analyses were performed in SAS version 9.4 (SAS Institute Inc., Cary, NC). Descriptive statistics were also carried out in Excel. Generalised linear mixed models (GLIMMIX procedure) with a binomial distribution and logit link function were applied with separate analyses for pigs and cattle. Re-stunning was modelled as a binary response variable. For pigs, the models included stun-to-stick interval as a covariate, and type of stunning system, slaughterhouse visit, and observation day as fixed effects. For cattle, the models included stun-to-stick interval and age as covariates, and slaughterhouse visit, sex, breed type, and shot accuracy as fixed effects. For more detailed information regarding the models, see Paper II.

3.4 Papers III and IV – Traumatic injuries detected at slaughter

In both Paper III and IV, chronic traumatic injuries (CTI) were defined as older injuries sustained on-farm, whilst acute traumatic injuries (ATI) were defined as more recent injuries that occurred during transport or at the slaughterhouse (definition from guidelines for meat inspection, Swedish Food Agency, 2025).

3.4.1 Paper III - Cattle

The observational study (Paper III) was based on routine post-mortem inspection data collected by official veterinarians who were employed by the Swedish Food Agency in Swedish slaughterhouses, following EU Regulation (EC) 2019/627 and a standardised national framework for condemnation. The data were obtained from the national dairy and beef recording schemes managed by Växa Sverige AB (national advisory cooperative for cattle) and included 336,071 cows and heifers of both dairy and beef breeds that were slaughtered between January 2020 and December 2022 (116,512, 106,390, and 113,169 in the years 2020, 2021, and 2022, respectively). This represented 56.2% of all cows and heifers slaughtered in Sweden during that period. Of these, 12.7% originated from farms certified under KRAV's organic standards. For each carcase, information on animal category, production system, slaughter remarks, condemnation data, carcase weight, carcase conformation score, carcase fatness score, slaughter date, slaughterhouse, and slaughter region was included.

Data editing, descriptive statistics, and statistical analyses were performed in SAS version 9.4. Logistic regression models (PROC GLIMMIX, binomial distribution, logit link) were used to analyse differences in the response variable's injury prevalence (CTI and ATI). Fixed effects included production system (organic, conventional), slaughter year (2020–2022), slaughter month (12 classes, January-December), animal category (cow, heifer), along with the interaction between production system and slaughter month. Carcase weight was included as a covariate to adjust for differences in size and partial breed effects, and slaughterhouse nested within slaughter year was added as a random effect to account for variation related to management, enterprise size, and geographic location.

3.4.2 Paper IV - Pigs

Paper IV followed the framework of Paper III but instead focused on pigs. Data from routine post-mortem inspection were provided by Farm and Animal Health Sweden (national livestock health organisation), which compiles national slaughter data from most Swedish slaughterhouses. The dataset included 7,131,016 finishing pigs slaughtered between January 2019 and December 2021 (2,357,611; 2,369,936; 2,403,469 from the years 2019, 2021, and 2022, respectively), representing approximately 94% of all pigs slaughtered in Sweden during the period. The pigs were commercial hybrids

reared under standard Swedish production conditions and slaughtered at commercial slaughterhouses when aged 5–6 months and weighing around 120-130 kg at slaughter. For each carcase, information on slaughter remarks, condemnation data per remark, carcase weight, lean meat content, and slaughter date was included. In addition, anonymised information on which farm the pig originated from, as well as information on the regional location of the farm, was provided.

Data editing, descriptive statistics, and statistical analyses were performed in SAS version 9.4. Logistic regression models (PROC GLIMMIX, binomial distribution, logit link) were used to analyse the response variable's injury prevalence (CTI and ATI). The models included slaughter month, slaughter year, and slaughter region (classified as high- or low-throughput regions) as the fixed effects, with slaughter weight and lean meat content included as continuous covariates. Condemnation data were analysed using general linear models (PROC GLM), with traumatic injuries (present or not), slaughter year, month, and region as fixed effects, and slaughter weight and lean meat content as covariates.

3.5 Paper V - Assessing the economic outcomes of reduced stun failures

Two strategies were identified as being the most critical for reducing stun failures and improving stunning efficiency, one for pigs (Strategy I) and one for cattle (Strategy II). These models included one baseline scenario and one alternative scenario each, where slaughterhouses were assumed to invest in an "action package" designed to reduce stun failures and enhance stunning efficiency. This package contained investments in new stunning equipment, regular maintenance performed by manufacturers and in-house personnel, and improvements to SOPs at stunning.

The baseline scenarios in each strategy, one for pigs and one for cattle (Table 2), were developed to represent large-scale slaughterhouses in Sweden based on previous studies (Jerlström et al., 2025a-c). These were subsequently validated through expert elicitation with slaughterhouses and manufacturers. This was simply because there is limited up-to-date peer-reviewed scientific literature on the costs of stunning equipment and maintenance. Data for investment and operational costs were obtained from slaughterhouses and manufacturers.

Table 2. Assumptions for the modelled baseline pig and cattle slaughterhouses located in Swealand, Sweden

Assumptions	Pig slaughterhouse	Cattle slaughterhouse	References
Daily slaughter capacity, no of animals	1,050	133	Jerlström et al., 2025a
Annual slaughter capacity, no of animals (245 days with slaughter)	257,250	32,585	Jerlström et al., 2025a
Stunning equipment	Backloader CO_2 group stunning system (four gondolas)	Cartridge-driven captive bolt	Jerlström et al., 2025a
Number of people working on the slaughter line, from the stable to the chilling area	20	25	Expert elicitation
Mean of stun failures (%)	3.9	7.3	Jerlström et al., 2025a
Highest rate of stun failures (%)	16.0	18.5	Jerlström et al., 2025a
Average rate of stun failures in the baseline scenario (%)	13	15	Expert elicitation
Stun-to-stick interval	90	106	Jerlström et al., 2025a
Average annual prevalence of ATI (%)	0.44	1.0	Jerlström et al., 2025b; 2025c
Average annual condemnations due to ATI (kg)	5,826	16,569	Jerlström et al., 2025c

Economic outcomes were assessed using a stochastic partial budget model with Monte Carlo simulations (5,000 iterations) in @Risk 8.2 (Palisade Corporation, Ithaca, NY), an approach commonly used to evaluate economic consequences of management changes in animal production systems (Ahmed et al., 2020; Alvasen et al., 2017; Gummow & Mapham, 2000; Liang et al., 2017). This framework accounted for uncertainty in key parameters such as labour costs, maintenance costs, and equipment investment by using cumulative distribution functions. Tornado diagrams and regression analysis were used to identify the most influential factors on net benefit (Palisade, 2025). Lists of input variables, units, and distributions

associated with the transition from baseline to alternative scenarios are provided in Tables 2 (Strategy I) and 3 (Strategy II) in Paper V.

The net benefit change was calculated by partial budgeting as:

(Increased revenue + Reduced costs) – (Increased costs + Reduced revenue)

For Strategy I, the benefits were related to reduced costs, namely decreased labour time at the slaughter line due to fewer re-stuns and smoother process flow, reduced costs of services by manufacturers and in-house technical personnel, reduced cost of ammunition due to fewer re-stuns, and fewer breakdowns of stunning equipment. Costs were associated with the main cost component of investing in the new paternoster stunning system (Backloader with four gondolas), which was modelled as an annuity to account for annual depreciation and cost of invested capital.

For Strategy II, the benefits can be seen in terms of decreased labour time at the slaughter line, reduced occurrence of re-stunning which results in lower ammunition use, and lower replacement costs of captive bolts over time. Furthermore, the increased costs were composed of investment costs for a new stun box with a head restrainer (modelled as an annuity as was the case in Strategy I), and the purchase of two cartridge-driven captive bolts for cattle which were expected to function for five years. This also generates increased costs of maintenance of captive bolts, and the stun box.

No revenue changes were considered in Strategy I or II.

4. Main findings

Together, the five studies presented in this thesis illustrate how animal welfare at slaughter has economic relevance to slaughterhouse businesses. Each paper addresses a different aspect of the slaughter process, from a more comprehensive perspective, describing the role of animal welfare on the economic performance of the slaughterhouse businesses, to assessments of stunning efficiency, to mapping of traumatic injuries in cattle and pigs, and lastly to economic simulations of investments aimed at improving animal welfare.

This chapter presents the main findings from Papers I–V, but more detailed results are provided in each article.

4.1 Paper I – Introducing an economic model for animal welfare

This study developed and validated a formal economic model to assess the impact of animal welfare improvements on slaughterhouse profitability. By introducing animal welfare (*AW*) as an intangible asset in the production function, the model conceptualises welfare investments in the same way as traditional inputs such as units of labour (*L*), units of capital (*K*), units of energy (*E*), and units of materials (*M*). To follow the development of the model, see Paper I. Revenues depend on both the carcases (*q1*) and the by-products (*q2*), where *q* is the number of units produced and sold, and the price (*p1*) of *q1* and the price (*p2*) of *q2*. Taking the fixed cost, *FC*, variable cost, *VC*, and revenues into account, the profit function, *π(q)*, of the slaughterhouse will be:

$$\boldsymbol{\pi(q1) = [p_1 * q_1 + p_2 * q_2] - [FC + VC(q_1)]}$$

where:

$$\boldsymbol{q_1 = f(K, L, M, E, AW)}$$

$$\boldsymbol{q_2 = f(q_1)}$$

and $\boldsymbol{FC = P_k * \overline{K}}$, and K is fixed in the short-term. P_k is the cost of capital and $\overline{K}$ is the fixed number of units in the cost function.

Validation of the model through focus group interviews with Swedish slaughterhouse personnel demonstrated that improved animal welfare can contribute to profitability. This is primarily achieved through enhanced workflow efficiency, reduced labour requirements, and improved carcase and by-product quality. Respondents highlighted that the use of by-products plays a major role in profitability and that investments in lairage design and drive-races not only ease animal flow but also improve working conditions for personnel (Figure 7).

Figure 7. Thematic results emerging from the interview material in the focus group interviews.

The study also identified challenges in measuring the direct financial return of investments in animal welfare improvements and a lack of market incentives for FBOs to communicate welfare improvements to consumers. Whilst all participating slaughterhouses had either implemented or planned improvements (A few examples are presented in Table 3, and a complete list in Table 2, Paper I), branding these investments was perceived as difficult due to limited consumer understanding and interest in the slaughter process.

Overall, this study developed a conceptual framework where animal welfare can be regarded as a production factor in the form of an intangible asset. The model provides a novel tool for making these often-hidden links visible and for exploring how investments in animal welfare improvements may influence the economic outcome at the slaughterhouse level. Furthermore, the results reflect how slaughterhouses view animal welfare and investments in animal welfare in relation to economics. The findings highlight the role of both FBOs and policymakers in considering animal welfare as an integral part of economic decision-making at slaughter.

Table 3. Two examples of investments by pigs and cattle slaughterhouses in animal welfare improvements, respectively, and the expected effects on economic outcomes and animal welfare.

Animal	**Animal welfare improvements**	**Expected effect on economic outcome**	**Expected effect on animal welfare**
Pigs	Larger CO_2 dip-lift for stunning pigs Automated driving system to the dip-lift, where the pigs enter at the long side instead of the short side.	High investment cost (*FC*) Increased production efficiency due to improved slaughter process flow Reduced labour costs (*L*) due to improved work environment	Decreased levels of stress for pigs and for slaughterhouse personnel during handling
	New design of the sticking section	Increased revenues from by-products (q_2) due to higher yield of heads and ears	Inappropriately stunned animals could experience some levels of distress if their head hit the interior
Cattle	Rebuilt a stunning box Planned reconstruction of the height of the vertical hydraulic tailgate	Reduced labour costs (*L*) due to improved work environment, i.e., easier handling procedures Increased production efficiency due to improved slaughter process flow Improved carcase quality (q_1 *and* q_2) due to less bruising on the back of cattle, and thus increased revenue, *R(q1)*	Decreased levels of stress for cattle and for slaughterhouse personnel during transportation to the stunning box
	Planned investments in the sticking section and stunning box	Increased production efficiency due to improved slaughter process flow Improved work environment, i.e. lower sound level and higher safety for the employees (*L*)	Decreased levels of stress, which could have an impact on carcase quality

4.2 Paper II – Assessing stun quality at slaughter

Most animals were adequately stunned, 96.1% of the pigs (n=2,795) and 92.7% (n=330) of the cattle. The remaining proportion of animals showed variation in stunning outcomes, which also varied widely between slaughterhouses. Among pigs, shallow or poor stuns ranged from 1.2 to 16.6%, whilst for cattle, the corresponding range in stun quality was between 0 and 18.5%. Re-stunning rates were on average 4% for pigs and 5.6% for cattle but varied between 1.6 and 6.4% in pigs and 0 to 14% in cattle.

For both pigs and cattle, the main finding was that longer intervals between the stunning and sticking were associated with higher risks of inadequate stunning and an increased occurrence of re-stunning. The average stun-to-stick interval was 106 s (± 15.6 SD), ranging from 77 to 192 s for cattle. For pigs, the average stun-to-stick interval was 90 s (± 21.5 SD), ranging from 32 to 199 s.

The results also demonstrate that equipment, together with the skill of the operator, affects the outcomes. For pigs, a higher proportion of inadequately stunned pigs was observed in slaughterhouses that use paternoster systems compared to those that use dip-lift systems. There were also large variations in the registrations of CO_2 concentration and temperature in several slaughterhouses. Additionally, the symptom of gasping has been a topic of debate, particularly because it can be confused with rhythmic breathing and agonal gasping (Holst, 2001; Atkinson et al., 2012; Lindahl et al., 2025). Of the pigs that displayed regular gasping in the present study, one-third also exhibited a positive corneal reflex. This combination has been suggested to be a strong indicator of insufficient stun quality. In cattle, nearly a quarter of all shots (23.4%) missed the optimal target area on the skull, and 22.8% of the shots were fired at a deviated angle (i.e., more than 20 degrees from the recommendation of 90 degrees). Unsurprisingly, shot accuracy influenced the likelihood of the cattle being re-stunned. Moreover, a higher proportion of bulls and steers were inadequately stunned compared to cows and heifers. There were six cartridge-driven captive bolts and two pneumatic stunners; however, no matter the type of device, in several cases, the bolt lengths (observations of 65–95 mm) were shorter than the recommended 120–150 mm, which likely affects stunning efficiency, especially in heavier cattle and bulls.

Overall, the results indicated that intervals of less than 59 s for pigs and 99 s for cattle were associated with lower rates of inadequate stunning. This

study also identified a discrepancy between animals displaying signs of inadequate stun quality and those that were re-stunned (Figures 7 and 8 in Paper II). Notably, several pigs and cattle that exhibited indications of not being fully unconscious continued along the line without being detected. Simultaneously, other animals were re-stunned without clear indications of needing so.

4.3 Papers III and IV – Traumatic injuries detected at slaughter

The results from Papers III and IV indicate that CTI are more common compared with ATI for both cattle and pigs. Furthermore, both CTI and ATI occurred more frequently during the winter and early spring months, declining in summer and early autumn. There was also a consistent annual decline in both CTI and ATI for both species.

4.3.1 Paper III - Cattle

In total, 9.4% of the cows and heifers' carcases was recorded with CTI and 1.0% with ATI between 2020 and 2022. Animals originating from conventional farms had a numerically higher prevalence of CTI (9.8%) compared to those from organic farms (6.9%), and this trend remained consistent across all seasons ($F = 95.9$, $P < 0.001$). In contrast, ATI were more frequent among animals from organic herds (1.2% of animals from organic farms and 1.0% of animals from conventional farms), particularly during the grazing season ($F = 2.7$, $P = 0.002$).

Both CTI and ATI were associated with increased carcase condemnation. On average, condemnation on carcases with CTI was 23.2 kg of meat compared with 5.1 kg in animals without such injuries ($P < 0.05$ with t-test). Condemnations due to ATI was 15.1 kg compared with 6.7 kg ($P < 0.05$ with t-test). The total condemnation during this period due to CTI was 738,196 kg, and ATI corresponded to 49,708 kg, representing nearly 34% of the total condemned meat.

4.3.2 Paper IV - Pigs

In total, the overall prevalence of injuries among finishing pigs was 0.67% for CTI and 0.44% for ATI between 2019 and 2021. These proportions represented almost 79,000 injured pigs during the study period.

Both types of injuries demonstrated seasonal patterns, peaking during the cold winter months and reaching their lowest levels in late, but still warm summer ($P < 0.001$ for both). There was also regional variation, where pigs raised in low-throughput regions had higher rates of both CTI and ATI compared to those from high-throughput regions.

Over a three-year period, condemnations due to traumatic injuries amounted to 38,319 kg of meat (CTI = 21,225 kg; ATI = 17,093 kg), representing about 16% of all condemned pig meat during the study period. Among pigs recorded with CTI, 57.7% resulted in meat condemnation, whereas the corresponding proportion for ATI was 59.8%. On average, carcases with CTI or ATI had condemnation weights that were more than 15 times higher than carcases without such injuries ($P < 0.001$ for both). A list of slaughter remarks and condemnations can be found in Supplementary Material Table S2, Paper IV.

4.4 Paper V - Assessing the economic outcomes of reduced stun failures

Both deterministic and stochastic simulations indicated that the transition from the baseline hypothetical pig and cattle scenarios to the alternative scenarios produced overall positive economic outcomes under most conditions.

For pigs, the economic modelling revealed a positive annual net benefit of 87,938 SEK (Table 4), with the predominant benefit drivers being reduced labour costs and reduced costs of base services by the manufacturer, whilst the new stunning system represented an annualised investment on the cost side.

Stochastic simulations showed a high probability of economic gain, meaning that the investment would be economically beneficial under most conditions, although the scale of benefits varied depending on labour costs and equipment prices (Figure 1, Paper V). The decreased rate of stun failures had a relatively small but nonetheless positive contribution to net benefit change (Figure 2, Paper V).

Table 4. The deterministic effects of the net benefit change of adopting Strategy I (for pigs).

Benefit change	**Value (SEK per year)**	**Cost change**	**Value (SEK per year)**
Reduced costs		***Increased costs***	
Reduced operating costs in terms of daily labour requirements	490,000	Paternoster Backloader stunning system, annuity	1,264,609
Reduced costs of base services by manufacturer	300,000	***Total cost change***	1,264,609
Reduced costs of "priority technical support" services by manufacturer	300,000		
Reduced maintenance costs by in-house technical personnel	150,000		
Reduced ammunition costs	112,547		
Total benefit change	1,352,547		
Net benefit change	87,938		

For cattle, the deterministic model indicated a small positive net benefit change of 37,467 SEK (Table 5), with the primary benefit drivers being reduced operating costs in terms of labour, and reduced costs of purchasing new captive bolts, whilst the new stun box with a head-restrainer represented an annualised investment on the cost side.

Stochastic simulations showed a wide variation of possible outcomes, suggesting that both economic gains and losses are probable depending on the underlying conditions (Figure 5, Paper V). However, the potential for improvement remains substantial when labour efficiency and investment conditions are favourable. Sensitivity analysis revealed that the decreased rate of stun failures among cattle also had a relatively small but nonetheless positive contribution to net benefit change (Figure 6, Paper V).

Table 5. The deterministic effects of the net benefit change of adopting Strategy II (for cattle).

Benefit change	Value (SEK per year)	Cost change	Value (SEK per year)
Reduced costs		***Increased costs***	
Reduced operating costs in terms of labour requirements	306,250	Stun box with a head-restrainer, annuity	287,812
Reduced ammunition costs	14,256	Maintenance costs of stunning equipment by personnel	34,920
Reduced cost of buying new captive bolts[1]	39,693	***Total cost change***	322,732
Total benefit change	360,199		
Net benefit change	37,467		

[1]Two captive bolts were purchased. The economic life length of these was estimated to be five years due to increased maintenance and technical repair.

Overall, the results demonstrate that reducing stun failures during the slaughter of pigs and cattle can be economically justified by implementing specific action packages consisting of new stunning equipment and improved equipment maintenance. The bioeconomic models developed in this study provide slaughterhouses with a tool to assess the costs and benefits associated with investments to reduce stun failures whilst considering uncertainties in economic variables.

5. General discussion

This thesis is grounded in the need to assess incentives for the slaughterhouse industry to invest in animal welfare improvements. Its interdisciplinary approach has been a key strength, helping to capture the complexity of the topic. The overall aim was to map animal welfare-related aspects during the slaughter of pigs and cattle and assess the economic relevance of animal welfare improvements for slaughterhouse businesses.

Therefore, this chapter focuses on connecting these dots: the animal welfare aspects of slaughter, particularly two strategies of improved stunning efficiency and prevalence of traumatic injuries, and the economic relevance of animal welfare at slaughter. One section is dedicated to policy recommendations, while perspectives for future research are interwoven throughout the chapter.

Detailed and specific discussions on the results in each paper are provided within the respective discussion sections of Papers I-V.

5.1 Animal welfare during slaughter

Across the studies included in this thesis, it became evident that several factors interact and impact animal welfare at slaughter. The results from Paper I showed that the most important factors were having a sufficient number of trained personnel and maintaining a process speed adapted to the design and technical constraints of the slaughter equipment of each specific slaughterhouse. This is also well established in the literature that poor slaughterhouse design, in terms of, e.g., drive races and stunning equipment, reduces animal welfare (Hultgren et al., 2014) and may lead to suboptimal workflow, frustration among workers, and reduced slaughter process flow (Grandin, 1995; Gallo et al., 2003; Wigham et al., 2018).

Together with the results from Papers II and V, it became clear that the role of committed management, implementation of robust SOPs in daily operations, effective stunning practices, consistent checks of stunning equipment, and continuous investments in animal welfare-improving practices are crucial for stunning efficiency and thus animal welfare at slaughter. An encouraging finding was that all slaughterhouses represented in the focus groups in Paper I had either invested or were planning to invest in animal welfare improvements, even when they are not legally required to

do so. The main reason they gave for this was the perceived notion that improved welfare is expected of them, and that they initially expected an improved slaughter process flow, but also improved animal welfare.

Taken together, these studies identified two main areas for how humane slaughter with procedures improving animal welfare can be enhanced:

1) **Technological measures**: well-functioning stunning equipment, including regular maintenance of stunning equipment, appropriate settings of stunning equipment (parameters such as bolt length, CO_2 concentration), and design and infrastructure of the facilities.
2) **Managerial measures:** robust and clear SOPs, implementation of SOPs, and systematic training of personnel.

These findings have also been highlighted by Grandin (2010; 2013) and Wigham et al. (2018), who showed that even advanced stunning equipment cannot ensure animal welfare in the absence of well-trained and attentive personnel. Similarly, attitudes and understanding of animal behaviour strongly influence the handling of and subsequent stress responses of livestock, both during transport and in slaughterhouses (Coleman et al., 2012; Wilhelmsson et al., 2023).

In the slaughterhouses' continuous effort to improve animal welfare, the farmer's role becomes apparent. Although this thesis focuses on the time the animals spend in the slaughterhouses, the importance of farm animals' prior experiences in life was underscored by slaughterhouse personnel in Paper I, and how these experiences impact their reactions within the slaughterhouse environment. Calm and animal-friendly handling procedures are crucial for the animals (Grandin, 1997), but also for slaughterhouses in terms of improved product quality (European Commission, 2007). However, slaughterhouses do not determine what animals they receive. Therefore, it is necessary to note the farmer's responsibility to select animals from the farm that are fit for the slaughter chain at any given point (transport, lairage, slaughter, processing, etc). Furthermore, farmers could endeavour to prepare the animals for the slaughterhouse by, for example, handling them more frequently so that they grow accustomed to people. Moreover, the results on the prevalence of chronic traumatic injuries, originating on farm, in Papers III and IV further emphasise that animal welfare on the farm has implications for the slaughterhouses.

The findings in Papers I-V provide guidance on aspects that slaughterhouses can prioritise when working with animal welfare

improvement measures. Two strategies of specific interest, discussed later in this chapter, are stunning procedures and the prevalence of traumatic injuries.

Paper I's findings highlight the importance of employing the right personnel. However, little is known about the consequences of slaughterhouse workers' perceptions of killing animals as part of their daily work (Pastrana-Camacho et al., 2023). These circumstances may contribute to the development of negative attitudes toward animals, which could potentially increase stress levels in animals at slaughter (Coleman et al., 2012; Hultgren et al., 2014). There is a need for future research to explore the psychological mechanisms, such as occupational stress, desensitisation, and cognitive dissonance, that shape the personnel's experiences and the implications this has for animal welfare at slaughter.

5.1.1 Monitoring and assessing stun quality

Nearly a century of research has provided clear evidence regarding the importance of rendering animals unconscious and insensible prior to bleeding to prevent unnecessary suffering at slaughter (Grandin, 2013; Gregory, 1989; Terlouw et al., 2024; Woolridge, 1922). Effective stunning procedures and equipment mark the cornerstone of humane slaughter and are thus essential for welfare. Consequently, well-established guidelines exist for assessing stun quality (Algers & Berg, 2022; Atkinson et al., 2012; 2013; EFSA, 2020a; 2020b). Nevertheless, the findings obtained in this thesis showed that both pig and cattle slaughterhouses struggled to ensure consistently effective stunning outcomes.

When assessing stun quality, attention is often directed toward the stun-to-stick intervals, which all commercial slaughter guidelines recommend keeping to a minimum (EFSA 2020a, 2020b). Prior to the introduction of EU Regulation (EC) 1099/2009, bleeding was required to occur within 60 s from stunning. Under current legislation, slaughterhouses may set their own stun-to-stick interval, however, they are expected to be kept as short as possible. The results in Paper II show that, in line with previous research, longer intervals between stunning and bleeding increased the risk of inadequate stunning, i.e., deviations in stun quality among both CO_2-stunned pigs (Holst, 2001), and mechanically stunned cattle. For pigs, this relationship was more expected, as CO_2 stunning is a reversible method and its efficiency is determined through exposure time and gas concentration, although,

depending on the exposure time, it can be irreversible. For cattle, however, mechanical stunning is intended to be an irreversible method as it is related to extensive brain damage (Gibson et al., 2012). Therefore, one would consider the stun-to-stick interval as being less important for cattle. However, this assumption is based on the shot being correctly placed on the cattle's forehead (Atkinson et al., 2013) as well as the captive bolt device possessing the proper cartridge strength and being well maintained (Gibson et al., 2015). Also, shot accuracy affected the likelihood of re-stunning, consistent with previous findings that greater deviation from the ideal shooting position on the skull increases the risk of failing to induce motor paralysis (Vecerek et al., 2020). The observed near-linear association between re-shooting likelihood and stun-to-stick interval length in cattle therefore indicates deficiencies in standardised criteria for assessment of stun quality, implementation of SOPs, and personnel training. This highlights the need for clearer guidelines on stun quality assessment, improved SOPs, and continuous training of personnel (Grandin, 2010). Considered together, these findings indicate that maintaining a short stun-to-stick interval remains critical for animal welfare, particularly for pigs, but knowledge about assessing stun quality plays a key role.

Monitoring and assessing stun quality are labour-intensive processes that demand skilled personnel (Dalmau et al., 2016). Depending on the size of the slaughterhouse, operators performing stunning may also be responsible for shackling and sticking, i.e., several tasks that require attending to different parts of the animal's body. Given these multiple responsibilities, combined with the pressure to maintain continuous process speed, these working conditions raise the question of whether the time required to monitor stun quality receives sufficient attention from managers.

When an animal must be re-stunned, regardless of how quickly this occurs, there is a risk that it may have already regained partial consciousness and thus experienced pain or distress (Terlouw et al., 2016a). This underlines the importance of having competent personnel who can act quickly, as well as readily available backup equipment to minimise the duration of suffering. Worker safety also plays a role here, since shackling animals that are not completely unconscious could potentially be very dangerous.

The large variation in stunning efficiency observed between slaughterhouses in Paper II again reflects systematic deficiencies in SOP design and implementation, training, or equipment maintenance, which have

also been reported by von Wenzlawowicz et al. (2012). These findings also point to the responsibility of the AWO, who is responsible for ensuring compliance with current legislation, but should also ensure that the slaughterhouses routines are followed (AWC, 2025). It was noted that the possibilities for the AWO to be present in daily operations varied between slaughterhouses. Several of them held other positions aside from being an AWO, such as slaughter manager, which forced them to have to prioritise their duties. The winning concept seemed to be the slaughterhouses that could spend most of their time in the AWO task. However, the management's role here must be highlighted, as in Paper I, having a committed management that supports the AWO and animal welfare work is essential (Wigham et al., 2020).

Beyond the animal welfare perspective, unreliable stunning equipment creates operational challenges, as noted in Paper V. Re-stunning and additional handling disrupt the slaughter process flow and increase both labour costs and stress among personnel.

5.1.2 Traumatic injuries: occurrence and implications

Bruising, skin lesions, and other traumatic injuries are well-established indicators of compromised welfare and poor handling (Faucitano, 2010; Huertas et al., 2015; Valkova et al., 2021). Quantifying these injuries in pigs and cattle contributes to increased knowledge of animal welfare at slaughter and provides information that could be used strategically in efforts to improve animal welfare. Moreover, it not only reflects the conditions that animals experience immediately before death but also provides indications of animal welfare on the farm. However, the observational studies in Papers III and IV cannot establish any causal effects; instead, they are discussed below in relation to other studies.

In cows and heifers, the prevalence of CTI was higher in conventional herds (9.8%) than organic herds (6.9%). Chronic injuries are often associated with housing design, flooring quality, and stocking density , factors that often differ between production systems. In Sweden, management practices vary between conventional and organic dairy and beef farms, particularly in terms of preventive animal healthcare and feed composition (KRAV, 2024). These differences suggest that animals from organic farms may be better adapted to cope with on-farm challenges prior to slaughter, which could contribute to the lower prevalence of CTI observed in this study (Hultgren et al., 2014).

The prevalence of ATI was lower in conventional herds (1.0%) than organic herds (1.2%) during the pasture season. Animals from conventional farms, which are typically kept outdoors for less hours during the day (a minimum of six hours per day is mandatory), may find the transition to the slaughterhouse environment less abrupt and stressful. This is because they spend more time indoors, even during the pasture period, and could potentially explain the differences observed among ATI. These possible reasons for injuries were also observed by Hultgren et al. (2014), who showed that organic cattle, despite generally experiencing better on-farm conditions, may encounter distinct welfare risks related to handling and transport.

In pigs, the overall prevalence of CTI and ATI was lower compared to cattle (0.67% and 0.44%, respectively), yet the large number of animals slaughtered every year means that this represented nearly 79,000 pigs during the three-year period. Whilst variations in the prevalence of injuries between farms was not investigated in this thesis, such investigations would be relevant in future research, to gain information on infrastructure and handling practices that can influence animal welfare.

Seasonal variation in pigs was assessed, showing higher injury rates and condemnations during winter and early spring and lower rates in summer and autumn. Similar patterns in pigs have been reported by Čobanović et al. (2020), who linked increased winter injuries to cold and slippery conditions that impair handling.

The significantly higher meat condemnation rates among injured animals, both for cattle and pigs, demonstrate that poor animal welfare results in tangible product losses and food waste. Further, from an operational perspective for the slaughterhouse businesses, each instance of trimming or condemnation also represents additional time and cost for the slaughterhouse personnel. To understand the direct implications of injuries on slaughterhouse businesses, further research is needed.

In accordance with previous studies, the findings in Papers III and IV support the potential use of post-mortem inspection data as an animal welfare surveillance tool (Comin et al., 2023). Although variability in inspection and classification of injuries remains a limitation (Collins & Huey, 2015), the slaughter remarks for traumatic injuries could provide useful animal welfare indicators (Vial et al., 2015). There is a need for standardisation and perhaps

a remote (Hansson et al., 2025) or digital reporting system to improve reliability, as well as comparability between slaughterhouses.

Both CTI and ATI are preventable, and their presence signals welfare issues that may also leave measurable marks on the economics of slaughterhouse businesses (Zappaterra et al., 2022). These studies demonstrate that traumatic injuries can provide information on management practices, as well as provide a framework for evaluating the costs related to poor animal welfare. Assessing the frequency and distribution of such injuries is therefore vital for identifying where preventive measures should be directed (on the farm, during transport, or within the slaughterhouse). Furthermore, analysing the location of injuries on the body can offer valuable insights into their underlying causes.

5.2 The economic relevance of animal welfare during slaughter

The central question of this thesis was whether animal welfare has economic relevance for slaughterhouse businesses. To start off with, the first study revealed a lack of motivation among the slaughterhouse respondents to internalise animal welfare in the decision-making process of the slaughterhouse business. This finding demonstrates that awareness of the economic implications of animal welfare improvements remains limited across the sector. However, one of the key findings obtained from the focus group interviews was that slaughterhouses had either invested in or were planning to invest in animal welfare-improving equipment and practices, such as new and improved drive-races and stunning equipment. The main expected economic effects were reduced labour costs due to easier handling procedures and better-constructed facilities (lairage, drive-races, stunbox), resulting in overall enhanced productivity. However, it is challenging to reliably measure the economic returns from these investments (PigStun, 2024). This makes it difficult for slaughterhouses to compare and prioritise investments based on animal welfare and economic outcomes. Developing and providing practical tools to support slaughterhouses in assessing both the animal welfare and economic outcomes of such investments could facilitate more informed decision-making.

Slaughterhouses also reported indirect economic benefits from improved animal welfare, including increased investments such as improved meat

quality, reduced labour costs, and calmer handling procedures due to decreased stress among both animals and personnel. Another important result from the focus group interviews is that the profitable use of by-products and a smooth workflow were highlighted as important factors for achieving an economic outcome. This is linked to animal welfare in terms of handling but is also connected to improved design of the sticking area, as reported by one slaughterhouse (Table S2, Paper I).

One of the primary contributions of this thesis is its perspective on animal welfare from an economic standpoint. Rather than treating animal welfare as purely a cost, this work presents it as an investment. In the theoretical model in Paper I, animal welfare was conceptualised as an intangible production factor, comparable to labour or capital, that contributes indirectly to productivity by enhancing process stability, reducing downtime, and improving product quality. This broadens the understanding of animal welfare in an economic context and suggests that it is an important component of sustainable slaughterhouse businesses.

Although this thesis did not examine consumer perceptions of slaughter procedures, the respondents in the focus groups in Paper I emphasised that communicating (and branding) the animal welfare-improving practices is difficult. They perceived consumers as having limited knowledge and little interest in slaughter processes(Gori et al., 2017), which makes it challenging to raise product prices based on improved animal welfare. Considering that many consumers are unaware of how slaughter is conducted in the first place (Abrams et al., 2015), they may also struggle to recognise or appreciate the significance of specific improvements.

One of the most critical aspects of animal welfare at slaughter is to ensure that the animals remain unconscious until death, as stunning failures directly compromise animal welfare (McKinstry & Anil, 2004). Based on the presented and discussed results from Paper II, together with findings from previous studies (von Wenzlawovicz et al., 2012; Atkinson et al., 2012; 2013), reducing stun failures emerged as the most important strategy to improve animal welfare in the slaughterhouses, which is why this issue was chosen in Paper V. Stunning efficiency, however, is not solely a welfare concern as it also has an economic effect on slaughterhouse businesses through reduced slaughter process flow (Grandin, 1995) and increased labour costs. The respondents in Paper I also supported the link between decreased stun failures and decreased labour, as well as the positive effect on

worker wellbeing, through the investments they had made in both new gas stunning systems and stun boxes (Table S2, Paper I). However, there are several important aspects of animal welfare at slaughter (Grandin, 2017), and the bioeconomic model developed in Paper V can, with minor adjustments, be used to simulate other animal welfare improvements at slaughter. Future studies should explore how additional strategies to improve animal welfare translate into measurable economic effects for the slaughter industry. It is also of interest to perform case studies in slaughterhouses where investments are planned or have been made, to gain more information on the economic variables and how these fluctuate.

As mentioned earlier in this section, proper equipment maintenance (Grandin, 2013), regular operator training (Verhoeven et al., 2014), and adherence to SOPs (von Wenzlawowicz et al., 2012; EFSA, 2020b) can determine stunning outcomes. Building on this knowledge, the "action packages" developed in Paper V combined these factors, i.e., investments in new stunning equipment, regular maintenance, and improvements to SOPs at stunning and bleeding. Although it was not possible to quantitatively include enhanced SOPs in the bioeconomic model, they provided the theoretical and conceptual foundation for the simulated scenarios. The importance of these factors was also emphasised by slaughterhouse experts in the expert elicitation. To strengthen personnel competence, routine management, and documentation systems of SOPs, future studies should assess how scientifically based state-of-the-art routines can be optimised and implemented in practice.

Economic modelling of animal welfare at slaughter is challenging. It requires realistic scenarios and assumptions based on commercial circumstances and access to detailed economic data from slaughterhouses, which are difficult to access. Indeed, there is currently only one partial economic calculation for small-scale slaughterhouses in Sweden available online (Hagberg et al., 2024), highlighting the scarcity of reference data. A major strength of this study was therefore the cooperation from participating slaughterhouses (and manufacturers) in providing economic figures. As all slaughterhouses operate under distinct conditions, establishing a universal baseline remains challenging, in comparison with, for example, pig production, where tools such as WinPig® provide farmers with information based on production data from most pigs produced in Sweden. However, this

represents an important knowledge gap that should be addressed in future research.

The economic findings of investing in the action packages to reduce stun failures revealed that labour-related variables, notably hourly salary, the number of workers on the line, and reductions in working hours due to fewer disruptions in the slaughter process flow, were the most influential factors for profitability, followed by capital costs for new stunning equipment (Figure 2 and 6, Paper V). These results align with research at the farm level which shows that labour and investment costs are the dominant economic drivers of animal welfare improvements in livestock production (Ahmed et al., 2020; Alvåsen et al., 2017; Bornett et al., 2003). Similar patterns have been reported in beef production, where labour time is the principal cost determinant (Holmström et al., 2023). This underscores the importance of having well-trained personnel that possess the necessary knowledge to prevent risks, such as incorrect shot placement, which can lead to extra time for re-shooting. Additionally, opportunities to reduce labour time for personnel are likely to positively contribute to the economic outcome.

Overall, the modelling scenarios for pigs and cattle proved that investing in action packages (new stunning equipment, improved SOPs, and regular maintenance) can reduce stun failures whilst improving both animal welfare and economic outcomes of slaughterhouse businesses. Although the results vary depending on slaughterhouse size, infrastructure, and input costs, the direction was consistent. However, as McInerney (2012) noted, market prices rarely capture the full social value of animal welfare, meaning that its broader economic contribution is likely underestimated. This implies that the actual benefits of welfare improvements may extend beyond those that are directly measurable in financial terms.

Taken together, the results demonstrate the value of considering animal welfare within the economic decision-making of slaughterhouses. Reducing stun failures and improving stunning efficiency introduce clear animal welfare benefits, but they represent minor direct economic gains compared with labour or investment costs (Table 4 and 5, Figure 2 and 6, Paper V).

For several decades, it has been argued that economic outcomes and animal welfare at slaughter are closely intertwined, with smoother production processes, improved worker safety and meat quality (Grandin, 1995; Gibson & Jackson, 2017; Macnaughten, 1932). However, this has never been estimated in realistic scenarios. This thesis contributes with

realistic strategies and quantitative evidence that animal welfare at slaughter and economic outcomes are inextricably intertwined.

5.2.1 Balancing animal welfare and economics

The relationship between animal welfare and economics is complex but must be clearly understood, as discussed in Papers I and V. The main challenge lies in translating animal welfare into a measurable unit (Bennet, 1995). When the economic return on animal welfare improvements is uncertain (McInerney, 2004), it becomes difficult to motivate farmers and slaughterhouse businesses to allocate resources to such measures. Although these investments in action packages (Paper V) may initially increase the costs for the slaughterhouse, they can generate both monetary and non-monetary benefits over time, such as enhanced reputation (e.g., strengthening the social licence for meat production and slaughter business operations) or improved personnel well-being. Economic factors remain a central driver for slaughterhouses and farmers, and even when there is a clear willingness to improve welfare, the economic resources and support do not always allow for it (Platto et al., 2020).

When animal welfare becomes too costly, the question arises of how far society and the industry are willing, or able, to go. Some studies show that higher welfare investments can lead to reduced profitability (Edwardes et al., 2024), whilst others suggest that reduced welfare may coincide with greater profit margins (He et al., 2022). This underscores the tension between animal welfare and profitability: when welfare and profitability align, the decisions are straightforward; when they conflict, trade-offs must be negotiated. Importantly, certain animal welfare standards are defined by law, such as stunning prior to bleeding in Sweden, and are therefore non-negotiable, regardless of the cost. These legal standards represent society's ethical baseline. Thus, discussions about how much animal welfare we can "afford" require an ongoing dialogue between farmers, policymakers, and consumers. However, the economic information on animal welfare investments must also be available. Taken together, the findings presented in this thesis provide an empirical basis for such discussions and can strengthen both policy design and business strategies.

Although farmers, as well as slaughterhouses, bear the primary responsibility for improving animal welfare, the roles of consumers and retailers should not be underestimated (Balzani & Hanlon, 2020; Gocsik et

al., 2013; Schroter & Mergenthaler, 2021). This was highlighted in Paper I, where the respondents pointed to consumers' willingness to pay. This is an important estimate that could potentially be integrated into economic analyses of slaughterhouse investments in animal welfare-improving practices. Whilst this approach was not included in this thesis, future studies could quantify whether consumers are willing to pay more for meat from slaughterhouses that invest in welfare improvements, and how this could be incorporated into economic models. It should be again noted that one hindrance could be the difficulties in branding this to society. Additionally, one important challenge persists which is that despite strong public concern for animal welfare in Europe (Eurobarometer, 2023), consumers rarely translate ethical preferences into consistent purchasing behaviour (Lusk, 2011; Napolitano et al., 2008).

5.2.2 The economics of animal welfare: a wicked problem?

Although the concept of "wicked problems" has not been a central focus of this thesis, it provides a useful lens through which to consider the economic implications of animal welfare at slaughter. Applying this framework highlights why the issue persists despite technical advances and regulatory efforts, and why it continues to present questions for both industry and society. Therefore, it is discussed here to place the results of this thesis in a broader context and possibly provide future research ideas.

Wicked problems are characterised by complexity, conflicting values, and the absence of clear solutions (Termeer et al., 2019). They are not solved once and for all but require continuous negotiation between stakeholders (Head, 2018). In practice, this means that measures to enhance animal welfare at slaughter may be technically feasible but still face resistance because they do not align with societal expectations or economic circumstances.

Several features of wicked problems resonate with the current debate on animal welfare at slaughter. Firstly, there are conflicting perspectives: whilst industry actors emphasise efficiency and profitability, citizens and consumers increasingly demand higher welfare standards but are also reluctant to pay increased prices. These competing framings influence both how the problem is defined, and which solutions are considered legitimate (van den Ende et al., 2023). Secondly, the problem is systemic. As discussed at the beginning of this chapter, welfare outcomes at slaughter are closely

related to on-farm management, transport conditions, facility design, infrastructure of personnel, and the competence of personnel. Improvements in one area may generate new challenges in another, creating unintended consequences that are difficult to predict. Thirdly, poor animal welfare can lead to direct economic losses through e.g. carcase condemnations, but also indirect costs through reputational risks, consumer trust, and access to markets and finance, as discussed in the case of surplus dairy calves in North America (Bolton & von Keyserlingk, 2021).

Attempts to address animal welfare at slaughter often rely on gradual technical improvements, such as refinements in stunning equipment, stunning procedures or the design or infrastructure of facilities. Whilst these are important, they rarely resolve the underlying tensions between ethical expectations, economic pressures, and cultural values (Head, 2018). This persistence is typical of wicked problems, where interventions provide partial relief but do not eliminate the issue.

Future research within animal welfare in general, but particularly animal welfare at slaughter in relation to economics, could therefore benefit from adopting approaches developed for other wicked problems. Participatory and systems-oriented methods can help to capture multiple perspectives and explore trade-offs (Eelderink et al., 2020). Comparative studies across the slaughterhouse sector and between countries could also reveal which governance measures are most effective in enabling adaptive management of animal welfare whilst balancing economic perspectives.

In summary, framing the economic implications of animal welfare at slaughter as a wicked problem highlights the need for ongoing, adaptable, and inclusive processes that recognise uncertainty and conflict, and that aim for practical improvements without assuming final solutions. This perspective can assist slaughterhouse businesses and regulators in identifying practical strategies that enhance both animal welfare and economic sustainability.

5.3 Methodological considerations and limitations

The major strength of this thesis lies in its interdisciplinary approach. However, certain methodological considerations and limitations must be highlighted. Further details from these discussions can be found in each Paper.

The study design in Paper I provided an in-depth understanding of industry perspectives; however, it relied on a small sample and qualitative validation as opposed to econometric testing. Future focus group interviews should include financial managers and involve the collection and analysis of more detailed data on the economic outcomes of slaughterhouses. This would help broaden the understanding of how animal welfare is integrated into decision-making at various levels in the slaughterhouse businesses.

In Paper II, confidentiality agreements with the slaughterhouses restricted the disclosure of facility-specific information and data. The confidentiality agreements also limited the possibility of making comparisons between facilities. Whilst a limitation, it was unavoidable, as slaughterhouses would not have participated otherwise. Slaughterhouses operate in a competitive market, and without confidentiality agreements, they would risk important internal information being accessible to competitors. Furthermore, the assessment of stunning efficiency was based on established behavioural indicators of consciousness and measurements of stun-to-stick intervals. Although widely recognised (Atkinson et al., 2013; EFSA, 2020a, 2020b; Grandin, 2013), such indicators involve some degree of observer subjectivity. Some of these indicators have been discussed in terms of how to properly assess them, it is essential that there is unity in this approach. Nevertheless, when assessing stunning efficiency at slaughter, it is usually better to stun the animal in instances of uncertainty, rather than not doing so. Stun quality was assessed from stunning until two minutes after bleeding for both pigs and cattle. In future studies, assessments could be divided into two parts: one from stunning to bleeding and another from bleeding until two minutes post-bleeding to provide additional information on the causes of stun failures.

In Papers III and IV, analyses of traumatic injuries relied on post-mortem inspection data, which provide large-scale, cost-effective welfare information but are affected by inconsistencies in lesion classification and recording (Collins & Huey, 2015). Even though there are harmonised scoring systems in Sweden, the large number of assessors leads to variation between facilities and over time. Having stronger linkages between slaughter and farm-level data would enhance the value of the inspection data for welfare surveillance (Comin et al., 2023).

In Paper V, the economic modelling applied a stochastic partial budgeting (SPB) approach, combining empirical data with expert elicitation to simulate

realistic scenarios (Dhoubhadel & Stockton, 2010; Gummow & Mapham, 2000). The model represents scenario-based simulations as opposed to a specific slaughterhouse, which is both a limitation and a strength. The results are estimates that are only as reliable as the input data, and inaccuracies can lead to biased outcomes. Although the assumptions adopted in this study were likely robust, substantial variation exists among input variables in commercial settings. Whilst this method effectively handles uncertainty, the results depend on assumptions about key parameters such as labour costs and equipment prices. Sensitivity analyses helped to identify influential variables; however, access to detailed financial data from additional slaughterhouses would further strengthen validity. Gathering this type of economic information was challenging, as also noted in the PigStun project (2025). Expert elicitation helped fill this gap and added useful context to the analysis, although it may have introduced some bias due to the subjective nature of expert input.

Stochastic partial budgeting for evaluating animal welfare investments at the slaughterhouse level is a useful and adaptable tool, easily customised to individual facilities and applicable beyond Sweden. However, it is important to note that this method does not assess overall business profitability but rather the economic effect of a specific change relative to a baseline scenario. Alternative methods such as Net Present Value (NPV) analysis or Real Options Theory (ROT) were also considered. By discounting future cash flows, the net present value (NPV) provides a static measure of profitability and a clear estimate of long-term returns on investment. However, it assumes certainty in costs and benefits and does not account for the flexibility to adapt decisions over time. In contrast, ROT explicitly incorporates uncertainty and managerial flexibility, allowing investors to value the option to postpone, expand, or abandon an investment as new information becomes available (Wang & Halal, 2010). Although both methods can offer valuable insights, the SPB approach was selected in Paper V because it better accommodates uncertain and context-specific data, integrates expert knowledge, and captures the short- to medium-term economic effects typical of slaughterhouse investment decisions.

The interdisciplinary approach of this thesis has been essential; however, learning and applying methods from multiple disciplines have presented challenges.

5.4 Policy incentives and societal responsibility

Whilst the economic simulations in Paper V showed that investments targeted at reducing stun failures are profitable under most conditions, they also revealed that in certain scenarios, they can have neutral or even negative economic outcomes. Nevertheless, ensuring that animals are effectively stunned remains a non-negotiable requirement - particularly within the Swedish context. However, this highlights a broader dilemma: economically valuable outcomes that are beneficial to society do not necessarily translate into direct economic returns for slaughterhouse businesses. Even when such investments do not lead to a negative net benefit, they may fail to generate sufficient incentive under existing market conditions. This reflects a wider societal challenge, which is how to ensure that the responsibility and costs of safeguarding animal welfare are appropriately shared. Thus, policymakers would benefit from a clearer understanding of whether existing market mechanisms provide adequate incentives for welfare investments, or if complementary policy measures are needed to encourage them.

Slaughterhouse businesses often face the paradox of being expected to meet increasingly high animal welfare standards without receiving corresponding economic compensation. This suggests that animal welfare at slaughter functions as a public good, providing benefits that extend beyond the slaughterhouse (Fernandes et al., 2021; Henningsen et al., 2018). To encourage slaughterhouses to invest in improvements to animal welfare, policy frameworks could offer a combination of economic and regulatory incentives, for instance, targeted investment support or tax reductions for welfare-enhancing technologies. Although price premiums for animal welfare-friendly products are intended to reward the farmer or slaughterhouse, evidence suggests that these rarely reach back (Ahmed et al., 2020; Henningsen et al., 2018). Meanwhile, retailers and restaurant chains have begun to take a more active role by auditing suppliers and promoting higher animal welfare standards in their marketing (Grandin, 2013; Harvey & Hubbard, 2013), which has contributed to greater awareness and improved welfare practices in slaughterhouses.

The observed high rate of stun failures in Paper II also raises an important policy question: why has existing, evidence-based knowledge on the assessment and monitoring of stun quality and equipment maintenance not been fully implemented across the industry? Although slaughterhouses above a certain size are required to appoint an AWO and ensure that all

personnel handling, stunning, or bleeding animals hold a certificate of competence, these measures appear insufficient in preventing adequate stunning. To address this, regular renewal of the certificate would help to ensure that skills and knowledge remain up to date (Animal Welfare Committee, 2025). This should be complemented by mandatory practical training courses. Furthermore, ensuring that AWOs have enough time and resources to effectively perform their duties is a management issue that warrants further attention.

A comprehensive labelling framework that integrates both resource-based and animal-based measures (Tuyttens et al., 2025) could simultaneously improve consumer information and generate incentives for continuous welfare improvement throughout the supply chain. However, there are multiple methodologies for assessing animal welfare on farms (and a few in slaughterhouses), with no consensus on how to combine indicators into a single reliable animal welfare index (Bennet et al., 2012; Tuyttens et al., 2025). Moreover, various welfare aspects must be prioritised and weighted, which involves both ethical and technical considerations (Christensen et al., 2012; Lagerkvist et al., 2011). Within a slaughterhouse context, this could be the balance between minimising pre-slaughter stress during handling and lairage and ensuring high and consistent stunning efficiency. Nevertheless, developing a transparent and scientifically based welfare index could enhance communication between slaughterhouses and consumers, improve public trust, and ultimately transform welfare performance into tangible economic measures.

At present, there is a notable lack of consultancy services that integrate both animal welfare and its economic outcomes in slaughterhouses. Whilst advisory organisations (e.g., Växa Sverige and Farm and Animal Health) exist for farmers, it is predominantly private consultants that are associated with slaughterhouses. Developing individualised economic analyses for each slaughterhouse that demonstrate how animal welfare improvements can be implemented in the economic calculations and in relation to the specific circumstances and size, would promote higher animal welfare standards and increase awareness in the slaughterhouse businesses. It would also enable slaughterhouses to benchmark their performance against others in the sector and to exchange knowledge about effective and ineffective practices.

5.5 What do we owe them?

From an economic perspective, livestock are often viewed as a monetary resource within a production system (McInerney, 2012) that provides humans with food, clothing, and other services. The higher the productivity, the greater the animal's utilitarian value. However, this perspective is limited and, to a certain extent, problematic, as animals are sentient beings and should not be merely regarded as monetary resources. They should be protected from unnecessary suffering throughout their lives, including the time of death.

The concept of a social licence to operate is particularly relevant in this context. The continued acceptance of meat production depends on public confidence that animals are treated humanely and that slaughter practices minimise suffering (Broom, 2022). However, this acceptance is not static; it exists only so long as societal expectations are met. When the industry perceives animal welfare as a secondary concern, especially during periods of economic pressure, it risks approaching a threshold where the social licence is weakened or withdrawn. Once that line is crossed, and public opinion or market dynamics shift, the pressure to adapt can become both rapid and costly. This can be seen in the cases of fast-growing broilers in Norway, where public concern over welfare issues associated with fast-growing broiler breeds led to consumer backlash and prompted retailers to phase out these lines in favour of slower-growing breeds with higher welfare standards. A stepwise and proactive adaptation to evolving societal expectations is therefore more sustainable, benefiting both the industry and society as a whole.

Although this thesis primarily addressed the economic dimensions of animal welfare at slaughter, its findings inevitably raise broader ethical questions about the moral responsibilities of killing of animals for food. Even under well-regulated conditions, the act of slaughter represents a moral boundary where human control over animal life must be carried out with sensitivity, professionalism, and care. Whilst the principle that animals should be protected from unnecessary suffering during humane slaughter is accepted, the definition of "unnecessary" continues to evolve with scientific understanding and societal values.

The occurrence of stun failures indicates that we have not yet achieved the concept of completely humane slaughter. Considering the scientific progress on animal welfare, this calls for reflection. A serious animal welfare

issue identified in Paper II was that pigs and cattle exhibiting signs of inadequate stun quality were not always detected by the slaughterhouse personnel, with animals potentially regaining partial consciousness and continuing unnoticed on the slaughter line.

It should be highlighted that the welfare experience of the individual animal extends far beyond the moment of stunning; it also encompasses handling, restraint, and environmental conditions. Thus, these factors must not be overlooked when evaluating overall animal welfare at slaughter.

Ultimately, the question of what we owe our animals goes beyond compliance and operational efficiency for slaughterhouse businesses. Can we have humane slaughter procedures and expect economic return? The findings of this thesis suggest that animal welfare and economic outcomes can go hand in hand. Nevertheless, each slaughterhouse must adapt these principles to its own context.

6. Main conclusions

This thesis provides new insights into animal welfare during the slaughter of CO_2-stunned pigs and mechanically stunned cattle, clarifying its economic relevance. The main conclusions are:

- ⊗ A longer time between stunning and bleeding is associated with increased risk of inadequate stun quality, both before and during bleeding

- ⊗ Longer time between stunning and bleeding is associated with increased likelihood for re-stunning

- ⊗ Stunning efficiency varies considerably between slaughterhouses

- ⊗ The prevalence of stun failures has implications for both animal welfare and economic outcomes

- ⊗ The main drivers of net benefit change for reducing stun failures were costs related to labour and investments in new stunning equipment

- ⊗ According to the slaughterhouse businesses, investments in animal welfare improvements are an essential factor to enhance animal welfare

- ⊗ Key factors for the economic outcome when investing in animal welfare-improving practices are reduced labour costs and enhanced productivity

- ⊗ Modelling animal welfare during slaughter allows slaughterhouses to include animal welfare considerations in their decision-making

- ⊗ Both chronic and acute traumatic injuries are related to higher condemnation rates, leading to direct and indirect costs for the slaughterhouse businesses

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Popular science summary

Every year, millions of pigs and cattle are raised and slaughtered for human consumption. Although the time an animal spends in the slaughterhouse is short compared with its life on the farm, it represents one of the most critical and sensitive stages for its welfare. During this time, the animal is handled by unfamiliar humans, stunned, and bled - processes that, if not performed properly, can cause unnecessary suffering. However, aspects of improving animal welfare during slaughter are often considered an additional cost to the slaughterhouse business. Is that actually the case, or is it possible that better welfare at slaughter also could have economic value for the slaughterhouses?

Animal welfare at slaughter depends on many factors, including how animals are handled, the design of the slaughterhouse, the quality of the stunning process, and the skills of the personnel. Within the European Union, animals must be rendered unconscious before bleeding, usually by mechanical stunning in cattle and carbon dioxide (CO_2) stunning in pigs. In Sweden, this requirement is stricter than in most countries, as no exceptions are permitted. However, stunning is a technically demanding procedure and ensuring that each animal is rendered fully unconscious until death requires not only functional equipment but also skilled and attentive workers. Failures in this process can cause unnecessary suffering and interrupt the slaughter process, which leads to higher labour costs and reduced operational efficiency. This thesis, therefore, examined both animal welfare outcomes and their economic relevance in commercial slaughterhouses through five studies, primarily focusing on Sweden but also relevant to other countries.

In order to explain how investments in animal welfare may influence profitability, the first study of this thesis introduced an economic model that viewed animal welfare as an intangible asset within the slaughterhouse production system. More traditional factors such as labour, capital, and materials were also included in the model. Focus group interviews with slaughterhouse personnel validated the outcomes of the model - investments in animal welfare can affect profitability in several ways: by improving workflow, reducing labour demands, and enhancing the quality of carcasses and by-products. Thereto, they emphasised that by-products played a significant role in profitability. Many facilities had already made, or were planning to make, welfare-related investments such as redesigned drive-

races, improved lairage areas, or new stunning boxes. This made handling calmer for animals, improved the working environment for employees, reduced noise, and increased overall production efficiency. However, the representatives from the slaughterhouses also highlighted challenges in measuring the financial return on such investments and noted that consumer awareness of slaughter practices is low, which makes it difficult to communicate the benefits of improvements to the public.

The second study assessed stunning efficiency in pigs and cattle under commercial conditions at eleven Swedish slaughterhouses. Most animals were adequately stunned, but there was notable variation between slaughterhouses. Around 96% of pigs and 93% of cattle were effectively stunned, while the rest showed signs of inadequate stunning. In total, 4% of the pigs were re-stunned and nearly 6 % of the cattle. The likelihood of initially poor stun quality, or inefficient stunning between stunning and bleeding, increased when the stun-to-stick-interval, known as the time between stunning and bleeding, increased. The likelihood for re-stunning also increased with longer stun-to-stick intervals. For pigs, the risk increased after about one minute, while for cattle the critical point was around one and a half minutes. In pigs, differences were also linked to the type of CO_2 stunning system: dip-lift systems produced more consistent stunning results than paternoster systems. In cattle, about a quarter of the stunning shots missed the ideal position on the skull, often due to short bolt lengths or poor maintenance of the equipment. The study showed that proper training, careful equipment maintenance, and short stun-to-stick intervals are essential to ensure that animals remain unconscious until death and that the slaughter process runs smoothly.

The third and fourth studies examined traumatic injuries in pigs and cattle using Swedish slaughter inspection data from over seven million pigs slaughtered between 2019 and 2021, and three hundred thousand cattle slaughtered between 2020 and 2022. These injuries, such as bruises, skin lesions, and fractures, indicate compromised welfare before or during slaughter and lead to meat losses and economic costs. Chronic injuries were more common than acute ones in both species, affecting around 9% of cattle and less than 1% of pigs. Seasonal patterns suggested that injury rates increased in colder months, likely due to handling procedures and environmental challenges. Carcases with injuries lost significant amounts of saleable meat, on average more than twenty kilograms per injured cattle

carcase. In pigs, condemnations linked to injuries accounted for about 16% of all condemned meat during the studied period, and for cattle, the corresponding figure was 34%. Overall, these studies showed that injuries not only affect animal welfare but also reduce product value and increase food waste. This link between welfare at slaughter and conditions on farms and during transport demonstrates that animal welfare at slaughter is influenced by events that occur earlier in the animals' lives; injuries sustained on farms or during transport can cause pain and distress during slaughter.

Overall, these studies showed that injuries not only affect animal welfare but also reduce product value, while increasing food waste. This link between welfare at slaughter and conditions on farms and during transport demonstrates that animal welfare at slaughter depends on what happens earlier in the animals' lives; injuries on farms or during transport can cause pain and distress at slaughter.

The final study used economic simulations to estimate the financial effects of reducing stunning failures. By modelling different scenarios for pigs and cattle, the study showed that investing in new stunning equipment and improving equipment maintenance and standard operating procedures could be economically justified. Under most conditions, the benefits slightly outweighed the costs. For pigs, the annual net benefit of upgrading the stunning system was estimated at nearly 90,000 SEK, while for cattle it was around 37,000 SEK. The most important factors driving these positive outcomes were lower labour costs, smoother workflow, and fewer equipment breakdowns. Although the financial gains were relatively modest, they demonstrated that improving welfare does not necessarily reduce profitability and can in fact support a more efficient and sustainable production process.

Overall, the results of this thesis show that animal welfare at slaughter is both an ethical and an economic concern. Humane handling and effective stunning not only reduce suffering for animals but also improve product quality, reduce waste, and enhance worker safety and morale. The findings also underline the importance of management commitment and regular training for slaughterhouse personnel, as well as the need for well-functioning equipment. However, welfare improvements are not always easy to measure in monetary terms, and the benefits are often long-term or indirect. For this reason, economic incentives or policy measures may be

needed to encourage slaughterhouses to invest in welfare-enhancing technologies and training. Since slaughterhouses operate under strict legal and ethical obligations, these investments also strengthen public trust and the social legitimacy of meat production.

This thesis demonstrates that animal welfare and economic outcomes are not mutually exclusive. On the contrary, they often move hand in hand. When animals are treated calmly, equipment works as intended, and when personnel are properly trained, the slaughter process becomes safer, more efficient, and more humane. Achieving this balance requires continuous effort, since failures, such as an animal showing signs of consciousness after stunning or injuries caused by rough handling, have welfare and economic implications. Humane slaughter is therefore not only a legal requirement but also a matter of professional pride and ethical responsibility. It reflects the values of the people who produce meat and the society that consumes it.

This research contributes new knowledge about how animal welfare at slaughter can be improved and its economic relevance. By integrating animal science with production economics, it provides practical tools for decision-making within the slaughter industry and insights that can guide future policy. The findings show that investments in animal welfare, whether through improved stunning systems, better facility design, enhanced training, or a combination of the above, can bring benefits that extend beyond the slaughterhouse. Ultimately, they help ensure that animals are treated with respect in their final moments while supporting efficient, responsible, and economically sustainable food production.

Populärvetenskaplig sammanfattning

Varje år sker uppfödning och slakt av ett stort antal grisar och nötkreatur som ska bli mat på våra tallrikar. Även om tiden på slakteriet är kort jämfört med djurens liv på gården, är den mycket viktig för deras välfärd. Under de sista timmarna i livet hanteras djuren av för dem okända människor i en okänd miljö, för att sedan bedövas och avlivas. Om dessa moment inte utförs på rätt sätt, kan det orsaka stort och onödigt lidande. Samtidigt betraktas djurvälfärd vid slakt ofta som en kostnad, snarare än en investering för slakterierna. Men är det verkligen så? Hur hänger djurvälfärd och slakteriföretagens ekonomi egentligen ihop? Denna fråga står i centrum för den här doktorsavhandlingen, som genom fem studier undersöker djurvälfärdsaspekter vid slakt och den ekonomiska relevansen för slakteriföretagen av att investera i dessa.

Djurvälfärden vid slakt påverkas av många faktorer: hur djuren hanteras, hur slakterierna är utformade, vilken utrustning som används samt personalens kunskap och erfarenhet. Inom EU krävs att djuren görs medvetslösa (bedövas) före avblodning, vanligen genom mekanisk bedövning av nötkreatur och koldioxidbedövning (CO_2) av grisar. I Sverige är reglerna för bedövning vid slakt särskilt strikta, och inga undantag från kravet på bedövning tillåts. Samtidigt är bedövning en tekniskt krävande process som ställer höga krav på både utrustning och personal. För att varje djur ska förbli medvetslöst fram till döden inträffar till följd av blodförlust krävs att tekniken fungerar felfritt och att de som utför arbetet är både är uppmärksamma och kompetenta. Misslyckanden i bedövningsprocessen kan både leda till att djuren utsätts för onödigt lidande, och till avbrott i produktionen, vilket kan leda till ökade kostnader för företaget. Upptäcks ett otillräckligt bedövat djur ska det omedelbart bedövas om.

I den första studien utvecklades en ekonomisk modell som integrerar djurvälfärd som en immateriell produktionsfaktor i slakteriets produktionsfunktion, likvärdig med traditionella insatsfaktorer som arbete, kapital och material. Genom fokusgrupper med slakteripersonal validerades modellen och de som deltog i intervjuerna berättade att investeringar i djurvälfärd kan påverka lönsamheten på flera sätt, till exempel genom ett bättre arbetsflöde, minskade personalkostnader och högre kvalitet på både slaktkroppar och biprodukter. De påpekade också att biprodukterna spelade en viktig roll för lönsamheten i stort. Många av slakterierna hade redan gjort,

eller planerade att göra, investeringar för förbättrad djurvälfärd, till exempel nya drivgångar, förbättrad stallmiljö och modernare bedövningsboxar. De menade att förutom att dessa investeringar gjorde djuren lugnare, förbättrade de även arbetsmiljön och gjorde produktionen effektivare. Samtidigt betonade de som deltog i intervjuerna att det är svårt att mäta den ekonomiska vinsten i kronor och ören, och de upplevde det även svårt att marknadsföra investeringarna till följd av konsumenternas distans från hur slaktprocessen fungerar.

Den andra studien undersökte bedövningskvaliteten hos grisar och nötkreatur vid elva svenska slakterier. Resultaten visade att de flesta djuren bedövades korrekt, men att skillnaderna mellan anläggningarna var stora. Ungefär 96 % av grisarna och 93 % av nötkreaturen visade tecken på att vara djupt medvetslösa, medan resterande andel visade tecken på otillräcklig bedövning. Totalt ombedövades 4 % av grisarna och ca 6 % av nötkreaturen. Risken för att djuren blivit antingen initialt dåligt bedövade, eller uppvisade tecken på dålig bedövningskvalitet, ökade när sticktiden, dvs. tiden mellan bedövning och avblodning, blev längre, vilket även sannolikheten för att djuren behövde ombedövas gjorde. För grisar ökade risken för att de visade tecken på att vara otillräckligt bedövade vid en sticktid på drygt en minut och för nötkreatur på omkring en och en halv minut. Hos grisar spelade även typen av koldioxidsystem roll: bedövning i diplift-system gav jämnare och bättre resultat än i paternoster-system. Hos nötkreatur placerades ungefär en fjärdedel av skotten utanför den ideala träffpunkten på huvudet, vilket ledde till högre sannolikhet för ombedövning hos dessa djur. Sammantaget visade studien att sticktiden är avgörande för djurvälfärden, men den belyste också vikten av välutbildad personal som vet vilka tecken de ska titta efter vid bedömning av bedövningskvalitet. Detta är viktigt både för att minimera risken att djuren utsätts för onödigt lidande vid slakt och för att säkerställa att djur som inte är tillräckligt bedövade upptäcks och bedövas om.

I studie tre och fyra analyserades förekomsten av traumatiska skador på nötkreatur och slaktgrisar, baserat på besiktningsdata från svenska slakterier på mer än sju miljoner grisar som slaktades mellan 2019 och 2021 och över trehundratusen nötkreatur som slaktades mellan 2020 och 2022. Skador, exempelvis blåmärken, hudsår och frakturer, tyder på bristande djurvälfärd på gården, på transporten eller på slakteriet och leder till köttförluster och direkta ekonomiska konsekvenser. Kroniska skador som uppkommit innan djuren kommit till slakteriet var vanligare än akuta skador som uppkommit

under transport eller på slakteriet. Hos nötkreatur var ungefär 9 % av djuren drabbade av kroniska skador, jämfört med under 1 % hos grisar. Både kroniska och akuta skador ökade under de kallare månaderna, vilket skulle kunna bero på miljöförhållanden vintertid, tex halkiga golv på transportbilarna eller ventilation. Skador hos nötkreatur stod för 34 % av det kasserade nötköttet under perioden, medan motsvarande andel för grisar var 16 %. Studierna visade hur skador kan leda till minskat produktvärde och ökat matsvinn, men signalerar också försämrad djurvälfärd och hur förhållandena vid slakt hänger ihop med vad som sker med djuren på gården och under transporten till slakteriet.

I den femte och sista studien användes ekonomisk simulering för att uppskatta hur minskad förekomst av otillräcklig bedövning, dvs. bättre bedövningskvalitet, vid slakt påverkar ekonomin. Genom att modellera scenarier för både grisar och nötkreatur visade resultaten att investeringar i ny bedövningsutrustning och bättre underhåll ofta kan löna sig ekonomiskt, utöver vinster för djurvälfärden och arbetsmiljön. För grisar beräknades den årliga nettovinsten av att uppgradera bedömningssystemet till nära 90 000 kronor, och för nötkreatur till omkring 37 000 kronor. De största vinsterna uppstod genom minskade arbetskostnader till följd av färre driftstopp och ett jämnare arbetsflöde. Vinsterna var inte stora, men de visade att djurvälfärd och lönsamhet inte står i motsats till varandra – snarare tvärtom. Många av fördelarna med förbättrad djurvälfärd vid slakt är svåra att mäta i siffror och är märkbara först på längre sikt. Därför kan ekonomiska incitament och politiska styrmedel behövas för att uppmuntra investeringar i djurvälfärdshöjande åtgärder på slakterierna.

Den här avhandlingen bidrar med ny kunskap om hur djurvälfärden vid slakt kan förbättras och vilken ekonomisk betydelse det har för slakteriföretaget. Genom att integrera husdjursvetenskap med produktionsekonomi ger den praktiska verktyg för beslutsfattande inom slakterinäringen och insikter som kan vägleda framtida policyarbete. Resultaten indikerar att investeringar i djurvälfärdsförbättrande åtgärder, oavsett om det handlar om förbättrad bedövningsutrustning, förbättrad infrastruktur (ex. drivgångar), utbildning av personal eller en kombination av dessa, kan medföra fördelar som sträcker sig bortom slakteriets direkta verksamhet. En human slaktprocess som präglas av professionalism och omsorg uppfyller inte bara lagens krav utan också yrkesstolthet och etiskt ansvar – att respekten för djuren ska upprätthållas till sista hjärtslaget.

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Appendix

Appendix I: Stun quality protocol for pigs. Stun quality level, criteria and symptoms with definitions used to classify the stun quality of CO_2 stunning of pigs from stunning until two minutes after sticking (summarised from Welfare Quality®; Atkinson et al., 2012; EFSA, 2020a)

Stun quality level	**Criteria**	**Symptom**	**Definition**
Poor	The stun depth is inadequate, and the recovery risk is considered imminent because it indicates some form of consciousness and a high risk for poor welfare. Immediate re-stunning is necessary	Righting reflex	Lifting the head or arching the back in an attempt to regain normal posture
		Pain reflex	Response to a painful stimulus, e.g., pricking the snout with a sharp object
		Blinking	Spontaneous blinking without external stimulation
		Rhythmic breathing	Regular, rhythmic inhalation and exhalation, visible in chest or flank movement, can also be felt by hand.
		Corneal reflex	Blinking in response to a stimulus of the cornea by either a fingertip or a writing pen
		Vocalisation	Repeat squeals or vocal sounds unrelated to reflexive dying sounds
Shallow	The stun depth is considered unacceptable due to the risk that the animal could recover. Re-stunning is necessary as a precaution to avoid recovery of consciousness	Nystagmus	Rapid side-to-side eyeball movement (twitching)
		Convulsion	Strong, involuntary seizure-like muscle contractions (not minor twitches)
		Eyeball rotation	Eyeball rotated with sclera visible; little or no iris seen, 40+ s post-stun
		Regular kicking	Repeated limb movements
		Regular gasping	Opening of the mouth with the sound or appearance of short gasps of air while flexing the head forwards, more than 3 times in 10 s

Doubt	If shown, the animal is considered adequately stunned but requires continual monitoring	Irregular gasping	Occasional opening of the mouth while flexing the head forwards with the sound or appearance of short gasps of air intake at sporadic intervals
		Irregular kicking	Sporadic limb movement
Good	The animal is in a state of deep unconsciousness and adequately stunned, and there is no risk of poor animal welfare	Whole body relaxation, fixed eyeballs, and dilated pupils	Whole body relaxation when leaving the stunning system, no eye movement, pupils fully dilated

Appendix II: Stun quality level, criteria and symptoms with definitions used to classify the stun quality of captive-bolt stunning of cattle from stunning until two minutes after sticking (summarised from Welfare Quality®, 2009; Atkinson et al., 2013; EFSA, 2020b)

Stun quality level	**Criteria**	**Symptom**	**Definition**
Poor	Inadequately stunned, with the highest risk of recovery and compromised animal welfare. Immediate re-stunning is required to prevent suffering	Righting reflex	Lifting the head or arching the back in an attempt to regain normal posture
		Pain reflex	Response to a painful stimulus, e.g., pricking the nostril with a sharp object
		Blinking	Spontaneous blinking without external stimulation
		Rhythmic breathing	Regular, rhythmic inhalation and exhalation, visible in chest or flank movement, can also be felt by hand
		Corneal reflex	Blinking in response to a stimulus of the cornea by either a fingertip or a writing pen
		Vocalisation	Repeat groaning or vocal sounds unrelated to reflexive dying sounds
Shallow	Inadequately stunned, but with a moderate recovery risk and compromised animal welfare. Re-stunning is necessary to eliminate recovery risk	Nystagmus	Rapid side-to-side eyeball movement (twitching)
		Gasping	Repetitive contraction and retraction of the lips and slight opening/closing of the mouth
		Eyeball rotation	Eyeball rotated with sclera visible; little or no iris seen, 40+ s post-stun
Doubt	If shown, the animal is considered adequately stunned but closely monitored and tested for reflexes	Tongue tension	Tongue is retained in mouth (not hanging down relaxed outside)
		Excessive kicking and delay of shackling or sticking	Strong limb movement causing delay or risk during shackling or sticking
Good	The animal is deeply stunned, and there is no concern of	Immediate collapse, fixed eyeballs, and	Animal falls immediately after stunning; no eye movement; pupils fully dilated

	recovery or reduced animal welfare	dilated pupils (posture)	
		Tonic and clonic phases of spasms (posture)	Tonic: rigid extension or contraction of the legs; Clonic: uncoordinated limb movements

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A formal model for assessing the economic impact of animal welfare improvements at bovine and porcine slaughter

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Abstract

The relationship between animal welfare at slaughter and slaughterhouse profitability is complex, with potential trade-offs between animal welfare costs and benefits. Slaughterhouses currently lack data support for decisions on investments that can improve both animal welfare and profitability. Therefore, this study mapped the economic impacts for slaughterhouse businesses of improved cattle and pig welfare at slaughter. Specific aims were to: (i) highlight the possible economic impact of animal welfare improvements, based on the scientific literature; (ii) develop an economic model demonstrating the theoretical contribution of animal welfare to slaughterhouse profitability; and (iii) validate the economic model through focus group interviews with slaughterhouse personnel in Sweden. The findings indicated that investing in animal welfare improvements could result in accumulation of an intangible asset that can be considered together with other production factors in the economic model. Model validation stressed the importance of selling by-products for the economic outcome and of smooth workflow for productivity. The study thus improves understanding of the economic impacts of animal welfare at slaughter and incentives for slaughterhouse businesses to improve animal welfare. The results are important for public and private policy-makers interested in enhancing animal welfare at slaughter.

Keywords: *abattoir, animal welfare, cattle, economic impact, pigs, profitability*

Introduction

There is considerable public interest in the welfare of farm animals in general and in the handling of animals at slaughterhouses in particular (Fernandes *et al* 2021). Therefore, many food chain actors (including slaughterhouse workers) are striving to improve the welfare of farm animals. Since consumption of beef and pork worldwide is expected to increase with a growing and increasingly wealthy global population, it is highly relevant to ensure acceptable welfare standards for animals produced for meat (Alexandratos & Bruinsma 2012). Animal welfare is defined by Fraser *et al* (1997) as the subjective experience of the animal and its biological functioning and adaptation to its current environment, and it includes all parts of an animal's life. Improving animal welfare means ensuring good living conditions for farm animals during their life and at slaughterhouse level, with the latter often requiring alterations to infrastructure such as avoiding slippery flooring or high-pitched motor noises (Grandin 2000), or training personnel in animal welfare-friendly stunning methods (Leary *et al* 2013). There is a considerable body of literature about the links between pre-slaughter stress, animal handling and meat quality (Costa *et al* 2006; Chulayo & Muchenje 2015), but the economic consequences for slaughterhouses of impaired welfare practices pre-slaughter are less well explored.

The relationship between animal welfare at slaughter and production costs is complex, with some costs being obvious and others challenging to evaluate using econometric methods. There is concern that increased animal welfare could be linked to higher production costs, leading to impaired competitiveness at farm and slaughterhouse level. Recent studies have considered the relationship between animal welfare and economic outcomes at farm level, focusing on pig production (Alvåsen *et al* 2017; Henningsen *et al* 2018) and beef fattening operations (Ahmed *et al* 2020). Other studies have indicated, but not verified, interactions between animal welfare at slaughter and slaughterhouse profitability (McInerney 2004; Gibson & Jackson 2017). At the same time, there is an ongoing debate about animal welfare at slaughter and the potential trade-offs between costs and benefits (Fernandes *et al* 2021). It is important for the slaughter sector to understand the economic consequences of improved animal welfare since it can aid their decision-making. However, there is a

lack of understanding about the relationship between animal welfare improvements and economic outcomes of cattle and pig slaughterhouse operations. This is problematic for slaughterhouses, which do not have sufficient data support for decisions about investments in animal welfare that can enhance both animal welfare and profitability. It is also problematic from a societal perspective, as policy-makers do not know whether slaughterhouses have sufficient economic incentive to invest in animal welfare.

Several studies have reported high consumer awareness and willingness to pay for farm animal welfare product quality attributes (Lagerkvist & Hess 2011; Leonardsson *et al* 2011). Napolitano *et al* (2008) found that providing information about animal welfare to consumers could have a major impact on their willingness to pay for animal-based food products. Moreover, animal-friendly products are considered by consumers to be of higher quality, healthier, more hygienic and safer (Alonso *et al* 2020). On the other hand, consumers seem to have low interest in receiving information about the slaughter procedure, which could be due to personal doubts towards the killing of animals for food (Gori *et al* 2017). Slaughterhouse businesses could benefit from listening to consumer demands and differentiate meat products, which would increase their competitiveness and improve animal welfare.

The overall aim of this study was to map the economic impacts for slaughterhouse businesses of improving the welfare of cattle and pigs at slaughter. Specific aims were to: (i) highlight the possible economic impact of animal welfare improvements, using a review of the scientific literature; (ii) develop an economic model to show the contribution of animal welfare to slaughterhouse profitability from a theoretical perspective; and (iii) validate the economic model through focus group interviews with slaughterhouse personnel in Sweden. This paper makes several novel contributions to the literature. It describes the first attempt to develop an economic model for slaughterhouses in relation to animal welfare and highlights how animal welfare enters the production function in slaughterhouses. The model can be used to relate proposed animal welfare improvements at slaughter to the economic outcome for the slaughterhouse business. The paper also improves understanding of the economic incentives for slaughterhouse businesses to improve animal welfare. The results can be used as a starting point for discussions on how investments in animal welfare improvements can be internalised in strategic decision-making by slaughterhouse businesses.

This paper starts with presenting a review of the relevant literature in the field of animal welfare at slaughter. It continues with a research approach where the methodology for developing the economic model and of the focus group interviews are described. In *Results*, the economic model together with the validation of the model and the identified themes from the focus group interviews are presented. The *Discussion* includes an analysis of the economic model and the potential economic effects of animal welfare improvements. Thereafter, *Animal welfare implications and conclusion* can be seen.

Literature review

Economic effects of animal welfare at slaughter

Since Lusk (2011) first identified a significant gap in the production economics literature concerning animal welfare, there are to our knowledge still no published studies on the relationship between animal welfare at slaughter and the economic outcome for the slaughterhouse business. Knowledge of how animal welfare improvements might affect the economic status of slaughterhouse businesses is important in identifying their economic incentives for improving animal welfare. This was shown by Lusk (2011), who proposed a scheme to quantify and trade units of farm animal welfare, due to the current lack of market incentives. The benefits of improving farm animal welfare (FAW), and animal welfare at slaughter, are difficult to evaluate from a purely economic perspective, since they take the form of intangible gains in productivity or competitive advantage and market premiums (Hemsworth *et al* 2002; Fernandes *et al* 2021). Production economics research can help reveal the economic incentives of slaughterhouses for improving or reducing animal welfare.

A study by Alleweldt *et al* (2007) found that poor meat quality can reduce the carcase grade, and thereby the wholesale value of the meat. Other studies have attempted to estimate the cost of animal welfare-related problems in slaughterhouses, such as the prevalence of carcase bruises. Huertas *et al* (2015) examined 15,157 carcases of cattle slaughtered in Uruguay and found that 60% were bruised to some extent, probably due to pre-slaughter handling of the animals, poorly maintained trucks and failures at trailer gate opening. Estimated direct losses of this carcase damage, calculated as the product of the number of bruises and the estimated weight of condemned carcases, divided by the total number of slaughter cattle observed, were 899 g per carcase (Huertas *et al* 2015). Considering the 2.5 million head of cattle slaughtered annually in Uruguay and assuming an average price of $US4 per kg (2012), the overall loss to the national economy due to bruises would be approximately $US8 billion per year. According to Grandin (1995), a one-minute delay in a large-scale slaughterhouse can cost as much as $US100–200. In Canadian slaughterhouses, beef spoilage due to dark cutting (DFD) represents around $US1.13 million in lost carcase value each year (Holdstock *et al* 2014), while in the Australian beef industry the corresponding annual loss is estimated to be $US26.6 million (Wigham *et al* 2018).

Economic effects of animal welfare improvements at slaughter

The literature suggests that animal welfare is a key factor for the economics of slaughterhouse businesses and that treating animals in a humane manner can bring many economic benefits for the industry (Grandin 1995; Gallo & Huertas 2015; Wigham *et al* 2018). Implementing animal welfare improvements could reduce production costs and

improve the quality of the output (carcases, meat and by-products). However, the literature does not provide any information on approaches to assess the economic effects of animal welfare improvements on slaughterhouse productivity. Reported effects are instead based upon reasoning and personal experiences (Grandin 1995). However, one important distinction when linking animal welfare to economics is that animal welfare concerns the single, individual animal and whether it experiences negative or positive states of welfare, while economics considers the perspective of society and focuses on factors relating to human demands and preferences (Gibson & Jackson 2017). Possible and feasible animal welfare factors at slaughter and their predicted impact on the economic outcome for the slaughterhouse business, identified from the scientific literature, are summarised in Table S1.

High stress in animals before slaughter impairs meat quality (Warner *et al* 2007), due to meat discards or entire carcase condemnations (downgrading and rejections), and thereby generates direct costs and foregone revenues for the slaughterhouse or the processing industry (Alleweldt *et al* 2007). Carcase defects such as pale soft exudative (PSE) and dark cutting represent an economic loss to the meat distribution chain and are a strong indicator of impaired animal welfare related to high stress levels in the live animal, which could have occurred at the farm, during transport or in the slaughterhouse (Grandin 1997, 2007).

Sub-optimal design of the slaughterhouse interior reduces animal welfare (Hultgren *et al* 2014) and may lead to sub-optimal workflow, which can cause frustration among workers and reduce the flow of animals through the slaughter process (Grandin 1996; Gallo *et al* 2003; Wiberg 2012). This reduces the production efficiency of the slaughterhouse business.

Knowledge and skills levels can be expected to vary considerably between slaughterhouse personnel, depending on, for example, experience and education (Atkinson *et al* 2013). Council Regulation (EC) No 1099/2009 (on the protection of animals at the time of killing), which came into force in the EU on 1 January 2013, requires formal education of all slaughterhouse personnel who handle animals. Prior to that, the amount of theoretical and practical training was possibly unsatisfactory in some slaughterhouses, although national legislation in some countries (including Sweden) already required training of slaughterhouse personnel. Previous studies indicate that there may be an opportunity to improve stockperson actions, and consequently reduce stress in cattle at slaughterhouses, by targeting attitudes with appropriate educational and training material (Breuer *et al* 2000; Coleman *et al* 2012). Improvements in animal welfare can also reduce the amount of labour required for handling and stunning if, for example, the animals move voluntarily through the system (Grandin 1995).

Research approach

Development and validation of the economic model

Our approach to assess the economic impacts of animal welfare at slaughter was based on a previous study that developed a formal economic model for pork production marketing chains, which assumed that slaughterhouses are profit maximisers (Den Ouden *et al* 1997). The economic model was based on a profit function, which describes the slaughterhouses' costs and revenues to find the optimal output level. Furthermore, animal welfare was presented as an intangible asset in the production function.

Structure and procedure of the focus group interviews

We used focus group interviews with slaughterhouse personnel to: (i) identify how the economic outcome in slaughterhouses may be related to animal welfare improvements; and (ii) validate the slaughterhouse-specific details of the model and inclusion of animal welfare in the model.

We conducted two focus group interviews with slaughterhouse staff members with different positions, since we wanted to determine whether they could see a connection between investments in animal welfare improvements and the economic outcome. The first focus group consisted of four female employees working with the quality assurance schemes and animal welfare in their respective slaughterhouse. The second focus group consisted of three male employees (although one could not participate in the whole group interview and was interviewed separately for the remaining parts), working as slaughter managers in their respective slaughterhouse. All seven participants had formal education in animal welfare according to EC 2009/1099. Approximately one week prior to the meeting, the participants received an email with instructions and questions to prepare for the interview. The meetings were arranged over virtual meeting platforms in November 2019 and April 2021, and each focus group interview lasted for three hours. Prior to the interviews respondents were informed about their anonymity and the confidentiality of the interview. They were also informed that they could choose to discontinue the interview at any time and refuse to answer any questions. Ethical approval for this study is not needed according to the Swedish Act 2003: 460 since we do not ask about the type of sensitive personal information that requires this.

The objective of the focus group interviews was to validate the economic model (see Equation 7) and to probe respondents about how different investments in animal welfare improvements might influence the economic outcome for their slaughterhouse. Focus group interviews are a quantitative method of deriving valuable, in-depth data from specific people of interest (Coyne *et al* 2014). The moderator allows the participants to influence the content but steers the discussions to cover a number of predetermined topics. This method facilitates study of values, motivations, attitudes and

behaviours that occurs in social interactions (Carson *et al* 2011; Algers & Berg 2017). Focus group interviews were considered particularly useful for our purposes since the interview format, where respondents can develop their responses based on other respondents' answers, allows them to go deep in their reasoning and uncover aspects they may not have considered initially. This was especially important for the research topic in this study, ie the relationship between investments in animal welfare improvements and the economic outcome for slaughterhouses.

The focus group meetings started with a presentation of the project and information about the current lack of data on the links between economics and animal welfare at slaughter. The focus group interviews then covered three main themes:

• The most important animal welfare factors influencing the economic outcome for the slaughterhouse;

• The economic model and slaughterhouse economics in general, ie the most important costs and revenues; and

• Previous and planned investments in animal welfare improvements at the slaughterhouse.

The focus group interviews were led by two female facilitators (JJ and HH) who had competence within animal science and animal welfare aspects of slaughter (JJ) and within agriculture economics at professor level and with substantial experience in research based on interviews (HH). One facilitator took notes and the other moderated the meeting. When necessary, both facilitators asked questions and took notes. The notes from the interviews were anonymised, summarised and subjected to thematic analysis to determine certain themes or concepts across the qualitative data (Braun & Clarke 2006).

Results

Developing an economic model for slaughterhouses

The slaughterhouse business normally purchases animals directly from farmers and either sells the products under its own brand or sells the carcase to retailers for further processing. Another option in Sweden is sub-contract slaughter, where farmers send their animals to the slaughterhouse for slaughter, processing and packaging and then sell the meat directly to consumers. This is a specific situation for northern Europe while in other countries the slaughterhouses provide these services. We based our economic model on the first option, ie where the slaughterhouse purchases the animals from the farmer. The animal then passes through the slaughter chain, comprising transport, slaughter, processing, manufacturing, distribution, portioning, packaging and finally retail sale. Based on the demand for beef or pork products, carcases are assigned to various processing options, thus determining the processing costs and the carcase value. This formal economic model for slaughterhouses handling cattle and/or pigs highlight how animal welfare can be considered at a conceptual level to affect the production process in slaughterhouses.

Any profit-maximising firm, including a slaughterhouse, can find its optimal output level by considering the point at which profits are maximised. At its most general level, the profit function of the slaughterhouse can be described as:

$$\pi(q) = R(q) - C(q) \quad (1)$$

where $\pi(q)$ is the profit of the slaughterhouse, $R(q)$ is the revenue function, $C(q)$ the cost function and q is the number of units produced and sold; and both revenues and costs depend on output. It is assumed that all products produced are sold. The optimal output is found by maximising the profit function (1).

In the case of slaughterhouses, revenues depend on both the carcases ($q1$) and the by-products ($q2$), ie hides, organs, bones and other parts of the animals produced as a consequence of production of meat carcases. The revenue from carcases mainly depends on the carcase classification and the price (SEK per kg cold carcase weight). All carcases produced in Sweden and intended for sale on the open market must be classified according to a set of Swedish Board of Agriculture and EU regulations (similar systems apply in other EU member states). Carcases of cattle are assessed according to the EUROP carcase classification system, which includes category (eg cow, heifer, bull), carcase shape and carcase fat composition. Carcases of pigs are assessed by category (eg slaughter pig, sow, boar) and carcase leanness (meat content percentage) according to the Hennessy Grading System (HGS), where the difference in reflectance between muscle and fat is measured by a probe in the *M. longissimus dorsi*. The carcase price group (SEK per kg cold carcase weight) is dependent on the classification result and carcase weight. Production of by-products ($q2$) is driven by the variable $q1$, and revenue is generated by the price ($p1$) of $q1$ and the price ($p2$) of $q2$. The slaughterhouse revenue function can then be described as:

$$R(q1) = p1 \times q1 + p2 \times q2 \text{ where } q2 = f(q1) \quad (2)$$

The process of transforming production factors into outputs can be described from the production function, which specifies how production factors such as capital services (K), labour services (L), material services (M) and energy services (E) produce q:

$$q = f(K, L, M, E) \quad (3)$$

where q units of output are the maximum level of production that can occur when using K units of capital services, L units of labour services, M units of material and E units of energy services.

For a slaughterhouse, the capital is long-term inputs such as buildings (capital); the labour is supplied by managers and employees (hours); the material is the live animals bought from the farmer (kg cold carcase weight); and the energy is electricity (Kwh) and water (litres).

The total production costs (TC) of the slaughterhouse can be described by the fixed (FC) and variable costs (VC), depending on the number of units produced. The slaughterhouse costs include wages, cost of capital and cost of other production factors. The slaughterhouse cost function can be described as:

$$C(q1) = FC + VC(q1) \quad (4)$$

To illustrate how animal welfare may affect the production process, animal welfare (*AW*) describes the input needed in the slaughter production system and decisions that can be made in detecting desired animal welfare objectives. In particular, through investments in specific animal welfare practices, it can be considered that the overall *AW* in the slaughterhouse increases. Based on the literature available, we identified a list of factors (Table S1) that can be assumed to have an impact on costs, revenues and *AW*, and thus on the economic output of the slaughterhouse. As a proxy, we considered accumulated investment in animal welfare in the slaughterhouse and handled it as an intangible asset that functions as a production factor. This is because investing in animal welfare improvements is assumed to lead to an increase in slaughterhouse output:

$$q = f(K, L, M, E, AW) \quad (5)$$

Production thus takes place with the production factors specified by the components indicated by the fixed and variable costs:

$$C(q1) = FC + VC(q1) \quad (6)$$

where $FC = Pk \times \acute{K}$ and k is fixed in the short term.

In the short term, the slaughterhouse has limited possibilities to change its use of production factors. It can relatively rapidly change the amount of labour needed to perform the activities but building a new housing facility is not possible in the short term. Therefore, $\acute{K}$ is the fixed number of units in the cost function and Pk is the cost of capital. Other costs, eg wages, vary proportionally with the scale of operation.

Taking the costs and revenues into account, the profit function of the slaughterhouse will be:

$$\pi(q1) = (p1 \times q1 + p2 \times q2) - (FC + VC[q1]) \quad (7)$$

where:

$$q1 = f(K, L, M, E, AW)$$

$$q2 = f(q1)$$

and $FC = Pk \times \acute{K}$ and k is fixed in the short term.

Validation of the economic model based on the slaughterhouses' investments in animal welfare improvements

To validate the economic model and the impact of animal welfare on the economic outcome for slaughterhouses, the respondents of the focus group interviews were asked to specify and discuss the costs and revenues, and where these stem from. The largest amount of money is obtained from selling the carcases but, interestingly, the respondents pointed out the importance of profitable by-products. Apparently, at least in some slaughterhouses, profit is obtained in particular by selling high-margin by-products. Therefore, the respondents stressed the importance of finding a market for the whole animal, including searching for new areas for by-products. Some examples of by-products include selling marrowbones for stock production, offal for production of dog food and export of, eg rumen to Asian markets and lower legs from cows and pigs to African markets. Earlier, when Sweden's hide industry was more well-developed, the slaughterhouses received higher returns from selling hides, but today the income from that source is low. Furthermore, the slaughterhouses send non-saleable by-products from the slaughter line (production waste) to biogas production. Some of the participating slaughterhouses had invested in their own biogas facility, which they expected to generate higher revenue than selling it to an external biogas company due to the high waste transportation costs. Several respondents were of the opinion that subcontract slaughter is an important service that generates considerable revenue.

The respondents specified and discussed fixed and variable costs of slaughterhouses. Fixed costs mentioned were labour (capacity building of employees), capital, inspection fees to authorities and certification companies (eg the National Food Agency or organic production auditors) and environmental work (eg laboratory samples and fees to laboratories). The variable costs referred to were material (ie consumer goods, knives, ammunition, special equipment and technology), energy (ie electricity, water, sewage water handling and treatment), and transport of animals from farm to slaughterhouse, meat to retailers, waste and by-products from the carcase, waste and specified risk material (SRM). The respondents emphasised that having the right number of slaughterhouse personnel in relation to the design and slaughter capacity was the most effective measure to influence fixed costs.

The respondents reported that their respective slaughterhouse had already invested, or is planning to invest, in animal welfare improvements (Table S2). The improvements mentioned were re-design of slaughterhouse interiors and improving the efficiency of the slaughter line. The respondents reported that this has led to a more efficient slaughter process flow, less stress for both animals and slaughterhouse personnel, improved carcase quality and an overall improved working environment. Several of the respondents reported rebuilding of the lairage area in order to create a buffer of animals to generate an even workflow and decreased stress when handling the animals. In some cases, rebuilding also enabled two active slaughter lines instead of one, which improved the slaughter process flow considerably and increased the ability to handle the animals in a non-stressful way.

However, animal welfare improvements were associated with high investment costs and the respondents noted that there were difficulties in measuring the pay-off from such improvements. Furthermore, the respondents did not believe that communicating with the public about the investments would increase sales. Some respondents argued that consumers, and the public in general, are not interested in the slaughter process as they live far from the reality of agriculture and food production. In addition, the respondents were not sure how they could internalise animal welfare in their economic decision-making.

Themes emerging from the focus group interviews

During interviews, we probed the respondents about aspects that they consider can contribute to both animal welfare and slaughterhouse profitability. Based on the interview material, we then identified six main themes. The respondents were asked to describe previous and planned investments in animal welfare improvements at their slaughterhouse and the expected economic effect, as well as the expected effect on animal welfare (Table S2).

Theme 1 General views on existing legislation, regulations and different standards

The respondents stated that the current animal welfare regulations can be difficult to implement and carry additional costs for slaughterhouses. One respondent highlighted the issue of transporting high-lactating cows from distant rural areas. According to the legislation (EC 2009), cows must be milked every 12 h. In practice, this may mean that the transporter cannot make any further stops on the route, and hence the transport costs increase.

The Swedish National Food Agency employs official veterinarians (OV) to monitor different aspects of the slaughter process at Swedish slaughterhouses. Individual differences in animal welfare assessment approach and thresholds between different OV inspectors have been reported (Arzoomand *et al* 2019) and were perceived by the respondents to affect the recorded level of non-compliance recorded or requests for correction, which may influence the costs. One respondent argued that the variation in OV inspectors' assessments could involve a risk of the slaughterhouse getting a bad reputation, potentially leading to a shortage of animals if farmers instead chose to deliver their animals to other slaughterhouses.

The respondents pointed out that there are different standards and certifications intended to increase animal welfare on the market and that the economic outcome for slaughterhouses can be affected by these if they comply with stated requirements and pay a membership fee. Although the intention is to increase animal welfare and encourage better decision-making by consumers at the point of purchase, some respondents claimed that the costs exceed the benefits for slaughterhouses. In addition, some farmers have their own standards that the slaughterhouse needs to take into consideration, which can complicate the slaughter process and requires increased efforts by slaughterhouse personnel.

Theme 2 Farm-level effects on animal welfare in slaughterhouses

In response to probing about the implications of animal welfare for the economic outcome for slaughterhouses, the respondents reported that animals' prior experiences in life play a crucial role in how they experience the situation at the slaughterhouse. The respondents generally believed that animals raised in extensive ranch-drift systems are more difficult to handle than those raised in intensive systems and that they display more stress on entering the slaughterhouse, probably due to limited prior contact with humans and indoor environments (Hemsworth *et al* 2011). In addition, all respondents stressed the responsibility of farmers for handling animals properly on-farm.

The respondents identified mixing of animals on-farm before transport to the slaughterhouse as a key issue for animal welfare, with animals with no prior relation to each other tending to fight and express stress-related behaviours during the transport and after arrival at the slaughterhouse. The respondents claimed this to be one of the main reasons for meat quality problems such as DFD or PSE. Another issue that several respondents pointed out was dirty animals arriving at the slaughterhouse, since this restricts the potential for hygienic slaughter. When de-hiding those animals, contamination is unavoidable and usually leads to condemnation of some or all of the carcase.

Theme 3 The role of proficient transporters

The respondents reported that proficient transporters with experience and a good understanding of animals and animal handling legislation, have a great impact on animal welfare and on the economic outcome for the slaughterhouse. Currently, no specific legislation exists regulating the loading facilities on-farm, which respondents viewed as problematic. In many cases, the same loading facilities are used for both cattle and pigs and transport drivers have to be flexible and solution-oriented when using these facilities, due to the large differences between the species. The respondents highlighted a need for optimising transport logistics but recognised that this is not always feasible. Another animal welfare-related cost mentioned by the respondents was severely sick or injured animals that have to be euthanased, either on the transport vehicle or in lairage. These animals are subject to total condemnation and cannot pass through the slaughter process, which is not only a waste of resources, ie meat and money, but also raises concerns about animal health, and thus animal welfare. This relates to the important issue of animals being fit for transport and slaughter and, not least, consumption.

Theme 4 Impact of slaughter process flow on productivity

The respondents described the workflow at slaughter as critical for productivity and for providing an acceptable work situation for slaughterhouse personnel. A good workflow is dependent on a good animal flow, which is closely linked to animal welfare. Likewise, maintaining a slaughter process speed that is adapted to the design and technical constraints of the slaughterhouse is essential. The respondents claimed that having a mechanical system for handling animals is key to achieving an even workflow. For animals with limited experience of being handled, they also claimed that an automatic driving system improves animal welfare since the human-animal interaction is reduced. One of the respondents explained that Danish slaughterhouses have different automated production lines depending on pig weight and believed that this improves animal welfare and decreases the cost of labour. Many respondents reported that one of the main reasons for frustration among personnel, as well as possible implications for the economic outcome, is unplanned disturbances in the slaughter process, eg animals

not accustomed to being handled. Thus, they believed it would most likely be beneficial for both slaughterhouse personnel and animals if the design were revised to facilitate easy driving to improve animal flow. Some of the main design features that the respondents specified were drive-race design, flooring and the overall lairage environment (eg barriers that prevent cattle from mounting each other). In addition, they believed that daily maintenance is fundamental in order to detect problems that need to be corrected.

The respondents considered overnight lairage at the slaughterhouse to be optimal for achieving an even slaughter process flow, and thus animal flow and workflow, although they were unsure about whether keeping animals in lairage overnight had positive or negative consequences for animal welfare. However, they reported that if animals can rest after transport, they are usually calmer to handle than if they are driven to the stun box immediately. One respondent reported that their slaughterhouse had a system for recording animal behaviour at night-time and that personnel with training in animal welfare visit the lairage in order to detect stressed individuals.

As mentioned, stress in animals before slaughter can lead to meat being discarded. The respondents reported that fighting in the lairage can lead to bruising, which must be removed from the carcase after stunning and de-bleeding, thus affecting the economic outcome. Several of the respondents reported greater problems with process-induced PSE in pigs (too-slow carcase cooling process) than with stress-induced PSE. Therefore, investment in new animal welfare-friendly equipment and drive-races was not expected to generate a lower prevalence of PSE carcases, although improved levels of animal welfare were expected.

Theme 5 The effect of experienced slaughterhouse personnel

The respondents emphasised that having a sufficient number of properly trained personnel is key for slaughterhouse productivity. They also claimed that the Swedish labour legislation can prevent managers from moving or removing unproductive personnel displaying negative, stressful handling behaviours to the animals before slaughter, which affects the economic outcome in several ways. Furthermore, having a safe and good working environment makes it easier to retain personnel. Some of the respondents highlighted the impact of continuous training of personnel, although the respondents did not view education on the principles of animal behaviour and methods of humane handling as a direct animal welfare improvement that might have implications for the economic outcome. However, some respondents reported that they occasionally provide standardised training sessions, and several respondents expressed an interest in further practical education in handling and slaughter techniques for their employees.

Theme 6 Importance of well-established dialogue between farmers, transporters and slaughterhouse management

To maintain an even flow of animals arriving at, and progressing through, the slaughter process, the respondents emphasised the need for slaughterhouse management to plan incoming animal deliveries with care. To do so, slaughterhouse management needs to have a well-established dialogue with the following actors:

- Farmers, who should send the correct number of animals (as pre-notified) to the slaughterhouse and, more importantly, only send animals in good condition for transport and slaughter. Animals that stay in lairage overnight also need to be in good condition.
- Transporters, who should transport healthy animals that are fit for transport. The transportation company also has a responsibility to optimise the transport route in order to be on time and maintain an even animal flow.
- Slaughterhouse personnel, who should provide information about when and where problems occur in the slaughter process, so that the right corrective measures can be taken, or future investments can be planned.

Discussion

We developed an economic model for slaughterhouses specialising in bovine and porcine slaughter processes and mapped the possible impact of animal welfare improvements on the economic consequences for the slaughterhouse business. In the economic model, we introduced animal welfare as a production factor in the production function of the model, in a similar way to other factors used in production (eg material, labour). In particular, we considered investments in animal welfare improvements as an intangible asset that contributes to the economic outcome. Previous studies have pointed out the importance of intangible assets when estimating business production functions in order to obtain consistent estimates for the inputs included (Marrocu *et al* 2012). Considering intangible assets is not standard in production economic models, but was done by Telldahl *et al* (2019) in a study estimating the impact of animal health on dairy production, which found that impaired animal health clearly resulted in loss of economic output. We validated the economic model and assessed the impacts of animal welfare improvements on the economic outcome, in two focus group interviews with slaughterhouse personnel. Thus, our formal model was tested in a qualitative framework, rather than in the econometric framework, which is the standard approach for testing economic models. We found that this exploratory setting was useful to discuss in depth: (i) how the economic systems in slaughterhouses function; and (ii) slaughterhouse personnel's perceptions on how animal welfare affects the economic outcome for the slaughterhouse. Thus, the focus group interviews functioned to validate the economic model in the study situation, where it was not possible to obtain the type of large-scale data typically used for econometric analysis.

This study adds to the existing scientific literature in the field by introducing an economic model for slaughterhouses that can be used in future research as a basis for mapping the economic impact of animal welfare and, for example, in scenario analysis of various animal welfare interventions and their economic consequences for slaughterhouses. Few previous studies have focused on the importance of animal welfare for the economic outcome at slaughter (Grandin 1995; Gallo & Huertas 2015; Wigham *et al* 2018). A common conclusion is that there are several economic consequences of impaired welfare at slaughter, eg increased labour requirements and line stoppages. However, ours is the first study to develop a model based on a profit function to describe the relationship between animal welfare and the economic outcome for slaughterhouse businesses.

In qualitative focus group interviews to validate the model, the respondents stressed the importance of profitable by-products and of continuous exploration of new areas that contribute to the economic outcome, and the magnitude of that contribution, rather than the profits obtained from selling the carcases. The quality of the carcase and by-products has a direct link to animal welfare, as physical injuries to the live animal (eg bruises and blood splashes) and stress-related meat quality problems such as PSE and DFD can be indicators of impaired welfare and generate a loss of income due to condemned meat. In the focus group responses, the main expected economic effects of improved animal welfare at slaughter were reduced labour costs due to easier handling procedures and better-constructed lairage facilities, drive-races and stun boxes, and overall enhanced productivity. The respondents confirmed that investing in animal welfare improvements, eg through redesign of the slaughterhouse interior and improving the efficiency of the slaughter line, can contribute to a positive economic outcome through reduced labour costs. The results also indicated that investing in animal welfare improvements is an essential part of the slaughterhouse business, although sometimes difficult to measure in a precise manner.

Furthermore, all slaughterhouses represented in the focus groups had invested, or were planning to invest, in animal welfare improvements, even when not legally required to do so (Table S2). New drive-race designs for both cattle and pigs were assumed to improve animal welfare by lowering stress in the animals during handling, supporting findings by Hultgren *et al* (2014). This can be expected to improve the slaughter process flow, as the flow of animals is increased, and to lower the number of staff required (Grandin 1995), thus having an expected direct effect on the economic outcome. However, the respondents reported uncertainty about measuring the economic effects in these terms. Furthermore, the effect on animal welfare could be indirect; with a workflow improved, personnel are less stressed when handling the animals, which leads to calmer handling procedures. One respondent reported that a recent animal welfare investment, involving re-design of the unloading area and improved design of the drive-race to the stunning box for cattle, had an effect on slaughterhouse profitability due to improved meat quality. This is in line with Alleweldt *et al* (2007), who found that improved meat quality could compensate for investment costs, despite slightly elevated operating costs.

Formal training of slaughterhouse personnel handling animals is currently based on theory (EC 2009), and the respondents wanted access to additional practical training in pre-slaughter handling and slaughter techniques, since this is important for the learning outcome. Several of the slaughterhouses represented already provide sporadic standardised training sessions, but the respondents in question did not see any direct link to economic output. On the other hand, they pointed out the importance of having a sufficient number of properly trained personnel as key to productivity. Other studies have indicated that training to improve animal handling could result in significant positive economic effects at slaughterhouse level, due to increased revenue from higher quality meat (Alleweldt *et al* 2007; Coleman *et al* 2012). Management therefore plays a crucial role for the slaughterhouse business (Grandin 2013). The respondents emphasised that managers need to have a well-established dialogue with slaughterhouse personnel, but also with farmers and transporters. If managers emphasise the importance of handling animals properly, generally advocate fair treatment of animals and employees, encourage training and actively seek to invest in appropriate slaughterhouse infrastructure to achieve this whenever possible, this may improve the general attitude at the slaughterhouse, hence resulting in improved animal welfare (Grandin 1995).

The respondents also highlighted the importance of farm animals' prior experiences in life. They all mentioned farmers' responsibility for handling the animals well on-farm and reported a link between stress-related behaviours from animals with no prior experiences of being handled and economic performance. Animals with previous rough handling experiences may also be more stressed when handled at the slaughterhouse compared with animals that have been handled in an animal-friendly way (Grandin 1997). The respondents mentioned difficulties with handling cattle and pigs from different rearing systems in slaughterhouse drive-race facilities. They reported that cattle reared in extensive systems are more difficult to handle than dairy cows reared in intensive systems, since they have limited experiences of, eg drive-races. Pigs reared on organic farms are reported to have more difficulty coping in crowded situations, eg during transport and in slaughterhouses, than pigs from conventional farms (Thorell & Wallenbeck 2012). Farmers also have an obligation to sort out the animals from the farm that are fit for the slaughter chain at any given point in time (transport, slaughter, processing etc). Future studies should investigate the possible relationship between animal handling, meat quality problems and economic outcome in relation to rearing system.

In addition to directly affecting product quality, impaired animal welfare at slaughter can be seen as a negative external effect of the economic activities that take place at the slaughterhouse. This holds also for poor animal welfare

at farms, according to McInerney (2004). Unless there are costs or foregone revenues associated with impaired animal welfare at slaughterhouse business level, the financial incentive to account for the negative external effects associated with poor animal welfare can be expected to be small. Therefore, the level of animal welfare provided by slaughterhouses may be lower than is desirable from a societal point of view. This means that various policy measures may be needed to incentivise investments to improve animal welfare, bearing in mind that:

• Unless slaughterhouses can find ways of increasing their revenues, they have little financial incentive to improve animal welfare beyond legal requirements. Animal welfare improvements were often associated with high investment costs and respondents reported difficulty in measuring the direct pay-off in terms of sales. Considering the investment constraints of slaughterhouses, animal welfare decisions should be discussed before new slaughterhouses are constructed or modernised. Our focus groups interviews indicated the opposite: animal welfare is not considered until after a slaughterhouse has been built or modernised.

• Investments in animal welfare improvements could be used for marketing purposes, but respondents highlighted an issue with branding investments in animal welfare due to lack of consumer and societal knowledge about the slaughter process. Interestingly, the respondents expected no increase in sales if they communicated the investments to the public. This is an obstacle for the slaughterhouse business, because if consumers do not have sufficient information they cannot contribute to an effective market solution (Lusk 2011). The literature suggests that consumers associate high food quality with higher animal welfare and are willing to pay more, especially if they are provided with information about rearing conditions of the animals and animal welfare (Napolitano *et al* 2008; Lagerkvist & Hess 2011). This raises the overall question of market failure through slaughterhouses experiencing difficulties with communicating what they are doing and how they are producing.

• Grants and investment support are one way of encouraging changes in production methods when the current market solution alone cannot promote the use of new methods. Such support could be based on compliance with several animal welfare and environmental practices, including the aspects considered in this study. From a policy perspective, there may be a need to provide a more diversified set of support payments that compensate for animal welfare costs and encourage better animal welfare directly in slaughterhouses. It is also important for slaughterhouse businesses to be transparent about their production process and to acknowledge the possibilities with branding their investments in animal welfare improvements.

There are some limitations of the study, eg we only interviewed Swedish slaughterhouse personnel working with quality assurance schemes and slaughter managers, and there was a clear division of females and males between these two positions, which demonstrates that this is a structural characteristic of the slaughterhouse sector. From a societal perspective, however, the respondents were not a representative selection of people. Future studies should therefore expand the interviews to include financial managers at slaughterhouses. Further, the study was conducted in Sweden, which has relatively strict animal welfare regulations and high animal welfare expectations from citizens and consumers. The temperate climate in Sweden creates a need for climate-controlled housing for pigs, and during a large part of the year for cattle, leading to high production costs related to housing. This has possible effects on handling and animal welfare at slaughter. Thus, the results need to be interpreted in relation to the Swedish conditions. The study includes slaughter of cattle and pigs and the situation, circumstances and relationships between animal welfare at slaughter and slaughterhouse economy may be different for other species. The slaughterhouses included in the study represented around 7% of the total Swedish slaughterhouses and varied in size from small- to large-scale. The main strength of this study was to describe the relationship between animal welfare and the economic outcome for slaughterhouse businesses.

Animal welfare implications and conclusion

This study is the first to: (i) develop an economic model to describe the impact of animal welfare at slaughter; (ii) map the possible economic effects of animal welfare improvements; and (iii) illustrate how the production function can be affected when animal welfare is improved. Focus groups' interviews revealed that the workflow in slaughterhouses is critical for productivity and that an even flow of animals improves the economic outcome, the work environment and animal welfare. To improve the process flow, the slaughterhouses invest in animal welfare improvements, eg improved drive-races and stunning equipment, which decreases pre-slaughter stress in animals and can contribute positively to the economic outcome through reduced prevalence of meat discards. We found that all slaughterhouses had invested in animal welfare improvements but had difficulties with developing methods to measure the economic effects. The slaughterhouses also found it difficult to brand their animal welfare improvements to consumers and society, due to limited possibilities for branding and marketing the (controversial) slaughter procedure. We identified a lack of motivation to internalise animal welfare in the decision-making process of the slaughterhouse business. On the other hand, we identified potential to implement different policy measures in order to exploit the economic effects of improved animal welfare. Lastly, animal-friendly handling in the slaughterhouse is vital, although focus group respondents believed that farmers play an equally vital role in handling animals on-farm, as this affects handling in the slaughterhouse. Our economic model provides a foundation for future research on the economic effects of animal welfare at slaughter and can be a useful tool for revealing the impact of animal welfare as an intangible asset, especially if complemented with animal welfare data from slaughterhouses.

Declaration of interest

The funder FORMAS has no influence on the study. The authors do not have any conflict of interest. Furthermore, the authors are neutral and objective in relation to the participating slaughterhouses.

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Unnecessary suffering during the slaughter of cattle and pigs: mapping stun quality and associations to stun-to-stick intervals

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Ensuring that animals remain unconscious and insensible until death occurs via blood loss is critical for animal welfare at slaughter. Two key factors are the rapid sticking procedure following stunning and a correct assessment of stunning efficiency. This observational study aimed to map and assess variations in stun quality among carbon dioxide (CO_2) stunned pigs and mechanically stunned cattle slaughtered under commercial conditions in Sweden. It also examined whether the duration of the stun-to-stick interval was associated with signs of consciousness. Data were collected between May 2023 and November 2024 across five pig slaughterhouses (n = 2,795 pigs) and six cattle slaughterhouses (n = 330 cattle). Stun quality was assessed based on established protocols and categorised as either good, doubt, shallow or poor. The primary findings revealed that longer stun-to-stick intervals were significantly associated with inadequate stun quality (i.e. shallow or poor stunning) and significantly increased the likelihood of re-stunning. In total, 96.1% of the pigs were adequately stunned. Notably, the proportion of pigs with inadequate stun quality ranged from 1.2 to 16.6% across slaughterhouses, with poor stunning observed in 0 to 9.1%. Re-stunning rates varied from 1.6 to 6.4%, and stun-to-stick intervals ranged from 32 to 199 s. For cattle, 92.7% of the animals were adequately stunned, with inadequate stunning ranging from 0 to 18.5%, poor stunning from 0 to 14.8%, re-stunning rates from 0 to 14.0%, and intervals between 77 and 192 s. The results indicated that intervals of less than 59 s for pigs and 99 s for cattle were associated with the lowest rates of inadequate stunning. Furthermore, the observed variation in stun quality among slaughterhouses highlights the potential for improvement in stunning practices, particularly in slaughterhouses with higher rates of stunning failures. Not all animals displaying symptoms of inadequate stunning were identified by the slaughterhouse personnel; instead, they continued along the

line, potentially conscious, which suggests critical gaps in monitoring. The correct use of stunning equipment, along with continuous training of personnel to accurately recognise signs of recovery, is crucial for protecting animals from unnecessary suffering throughout the slaughter process.

KEYWORDS

animal welfare, assessment, captive bolt stunning, cartridge, commercial slaughter, CO2 stunning, humane slaughter, pneumatic

1 Introduction

Humane slaughter of cattle (*Bos taurus)* and pigs (*Sus scrofa domesticus*) involves stunning followed by exsanguination, as mandated by Council Regulation (EC) No 1099/2009. Stunning is performed to induce unconsciousness and insensibility to pain, thereby ensuring that the animals avoid unnecessary distress prior to death (McKinstry and Anil, 2004; Terlouw et al., 2016). The subsequent exsanguination has two main objectives: to ensure death by inducing immense blood loss, and to ensure adequate meat quality. The interval between stunning and the initiation of bleeding should be kept as short as possible to prevent the risk of animals regaining consciousness and sensibility before brain death occurs due to blood loss, thereby minimising the risk of compromised animal welfare. Death is confirmed when both brain and cardiac functions have ceased (Jerlström, 2014), specifically when the respiratory and circulatory centres in the medulla oblongata are permanently inactive, and the brain is deprived of oxygen and nutrients (EFSA, 2004). Although definitions may vary, it is widely accepted that an unconscious animal is insensible and unable to perceive or respond to sensory stimuli, as its brain no longer processes sensory information (Blood and Studdert, 1988). As a result, it cannot experience pain or discomfort (Broom, 2022).

Slaughterhouses managed by Food Business Operators (FBOs) are profit-driven businesses that must maintain a consistent process flow of processed meat products according to the demands of the market, whilst simultaneously fulfilling consumer expectations for high animal welfare standards. Stunning prior to exsanguination is a crucial aspect of animal welfare at slaughter, and presents two primary challenges: 1) the potential for pain and fear during the stunning process itself, and 2) guaranteeing that the animal remains unconscious during the subsequent exsanguination procedures (Brandt and Aaslyng, 2015). The most commonly applied stunning methods for cattle and pigs in Europe include mechanical stunning with a penetrative captive bolt, electrical stunning by applying a current through the animal's head, and gas stunning, wherein animals are immersed in high carbon dioxide (CO_2) gas concentrations (EFSA, 2020a; 2020b). When performed correctly, mechanical stunning with a captive bolt results in irreversible unconsciousness, whereas electrical stunning is considered a reversible method, as the stunning effect will cease over time (EFSA, 2004). In gas stunning, the potential for irreversible stunning is related to the gas concentration and the duration of gas exposure. Stunning procedures are complex and present several challenges, as animal welfare, worker safety, product quality, and economic considerations (Jerlström et al., 2022) must all be contemplated.

Through the CO_2 stunning method, animals are exposed to an environment with high concentrations of CO_2. Following Council Regulation (EC) 1099/2009, a minimum of 80% CO_2 must be used, and the pigs must remain exposed for a duration long enough to render them unconscious. The effectiveness of CO_2-stunning in preventing animal suffering is dependent on several factors: exposure time, CO_2 concentration, the interval between stunning and sticking, and the efficiency of bleeding. The physiological principle of CO_2-stunning involves a combination of the acidification of brain cells and acute hypercapnia (high concentrations of CO_2), leading to a reduction in brain activity, decreased awareness, and ultimately unconsciousness or death (Rodríguez et al., 2008; Llonch et al., 2012; Atkinson et al., 2020). Higher CO_2 concentrations reduce the time required to achieve unconsciousness and/or death (Terlouw et al., 2016).

The principle of captive bolt stunning is to induce an immediate and irreversible loss of consciousness and sensibility in animals with a single shot. This method, frequently used among cattle, utilises a captive bolt device, usually a retractable rod, which penetrates the skull and causes substantial physical damage to the brain. Unconsciousness is achieved through shock waves generated by the bolt, which damages brain tissue, disrupts cerebral blood flow, and impairs neuronal function (Kamenik et al., 2019). The impact of the bolt specifically targets vital areas of the brain, disrupting cortical activity and increasing intracranial pressure, resulting in an immediate loss of consciousness (Terlouw et al., 2016; Terlouw and Le Neindre, 2024).

Within the EU, each FBO should define the maximum stun-to-stick intervals applicable at each separate slaughterhouse in their standard operating procedures (SOPs) (Council Regulation (EC) 1099/2009, 200), with the starting point being the generally accepted maximum duration of 60 s for pigs stunned with CO_2 gas and cattle stunned mechanically (Holst, 2001; EFSA, 2004; European Commission, 2017). However, many slaughterhouses struggle to meet this standard due to the technical design of their

systems, including the layout of the shackle line and the slaughter process speed. When mechanical stunning and sticking procedures are performed correctly, extended stun-to-stick intervals (i.e., longer than 60 s) do not necessarily risk animal welfare (Atkinson and Algers, 2007). However, only a few studies have focused on how stun quality is affected by increased stun-to-stick intervals, possibly because of the ethical and practical challenges of conducting such research.

To regularly monitor and evaluate indicators of consciousness, unconsciousness, and the risk of recovery, it is essential to ensure that animals do not display signs of sensibility from the end of the stunning process until death (Council Regulation (EC) 1099/2009). Such monitoring (Gregory and Shaw, 2000) is vital to prevent unnecessary suffering, including pain, distress, or prolonged discomfort caused by ineffective stunning. Stun quality assessment includes verification that equipment and stunning methods are effective and close observation of physical signs such as behavioural indicators related to consciousness or residual brain function (Levitis et al., 2009). If there are indications that an animal is inadequately stunned, or that the animal is about to regain consciousness or sensibility, immediate and rapid corrective measures, such as re-stunning, must be taken without delay (Verhoeven et al., 2014; SJVFS, 2019:8; Algers and Berg, 2022; Terlouw and Le Neindre, 2024).

Gregory et al. (1987); EFSA (2020a; 2020b), and Welfare Quality ® (2009) provide guidelines for assessing stun quality, including indicators such as an absence of corneal reflex, righting reflex, rhythmic breathing, and vocalisations. Other useful indicators include eyeball rotation, pain responses (e.g., pricking the snout or muzzle), and spontaneous blinking (EFSA, 2004; 2013a; 2013b; Grandin, 2013). However, certain indicators, e.g., gasping in pigs, defined as short, abrupt gasps of air, leave room for interpretation. Atkinson et al. (2012) demonstrated that gasping is an important indicator of insufficient stunning in pigs, and that the most frequent combination of symptoms was corneal reflex and regular gasping. Other studies consider gasping to be more of a rudimentary brainstem reflex (Raj, 1999) and a symptom of the dying process (Grandin, 2010).

In a Swedish study where stun quality was assessed among 998 cattle, most animals were stuck between 84 and 125 s after stunning. In total, 84.1% were adequately stunned, 12.5% were inadequately stunned, and 3.3% were categorised with an uncertain stun quality (Atkinson et al., 2013). A similar study examining 9,520 pigs revealed that slaughterhouses using a paternoster CO_2 gas stunning system generated a better stun quality compared to those using dip-lift systems (99.9% compared with 98.2%), and that stun-to-stick intervals reaching up to 100 s, when pigs were stunned in paternoster systems, did not risk animal welfare (Atkinson et al., 2012). However, the stun-to-stick interval must be adjusted according to the technical parameters (e.g., gas concentration or suitable cartridge strength) of the stunning method and its efficacy (EFSA, 2020a; 2020b).

Against this background, this study aimed to map and assess variations in stun quality in CO_2-stunned pigs and mechanically stunned cattle under commercial slaughter conditions. It also aimed to examine how prolonged stun-to-stick intervals may be associated with an increased risk of animals regaining consciousness, potentially leading to unnecessary suffering and compromised welfare.

2 Materials and methods

This observational study was conducted with the approval of the Swedish Animal Research Ethics Committee in Gothenburg in compliance with Swedish regulations (SJVFS 2019/9). In total, 2,795 finishing pigs from seven slaughterhouse visits (five slaughterhouses, with two necessary additional visits) and 330 cattle from six slaughterhouse visits (six slaughterhouses) were assessed between May 2023 and November 2024. The assessments were conducted at medium- and large-scale slaughter facilities (ranging from approximately 300-1,700 pigs or 31–210 cattle slaughtered per day) during routine slaughter operations. The number of animals assessed on each observation day varied depending on the slaughter speed and capacity of the facility, ranging between 17 and 93% of pigs and 8 and 94% of cattle slaughtered at the facility on the observation day. Observations were carried out for one to three days per slaughterhouse, but not always on consecutive days. The same observer with extensive experience in animal welfare at slaughter and expertise in evaluating stunning effectiveness performed all assessments. During each assessment round, the stun-to-stick interval, along with the clinical signs of unconsciousness and consciousness exhibited by the animals after stunning, were recorded. Only limited information on the involved slaughter facilities could be provided to maintain confidentiality.

2.1 Pigs

A total of 2,795 finishing pigs reared in commercial herds of halothane-negative hybrids of commercial breeds (originating from Topig Norsvin, Danavl, Scan Sverige) were assessed during routine stunning at five slaughterhouses with medium to large-scale processing rates. In accordance with EU legislation, the slaughterhouses used a standard stunning method involving a combination of gas concentration and exposure time that did not cause immediate death; thus, the pigs were ultimately killed by exsanguination. Three slaughterhouses were assessed once, whilst two were assessed on two occasions, following adjustments in CO_2-stunning parameters and slaughter routines. Recording at each assessment lasted between one to two days. In Sweden, finishing pigs are typically slaughtered at around five to six months of age, at a live weight of 120 kg. Pigs were stunned in groups, with different people operating the shackling and sticking, usually one person at each station. The total number of observations from each assessment occasion was as follows: 513, 168, 184, 379, 503, 513, and 514.

2.1.1 Stunning procedure and system settings

At each of the involved slaughterhouses, groups of pigs were placed within a cage that was lowered into a CO_2-filled pit. Two primary systems were used: the dip-lift system and the paternoster system. In the dip-lift system, a cage containing up to eight pigs was lowered into a pit at a depth of two to four metres, where pigs were exposed to the highest CO_2 concentration at the bottom, as CO_2 is a heavy gas (Figure 1). In the paternoster system, up to seven rotating cages, each carrying two to seven pigs depending on the model, moved through a CO_2 gradient in a pit three to eight metres deep (Figure 2). Live pigs were loaded at one end of the system, whilst unconscious pigs were unloaded for sticking at the other end. In this study, three slaughterhouses used the Butina® paternoster stunning system, and two used the Butina® dip-lift stunning system.

The CO_2 stunning systems included in this observational study operated under different gas concentrations, temperatures, and durations. Each slaughterhouse had adjusted parameters such as the number of pigs per cage, the time required to reach peak CO_2 levels, temperature, and the total exposure time based on operational requirements and the FBOs SOPs. These parameters were digitally recorded within the system, as regulated by EU Regulation 1099/2009, and provided to the research team by the FBO after each occasion. Group sizes in the cages were recorded by counting the number of pigs in each group as they fell out of the cage but are not presented here to maintain confidentiality. Data on CO_2 concentration and temperature were collected on 11 of 13 observation days, and exposure time data were collected on seven of 13 observation days. At one slaughterhouse, the system did not record CO_2 temperature, but this was resolved by installing a portable temperature meter. Furthermore, double-edged sticking knives with blade lengths ranging from 16 to 21 cm were used in all five slaughterhouses.

2.1.2 Stun-to-stick intervals

Stun-to-stick intervals were recorded individually using a stopwatch. Due to practical reasons, recordings were performed on only the last four pigs if the group size reached seven or eight. Stunning ceased when the cage stopped just before the gate was opened to empty the pigs onto the shackling table. In addition, the FBOs measured where the pigs passed the level of less than 80% CO_2 concentration, and this interval was added to the total stun-stick time. Among all pigs, bleeding was initiated through chest sticking, a procedure that involves severing major thoracic blood vessels (Figure 3). The time point at which the knife was inserted into the chest was used to define the end of the stun-to-stick interval.

2.1.3 Stun quality assessment

Stun quality was assessed by observing pigs for physical symptoms indicative of consciousness or risk of recovery from unconsciousness, following protocols developed in previous studies by Atkinson et al. (2012). These protocols have been proven as reliable and effective in identifying inadequate stun quality, using a five-level classification system. However, in the present study, the levels were modified to four levels, designated as “good”, “doubt”, “shallow”, and “poor” (Table 1). For statistical analysis, the stun quality levels were further pooled. Stun quality level 1 categorised deviations in stun quality into two classes: (1) good and doubt, and

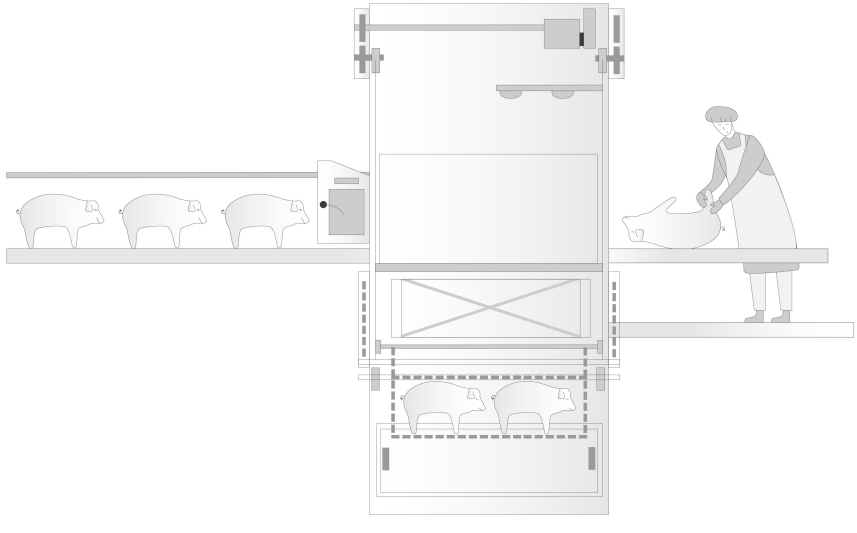

FIGURE 1
Illustration of a dip-lift system for stunning pigs with CO_2. The system contains one cage, with a capacity of between two and eight finishing pigs.

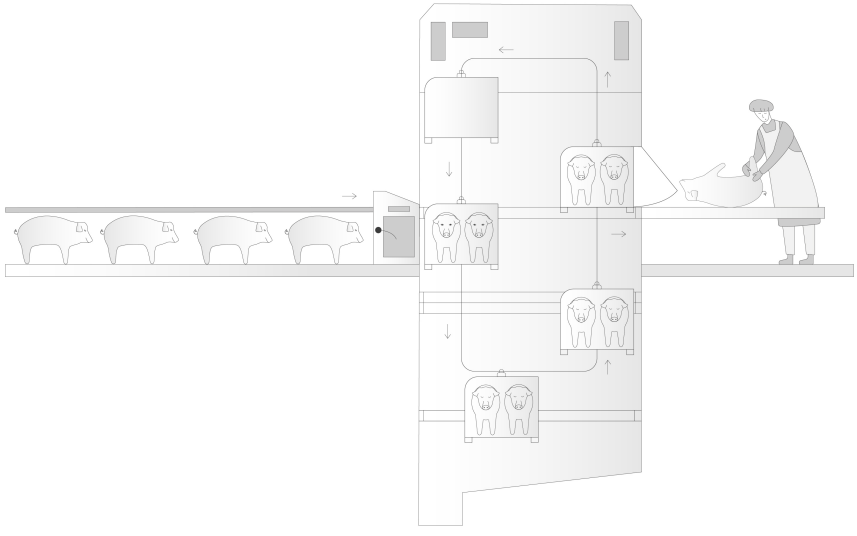

FIGURE 2
Illustration of a paternoster system for stunning pigs with CO_2. The system usually contains between four and seven cages, each with a capacity of between four and eight finishing pigs.

(2) shallow and poor. Stun quality level 2 targeted severe deviations, which also had two classes: (1) good, doubt, and shallow, and (2) poor (Table 2).

The corneal reflex, tested by carefully touching the corneal area of the eye with a fingertip, was intended to be tested on all pigs prior to sticking. However, this was not feasible for all animals. If pigs displayed symptoms of ineffective stunning, the corneal reflex was tested again, when possible. A blink response (fast or slow) was recorded as a positive corneal reflex. The pain reflex was assessed on a randomised subset of animals, typically all observed pigs in every fifth or sixth group of stunned pigs, depending on group size, by pricking the snout with the sharp point of a metal stick. A withdrawal response was recorded as a positive pain reflex. Stun quality was continuously assessed until two minutes after sticking. If the group size was seven or eight, observations were performed on the last four pigs in the group due to practical reasons.

2.2 Cattle

A total of 330 cattle were observed during routine stunning procedures at six Swedish slaughterhouses with medium- to large-scale processing capacities, over one to three days per site. At these slaughterhouses, observations were made on 38, 44, 57, 60, 62, and 69 cattle, respectively. The examined animals consisted of 183 females (125 cows and 58 heifers) and 147 males (114 young and mature bulls and 33 steers). The animals were further categorised into dairy breeds and beef and/or crossbreeds, with a distribution of 47.0% dairy breeds and 53.0% beef and/or crossbreeds. Information regarding age and carcass weight of the selected animals was obtained from the FBOs, but the sex and breed type were registered at the time of slaughter (Table 3).

2.2.1 Stunning procedure

Cattle were stunned individually in stun boxes with or without head restraint equipment. The shooter was generally not the same person who shackled and bled the animal, but this varied between FBOs. There were two types of pneumatic stunners and six types of cartridge-driven captive bolts (varying in calibre, bolt velocity, kinetic energy, bolt length, and diameter) used in the observed stunning events in this study. Five of the cartridge-driven captive bolts were.25 calibre, and one was.27 calibre. The length of these bolts varied between 65–95 mm, and the diameter ranged from 11.4 to 12 mm. The bolts of the two pneumatic stunners were 85 mm long, with diameters of 15.2 and 15.9 mm. Gun type was nested within the slaughterhouse, together with sample sizes that were too small for each gun type; therefore, no further statistical analysis of gun type effects was performed. Furthermore, the types of knives used for bleeding varied among the slaughterhouses. Single-edged sticking knives were used in four of the six slaughterhouses, with blade lengths ranging from 14.5 to 21 cm.

2.2.2 Shot accuracy

The application spot of the gun (shot accuracy and angle) was recorded on each animal's skull following decapitation. Proper shot precision is ensured by targeting the point where two imaginary

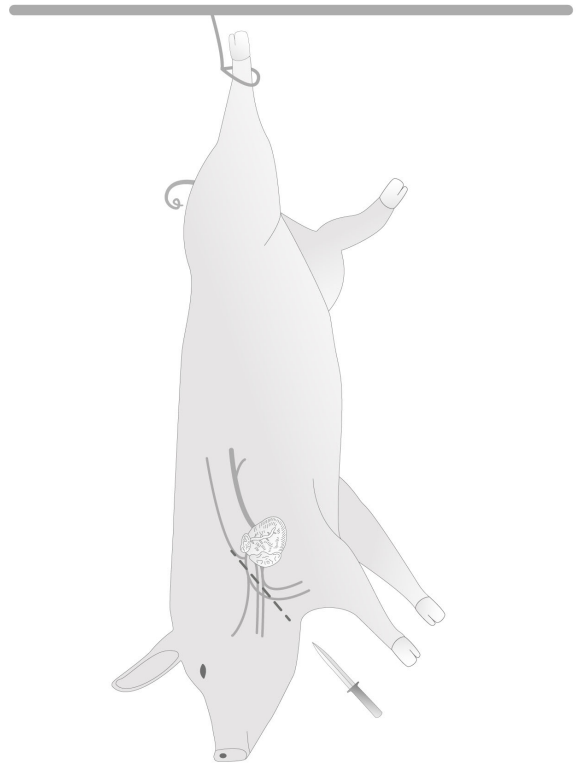

FIGURE 3
The recommended position of exsanguination for pigs with chest stick.

lines, drawn from the base of the horns to the opposite eye, intersect (Figure 4). The shot should occur no more than two cm from this ideal point (EFSA, 2004). If the shot hole was more than two cm outside the target area in any direction, it was considered inaccurate. If the angle of the shot deviated more than 20 degrees from the recommended perpendicular angle to the skull bone, it was recorded as a deviated angle (Figure 5).

2.2.3 Stun-to-stick intervals

The stun-to-stick interval was recorded using a stopwatch, timed from when the shot was heard or seen to when the knife was inserted into the chest to sever the large blood vessels in the thoracic cavity (Figure 6). Registrations were made on the type of cattle shot, i.e., dairy, beef, or crossbreed; sex (young bull, mature bull, cow, heifer, steer), the number of times the animal was shot, and the duration of the shots and re-shots. The type of captive bolt used (pneumatic or cartridge-driven) was also documented, with technical parameters provided by the FBOs, as well as the type of knives used for exsanguination.

2.2.4 Stun quality assessment

Signs of successful stunning include motor paralysis and immediate collapse within the stunning box, with no observable signs of corneal reflex, response to painful stimuli, attempts to regain an upright posture, vocalisation, or rhythmic breathing (Atkinson et al., 2013; EFSA, 2013a; 2013b; Grandin, 2013; Večerek et al., 2021). Additional indicators, such as tongue tension, could be used as complementary measures but cannot be relied upon as sole indicators of unconsciousness (Von Holleben et al., 2010).

Based on a stun quality protocol developed by Atkinson et al. (2013), stun quality was assessed and categorised into stun quality levels from the time of stunning until two minutes after sticking (Table 4). The protocol used in Atkinson's study was proven to be both feasible and effective in differentiating animals that exhibit high-risk signs of recovery and compromised animal welfare from those in moderate- and low-risk categories, using four levels of stun quality. In this study, we refer to the different levels as good, doubt, shallow, and poor. For statistical analysis, the stun quality levels

TABLE 1 Criteria used to classify the stun quality of CO_2 stunning of pigs from stunning until two minutes after sticking (summarised from Atkinson et al., 2012).

Stun quality	Criteria	Examples of signs
Good	The animal is in a state of deep unconsciousness and adequately stunned, and there is no risk of poor animal welfare.	No evidence of rhythmic breathing, righting reflex, vocalisation, convulsion, blinking and/or eye responses to stimulation.
Doubt	If shown, the animal is considered adequately stunned but requires continual monitoring.	Irregular kicks (or other movements), irregular gasps, but no eye reflexes.
Shallow	The stun depth is considered unacceptable due to the risk that the animal could recover. Re-stunning is necessary as a precaution to avoid recovery of consciousness.	Regular gasps, kicks, or body convulsions, but no eye reflexes.
Poor	The stun depth is inadequate, and the recovery risk is considered imminent. The criteria indicate some form of consciousness and a high risk for poor welfare. Immediate re-stunning is necessary.	Positive corneal reflex at sticking, with or without kicking or convulsions, spontaneous blinking, righting reflex, vocalisation, and/or positive pain reflex.

were further pooled in the same manner described for the pigs (Table 5).

A similar assessment to the one described for pigs involving the testing of corneal and pain reflexes was conducted on cattle. However, the selection of animals for the pain reflex test was based on how they landed after exiting the stun box; specifically, animals that had their heads positioned against the stun box were not tested, as it was not practically feasible to access them safely in that position.

2.3 Statistical analysis

Data editing and descriptive statistical analyses were performed with Excel 2016 (Microsoft Corp., Redmond, Washington, DC, USA). Statistical analyses were conducted using SAS Software (version 9.4 of the SAS system, SAS Institute Inc., Cary, NC, USA). The statistical unit for analysis was the individual animal (cattle or pigs). For cattle, a total of 309 observations (stun quality 1 and 2) and 315 observations (for the occurrence of re-stunning) were included in the statistical analysis. The corresponding observations for pigs were 2,775. Exclusion of observations was due to incompleteness.

Effects of stun to stick interval on the pooled categories stun quality 1 [good/doubt vs. shallow/poor], stun quality 2 [good/doubt/shallow vs. poor], and the occurrence of re-stunning [yes vs. no] was assessed with generalised linear models using the GLIMMIX procedure in SAS, applying a binomial distribution and a logit link function. Models were developed using a stepwise-backward selection of predictor effects, where non-significant effects and interactions were removed from the model. The final models for pigs (model 1) and cattle (model 2) are presented below.

Model 1:

$$y = Stun-to-stick\ interval + Type\ of\ stunning\ system + Slaughterhouse\ visit\ (Type\ of\ stunning\ system) + Observation\ day + e$$

where y is the binomial response variable being assessed (stun quality 1, stun quality 2, re-stunning), the stun-to-stick interval (s) was included as a covariate, and the type of stunning system (Paternoster/Dip-lift, 2 classes), slaughterhouse visit nested within stunning system (1-7, 7 classes), and observation day (1/2, 2 classes) included as fixed control class effects, and e represents a random error term to account for unexplained variability. Observation day was included to account for variations between different observation days.

Model 2:

$$y = Stun-to-stick\ interval + Age + Slaughterhouse\ visit + Shot\ accuracy + Sex + Breed\ type + e$$

where y is the binomial response variable assessed (stun quality 1, stun quality 2, re-stunning), the stun-to-stick interval (s) and age were included as covariates, and slaughterhouse visit (1-6, 6 classes), shot accuracy (Yes/No, 2 classes), sex (Female [cow and heifer]/Male [young bull, mature bull, steer], 2 classes), and breed type (Dairy/Beef [beef and crossbreed], 2 classes) included as fixed class control effects, and e represents a random error term to account for unexplained variability.

TABLE 2 Distribution across the four levels of stun quality, frequency of re-stunning, and the pooled categories stun quality 1 and 2, in pig observations.

Stun quality	Number of animals (%)	Number of re-stuns (%)	Stun quality 1 (deviations in stun quality)	Stun quality 2 (severe deviations in stun quality)
Good	2,647 (94.7)	2 (1.8)	2,686 (96.1)	2,753 (98.5)
Doubt	39 (1.4)	12 (10.6)		
Shallow	67 (2.4)	58 (51.3)	109 (3.9)	
Poor	42 (1.5)	41 (36.2)		42 (1.5)
Total	2,795	113 (4.0)	2,795	2,795

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TABLE 3 Distribution of carcass weight (kg) and age (months) among the studied animals.

Cattle category	N	Mean (± SD) carcass weight (kg)	Range (kg)	Mean (± SD) age (months)	Range (months)
Cows and heifers	183	314 (± 68.7)	166-514	51 (± 30.4)	13-175
Bulls (both young and mature)	114	353 (± 72.2)	240-643	20 (± 15.3)	11-128
Steers	33	337 (± 49.5)	240-415	25 (± 3.8)	18-34

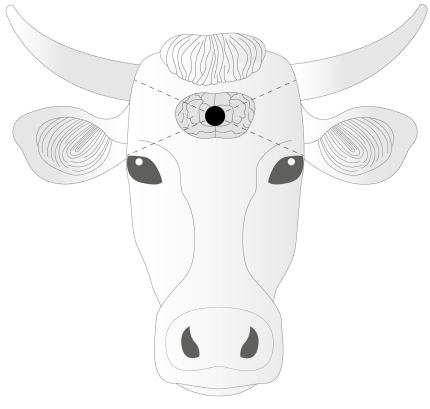

FIGURE 4
Optimal shot placement of the captive bolt. Shot holes outside this area (two cm radius) were recorded as inaccurate.

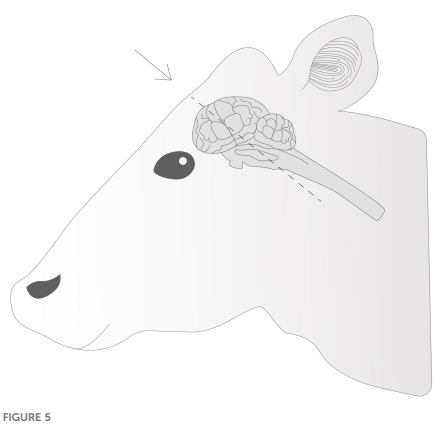

FIGURE 5
Optimum, perpendicular, shot angle. If this deviated by more than 20 degrees, it was recorded as inaccurate.

3 Results

3.1 Pigs

In the groups of observed pigs, the group size within the stunning system ranged from four to eight (5.3 ± 1.6). The CO_2 concentration settings ranged from 89 to 94%, and the minimum and maximum values of the actual CO_2 concentration on the observation days ranged from 85 to 92.9% and 87 to 95.1%, respectively. On 11 of 13 observation days, the actual CO_2 concentrations were below the system's set points, with five slaughterhouses containing average CO_2 concentrations below their respective set points. According to the SOPs of three slaughterhouses, the temperature settings should be between 15 and 20°C, and for two slaughterhouses, the range should be between 15 and 25°C. The observed CO_2 temperatures ranged from 14.1 to 25.2°C, and 15.6 to 25.2°C, respectively, on the days of observation, with actual temperatures falling below the set levels on one day of observation and exceeding them on three days of observation. Exposure times to CO_2 concentrations greater than 80% were set between 140 and 169 s. The average actual exposure times during the observation days ranged from 151.5 to 190 s and 150 to 183 s, respectively.

3.1.1 Stun-to-stick intervals

The average stun-to-stick interval was 90 s (± 21.5 SD), ranging from 32 to 199 s (Q1 = 74, Q3 = 107 s). A total of 113 pigs (4.0%) were re-stunned. Most of the animals, 1,760 (63.0%), were stunned in the paternoster systems, whilst 1,035 (37.0%) were stunned in the dip-lift system.

3.1.2 Stun quality and the impact of stun-to-stick intervals on stun quality

Of the 2,795 pigs, 96.1% were adequately stunned, i.e. there were no deviations in stun quality. Inadequate stunning was observed among 3.9% of the animals, with 2.4% displaying signs of shallow stunning and 1.5% showing symptoms of poor stun quality (Table 2). The percentage of pigs demonstrating deviations in stun quality (stun quality 1) varied between slaughterhouses, ranging from 1.2 to 16.6%. Severe deviations in stun quality (stun quality 2) ranged from 0 to 9.1%. Additionally, the percentage of pigs that were re-stunned varied between slaughterhouses from 1.6 to 6.4%.

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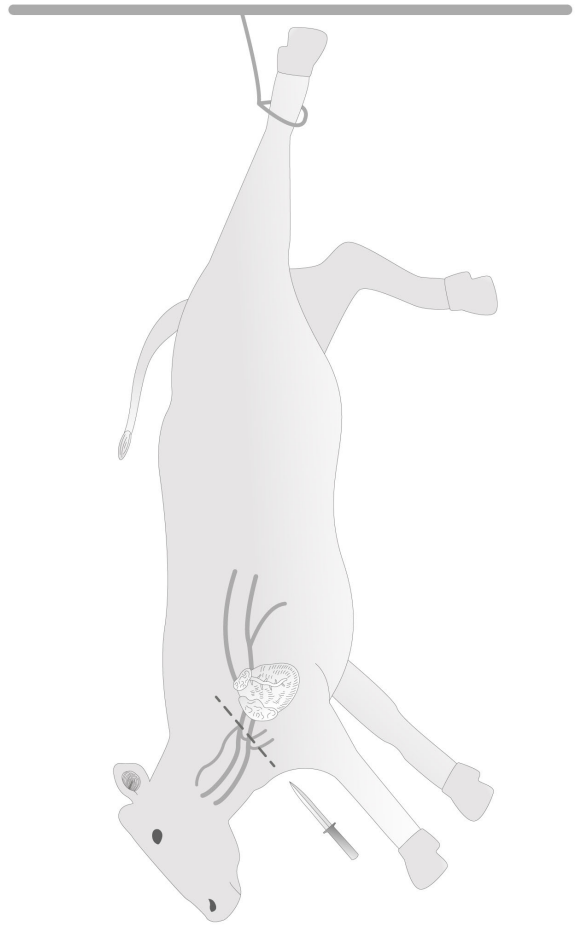

FIGURE 6
The recommended position of exsanguination for cattle with chest stick.

Corneal reflex was tested on a total of 2,767 pigs (missing 28 observations) either before or in close connection to sticking. Pain reflex was assessed on a subset of pigs, typically every fifth or sixth group of stunned pigs, depending on group size and slaughter process speed, resulting in a total of 1,093 pigs (missing 1,702 observations), with one (0.1%) having a positive response.

The two most frequently observed indicators of inadequate stun quality were regular gasping (n=104, 3.72%) and positive corneal reflex (n=42, 1.52%). Other observed indicators included irregular gasping (n=33, 1.18%), irregular kicking (n=11, 0.39%), regular kicking (n=2, 0.07%), rhythmic breathing (n=1, 0.04%), and convulsions (n=1, 0.04%). Vocalisation, spontaneous blinking, nystagmus, eyeball rotation, and righting reflex were never observed throughout the study. Further, a positive corneal reflex was detected in 37 (35.56%) of the pigs that demonstrated regular gasping and six (18.18%) with irregular gasping.

3.1.2.1 Impact of stun-to-stick intervals on stun quality and re-stunning

The stun-to-stick interval had a significant effect on deviations in stun quality (stun quality 1: b=0.046, F=57.52, p<0.001), indicating that increased intervals are related to an increased proportion of pigs with shallow or poor stun quality. There was also a significant effect of stun-to-stick interval on the proportion of pigs with severe deviations in stun quality, i.e., poorly stunned (stun quality 2: b=0.053, F=29.32, p<0.001). Additionally, the stun-to-

TABLE 4 Criteria used to classify the stun quality of captive-bolt stunning of cattle from stunning until two minutes after sticking (summarised from Atkinson et al., 2013).

Stun quality	Criteria	Examples of signs
Good	The animal is deeply stunned, and there is no concern of recovery or reduced animal welfare.	Immediate collapse, no attempt to get up, eyes open and not moving, pupils completely dilated.
Doubt	If shown, the animal is considered adequately stunned but closely monitored and tested for reflexes.	The tongue is retained in the mouth, excessive kicking with the limbs that produces a danger to the operator.
Shallow	Inadequately stunned, but with a moderate recovery risk and compromised animal welfare. Re-stunning is necessary to eliminate recovery risk.	Nystagmus, characterised by side-to-side eye movements, eyeball rotation where the sclera is predominantly visible with minimal or no iris observed 40 s after stunning, gasping for air.
Poor	Inadequately stunned, with the highest risk of recovery and compromised animal welfare. Immediate re-stunning is required to prevent suffering.	No collapse, rhythmic breathing, positive corneal reflex, positive pain reflex (if possible to assess), spontaneous blinking, vocalisation.

stick interval had a significant effect on the proportion of re-stunned pigs (b=0.045, F=56.90, p<0.001), indicating that an increased stun-to-stick interval is related to a higher likelihood of re-stunning (Figure 7).

3.1.2.2 Impact of control factors on stun quality and re-stunning

The type of stunning system significantly affected the proportion of pigs with observed deviations in stun quality (F=59.40, p<0.001), indicating that a higher proportion of pigs stunned in paternoster systems had shallow or poor stun quality compared to those stunned in dip-lift systems. There was no significant effect regarding the type of stunning system used on the proportion of pigs with severe deviations in stun quality, i.e., poor stun quality. However, the type of stunning system had a significant effect on the proportion of pigs that were re-stunned (F=53.70, p<0.001), indicating that a higher proportion of pigs stunned in paternoster systems were re-stunned, compared to pigs stunned in a dip-lift system.

3.2 Cattle

3.2.1 Shot accuracy

Inaccurate shots, i.e., shots outside the target area (Figure 4), occurred in 74 (23.4%) of the observations (N=316). Of these, 11 animals were re-shot. Eight of the animals that were accurately shot (n=242) were re-shot. In total, 16 of the accurately shot cattle were inadequately or shallowly stunned. Inaccurately shot cattle were inadequately or shallowly stunned in seven of the observations. Shots below the target area were more common than shots above the target area (76.4% vs. 15.3%), with 8.3% of shots placed to the right or left.

Deviation in shooting angle (i.e., more than 20 degrees from the recommendation of 90 degrees, Figure 4) occurred in 78 (22.8%) of cattle (N=325). Of these, 10 animals were re-shot. Of the cattle shot with a correct shooting angle (n=247), six animals were re-shot. Three of the re-shot animals' skull observations could not be completed.

3.2.2 Stun-to-stick intervals

The average stun-to-stick interval was 106 s (± 15.6 SD), ranging from 77 to 192 s (Q1 = 90, Q3 = 118 s). A total of 19 cattle (5.6%) were re-shot. Most of the animals, 232 (70.3%), were stunned with cartridge-driven captive bolts, whilst 98 (29.7%) were stunned with pneumatically powered penetrating captive bolt guns. Among the 19 re-stunned animals, 16 were initially shot with cartridge-driven captive bolts, and three with pneumatic stunners.

3.2.3 Stun quality and the impact of stun-to-stick intervals on stun quality

Of the 330 cattle, 92.7% were adequately stunned. Among these, 31.9% exhibited doubtful symptoms, such as tongue tension or intense kicking in response to shackling or sticking. Shallow or poor stunning (stun quality 1) was observed in 7.3% of the animals, with 1.8% displaying signs of shallow stunning and 5.6% showing symptoms of poor stunning (Table 5). The percentage of animals demonstrating inadequate stun quality (stun quality 1) varied between slaughterhouses, ranging from 0 to 18.5%. The proportion of animals with severe deviations in stun quality, i.e. poor stun quality (stun quality 2) ranged from 0 to 14.8%. Additionally, the percentage of animals that were re-stunned varied between slaughterhouses ranging from 0 to 14.0%.

TABLE 5 Distribution across the four levels of stun quality, frequency of re-shots, and the pooled categories stun quality 1 and 2, in observations of cattle.

Stun quality	Number of animals (%)	Number of re-shots (%)	Stun quality 1 (deviations in stun quality)	Stun quality 2 (severe deviations in stun quality)
Good	201 (60.8)	6 (31.6)	306 (92.7)	312 (94.5)
Doubt	105 (31.9)	2 (10.5)		
Shallow	6 (1.8)	2 (10.5)	24 (7.3)	
Poor	18 (5.6)	9 (47.4)		18 (5.5)
Total	330	19 (5.6)	330	330

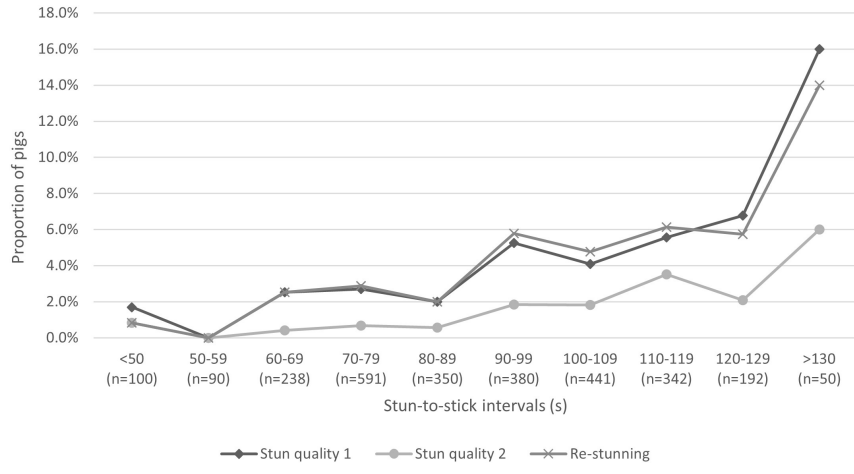

FIGURE 7
Descriptive statistics of the proportion of pigs (%) with deviations in stun quality (stun quality 1), severe deviations in stun quality (stun quality 2), and re-stunning (n=2,774).

Of the 144 male cattle, 12 out of 106 young bulls, one out of six mature bulls, and three out of 32 steers exhibited symptoms of inadequate stun quality, compared to the 179 female cattle, where the corresponding numbers were five out of 122 cows and one out of 57 heifers. In total, 16 of 144 (11.1%) male cattle and six of 179 (3.4%) female cattle showed symptoms of inadequate stun quality. Seven observations were missing due to incomplete registrations.

The two most frequently observed indicators within the stun quality category doubt were tongue tension (n=92, 28.13%) and excessive kicking in response to shackling or bleeding (n=36, 10.94%). Other observed indicators included righting reflex (n=12, 3.65%), eyeball rotation (n=7, 2.12%), positive corneal reflex (n=5, 1.52%), no loss of the standing posture (n=4, 1.21%), rhythmic breathing (n=4, 1.21%), blinking (n=2, 0.61%), and nystagmus (n=1, 0.30%). Vocalisation was never observed. Pain reflex was assessed in 77 cattle, all of which produced a negative response. The corneal reflex was tested on all animals before or in connection with sticking.

3.2.3.1 Impact of stun-to-stick intervals on stun quality and re-stunning

The stun-to-stick interval had a significant effect on the proportion of cattle with deviations in stun quality (stun quality 1: b=0.035, F=4.00, p=0.047), indicating that increased intervals are related to a slight increase in the proportion of cattle with shallow or poor stun quality. There was no significant effect of stun-to-stick interval on the proportion of cattle with severe deviations in stun quality. Moreover, the stun-to-stick interval had a significant effect on the proportion of re-shot cattle (b=0.050, F=6.53, p=0.011), indicating that an increased stun-to-stick interval is related to a higher proportion of re-stunned cattle (Figure 8).

3.2.3.2 Impact of control factors on stun quality and re-stunning

There was no significant effect of inaccurate shot placement on either the proportion of cattle with deviations in stun quality, i.e., shallow or poor stun quality, or the proportion of cattle with severe deviations in stun quality, i.e., poor stun quality. However, shot accuracy had a significant effect on the likelihood of cattle being re-stunned (F=7.64, p=0.006), indicating that a shot placed outside the optimal shot placement increased the proportion of re-stunned cattle, compared to a shot in the optimal target area. The sex of the animal (cow/heifer or bull/steer) had a significant effect on the proportion of cattle with deviations in stun quality (stun quality 1: F=6.39, p=0.012) and severe deviations in stun quality (stun quality 2: F=4.05, p=0.045), indicating that a higher proportion of bulls and steers were inadequately stunned compared to cows and heifers. However, sex had no significant effect on the likelihood of cattle being re-stunned. Furthermore, the breed of the animal (dairy or beef/crossbreed) did not have a significant effect on the proportion of cattle with deviations in stun quality, severe deviations in stun quality, or the likelihood of being re-stunned.

4 Discussion

The purpose of pre-slaughter stunning is to induce unconsciousness, thereby minimising pain and distress throughout the slaughter process (McKinstry and Anil, 2004). Guidelines have been established to assess the effectiveness of stunning (EFSA, 2020a; 2020b) with the aim of reducing unnecessary suffering at slaughter. In this study, we mapped and assessed variations in stun quality across five pig slaughterhouses,

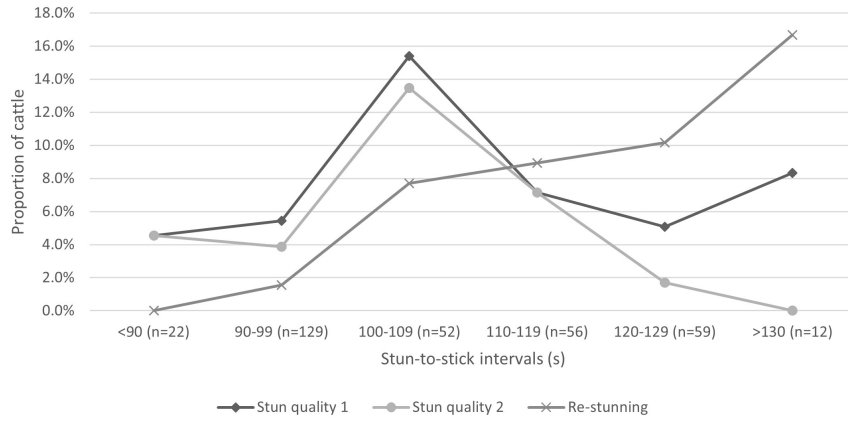

FIGURE 8
Descriptive statistics of the proportion of cattle (%) with deviations in stun quality (stun quality 1), severe deviations in stun quality (stun quality 2), and re-stunning (n=330).

two of which were visited twice (n = 2,795), and six cattle slaughterhouses (n = 330) in Sweden. We also sought to examine whether the duration of the stun-to-stick interval was associated with animals showing signs of consciousness during slaughter.

Our findings show that longer duration in the stun-to-stick intervals increased the risk of inadequate stunning, i.e., deviations in stun quality, in both CO_2-stunned pigs and mechanically stunned cattle. For pigs, the highest proportion of adequately stunned pigs, i.e., those without deviations in stun quality, was when the sticking time was between 50 and 59 s, whilst the highest proportion of inadequately stunned pigs, i.e., those with deviations in stun quality, occurred when the time to bleeding exceeded 130 s. Interestingly, stun-to-stick intervals of 90 to 99 s resulted in nearly double proportions of pigs with deviations in stun quality (shallow or poor) compared to 60 to 69 s intervals, supporting current recommendations to bleed pigs within 60 s (Figure 7). Regarding cattle, the proportion of animals with inadequate stun quality distinctly increased as the time between stunning and sticking increased. The highest proportion of adequately stunned cattle was found when sticking occurred within less than 90 s, whilst the proportion of inadequately stunned animals peaked between 100 and 109 s. A near-linear increase in the likelihood of re-stunning was observed as the time to sticking increased (Figure 8). This may indicate that increased intervals provide operators more time to assess animals, potentially increasing both caution and uncertainty in interpreting symptoms of poor stun quality. Additionally, we observed inconsistencies in re-stunning practices, as some cattle showing signs of inadequate stun quality were not re-stunned, particularly when the stun-to-stick interval was below 110 s. Conversely, certain animals lacking any clear signs of inadequate stunning were re-stunned, notably when stun-to-stick intervals exceeded 110 s. This inconsistency suggests a lack of standardised assessment criteria (and implemented SOPs) among slaughter personnel, highlighting the need for clearer guidelines, more elaborate SOPs, improved compliance with these, and improved and possibly repeated training (EFSA, 2020a; 2020b). Also, in the context of animal welfare, it is important to note that even when re-stunning is carried out promptly, animals may have already regained partial consciousness, thus been exposed to pain or distress (Terlouw et al., 2016), before re-stunning occurs.

4.1 Stunning efficiency for pigs

Among pigs, the results indicate that, on average, 3.9% of the animals showed signs of shallow or poor stunning, with 1.5% of pigs classified with poor stun quality, implying a high risk of recovery from unconsciousness or insufficient stun quality from the beginning. The variation in the proportion of poorly stunned pigs across the seven slaughterhouse visits ranged from 1.2 to 16.6%, including the two slaughterhouses that required additional visits due to equipment failures and issues with the implementation of SOPs. Although EFSA (2004) considered up to 5% of pigs with corneal reflex at the time of sticking to be acceptable, more recent research suggests that this threshold may be too high. Indeed, von Wenzlawowicz et al. (2012) reported a substantial variation in stunning effectiveness across slaughterhouses, and similar to our study's findings, they reported 1.8% of pigs with insufficient stunning, a finding consistent with Atkinson et al. (2012), who observed positive corneal reflex in 2.6% of pigs. Relying solely on fixed thresholds imposes risks of overlooking important contextual factors. A more comprehensive assessment would be more appropriate, including the competence of management and personnel in the implementation of SOPs, and their ability to operate and monitor stunning equipment. The assessment should evaluate personnel competence and responsiveness to deviations in stun quality, as well as faults in stunning equipment function

(EFSA, 2020a; 2020b). Such an integrated approach is essential to ensure high animal welfare standards.

We observed a significantly higher proportion of inadequately stunned pigs in slaughterhouses that use paternoster systems compared to dip-lift systems. This contrasts with Atkinson et al. (2012), possibly due to factors not recorded at the individual pig level and thus not accounted for in the present study, such as gas concentration and gas exposure time. However, since 2012, the carcass weight of finishing pigs has increased by 12% in Sweden (WinPig, 2024), and it is possible that slaughterhouses have not considered this when adjusting the capacity of individual cages. A major issue that significantly affects animal welfare is the use of undersized CO_2 apparatus (Grandin, 2013).

Over one-third of pigs that displayed regular gasping in the present study also exhibited a positive corneal reflex, an observation that is consistent with the findings by Atkinson et al. (2012), who identified this combination as a strong indicator of insufficient stunning. The interpretation of gasping, however, remains divisive within the scientific community. Raj (1999) described it as an indicator of residual brainstem activity, whilst Holst (2001) considered it to be a potential sign of recovery. Contrastingly, Grandin (2010) argued that gasping may simply be part of the natural dying process (referred to as agonal gasping). More recently, Verhoeven et al. (2016) emphasised its welfare implications, suggesting that gasping could induce breathlessness and distress in pigs that are still conscious. This divergence in scientific opinion was also identified recently by Lindahl et al. (2025), which underscores the urgent need for both a clearer definition and standardised interpretation of regular gasping as a welfare indicator at slaughter. Establishing harmonisation is crucial not only to refine stunning assessment protocols but, more importantly, to minimise the risk of pain, stress, and suffering for animals during slaughter.

We discovered large variations in the registrations of CO_2 concentration and temperature in several slaughterhouses, with values deviating from the SOPs set by the FBOs themselves. Although control system logs documented these variations, animal welfare officers (AWOs) and slaughter personnel did not consistently monitor them. Checks were typically only conducted when alarms were activated. The risk of critical parameters, such as gas concentration, falling below acceptable thresholds without any corrective action is highly concerning, as it can compromise both stun quality and animal welfare. Insufficient gas concentration has been linked to an increased incidence of symptoms indicating inadequate stunning (Rodriguez et al., 2008; Atkinson et al., 2012; Verhoeven et al., 2016). Similarly, deviations in CO_2 temperature, whether too low or too high, can alter the gas's physical properties, for example, by making it more volatile, which in turn reduces its effectiveness. We observed a lack of awareness among personnel regarding these risks and urge AWOs or designated personnel to address this issue through consistent, preferably daily, monitoring of CO_2 parameters from the logs. Monitoring and adjusting control system settings should be a prioritised response when signs of poor stun quality are observed, and this is also enforced by law (Council Regulation (EC) No 1099/2009).

4.2 Stunning efficiency for cattle

Among cattle, a total of 7.3% of animals displayed symptoms of shallow or poor stun quality, with 5.6% classified with poor stun quality, indicating a significant risk of animals not being fully unconscious after stunning, or recovering from unconsciousness before dying from blood loss. These findings are lower than reports from earlier research, where the frequency of inefficiently stunned animals was 9.2% (von Wenzlawowicz et al., 2012), 12.5% (Atkinson et al., 2013), and 31.8% for adult and young cattle of different sexes and breeds (Gouveia et al., 2009). The proportion of inadequately stunned animals in our study varied widely across the slaughterhouse visits, from 0 to 18.5%, suggesting that factors such as the type and condition of stunning equipment, as well as the skill and attentiveness of personnel (EFSA, 2020a; 2020b), play a critical role in stunning effectiveness. We also found that sex was associated with higher proportions of inadequately stunned animals with male cattle (young bulls, mature bulls, and steers) demonstrating higher rates of inadequate stunning compared to females (heifers and cows). This finding is consistent with findings from Atkinson et al. (2013), who reported that bulls were more likely to be insufficiently stunned. This underscores the need to consider animal characteristics and operator competence to enable consistent stunning outcomes.

We found a significant effect of shot accuracy on the likelihood of re-stunning, which was expected. Inaccurate shots (Figure 4) occurred in 23.4% of cattle in our study, which is substantially higher than the 8.0% reported by Atkinson et al. (2013). Notably, even among shots placed in the optimal position, 16 failed to induce an adequate stun, suggesting issues related to stunning equipment performance. In our study, most inaccurate shots were placed more rostrally, whereas previous studies reported misplacement primarily above the target area (Atkinson et al., 2013; Gregory et al., 2007). This variation emphasises the challenges of consistent shot placement (Terlouw et al., 2016) and reinforces the importance of ongoing personnel training, but also regular checks and services of the captive bolts.

An unexpected finding was that all involved slaughterhouses use guns with bolt lengths shorter than the current recommendation of 120 to 150 mm when stunning adult cattle (European Commission, 2017). Bolt length has a direct effect on brain damage (Wagner et al., 2019) and stunning efficiency; thus, this finding stresses the importance of up-to-date knowledge among slaughterhouse personnel and equipment upgrades, implying that slaughterhouse personnel require further training regarding how technical parameters of the guns affect stunning efficiency. Another important aspect is the cartridge strength, which directly influences the kinetic energy and speed of the bolt, and this must be adapted to the breed, sex, and size of the animal. Insufficient power can result in inadequate stunning, whilst excessive power can alter the performance of the bolt and increase the risk of equipment wear. Selecting an appropriate cartridge strength for the captive bolt used is therefore vital for both effective stunning and maintaining animal welfare (Gibson et al., 2015).

4.3 Sticking procedure

Of the 11 slaughterhouses included in this study (pigs and cattle), eight used knives shorter than 20 cm. Although all pig slaughterhouses used double-edged knives, only three used knives with a blade length of 20 cm or longer. Only two of the six cattle slaughterhouses used double-edged knives, and one used a knife that exceeded 20 cm. Wotton and Gregory (1986) demonstrated that the use of a 20 cm double-edged knife significantly reduced the likelihood of poor sticking and bleeding in pigs. Improper sticking, i.e., when the sticking wound is too small or inaccurately placed, can result in slow exsanguination and increase the risk of animals regaining consciousness (Anil et al., 2000; Brandt and Aaslyng, 2015). Studies have shown that brain responsiveness, and hence loss of consciousness, can persist for 14 to 23 s in pigs that are slaughtered without previous stunning (EFSA, 2004; Wotton and Gregory, 1986) and between 19 to 323 s in cattle bled without prior stunning (Newhook and Blackmore, 1982). For large-sized animals, or if the cut is incomplete, this time may be longer. In our observational study, we did not explicitly assess the association between knife length, blood loss, and stunning efficiency, but this is another factor that may warrant further attention.

This observational study had certain limitations in its design, as it did not consider the training or experience of the operators in the assessment of stun quality. First, due to confidentiality, detailed slaughterhouse-specific data could not be disclosed. Second, because this was an observational study, certain technical parameters (e.g., CO_2 settings) could not be evaluated for each cage of pigs. Future studies should therefore aim to include these registrations for each animal. Additionally, the presence of the observer may have positively influenced the slaughterhouse personnel's behaviour; for instance, they may have been more vigilant in recognising signs of insufficient stunning or more inclined to re-stun when uncertain in the presence of an external observer. Lastly, ethical concerns arose when the observer could not intervene in cases of stun failures not detected by slaughterhouse personnel.

This study enriches the existing scientific literature by providing key insights into how the time between stunning and sticking affects stun quality and the risk of exposing animals to unnecessary suffering at slaughter. Inadequate stunning not only compromises animal welfare (Cockram, 2020) but also disrupts operational efficiency (Grandin, 2000), with potentially increased costs due to process delays, additional labour (Jerlström et al., 2022), re-stunning, and greater resource use (e.g., ammunition). These findings underscore the importance of managerial factors influencing stun quality, such as equipment maintenance, training of personnel, and adherence to standard operating procedures. It also stresses the importance of adapting improvements to each slaughterhouse situation and circumstances. The variation in stunning efficiency across slaughterhouses necessitates regular support from equipment manufacturers, auditors, and regulatory authorities.

Further research is needed to validate gasping as a welfare indicator at slaughter, distinguishing it from rhythmic breathing, preferably by using EEG to assess brain activity (Forslid, 1987; Hjelmstedt et al., 2022). Future studies should also explore the physiological and neurological relevance of gasping across different gas concentrations and gas exposure durations. Additional studies on the effectiveness of training programmes for slaughterhouse personnel, especially regarding symptoms of inadequate stunning, appropriate re-stunning procedures, and monitoring of equipment, are also needed. Another priority is research on the development of real-time monitoring technologies, such as motion sensors or AI-based vision tools, which could enable a continuous, objective detection of signs of failed stunning, post-stunning recovery, and equipment failure during stunning.

4.4 Conclusions

The findings of this study show that longer stun-to-stick intervals are associated with an increased risk of inadequate stunning, i.e., with deviations in stun quality, in both pigs and cattle. Longer intervals are also associated with a higher likelihood of re-stunning. Stick times of less than 59 s for pigs and 99 s for cattle were associated with the lowest rates of inadequate stunning. Consequently, any extension of the stun-to-stick interval requires thorough, case-by-case evaluations based on the specific conditions of each slaughterhouse. Notably, the slaughter personnel failed to detect 10 pigs and 13 cattle that exhibited signs of inadequate stunning. These animals proceeded through the slaughter line, possibly still conscious, without proper monitoring or re-stunning. This raises concerns regarding the detection of deviations in stun quality, directly impacting animal welfare at slaughter, as these animals may have experienced unnecessary suffering. Furthermore, the variation in stun quality between slaughterhouses suggests the potential for improving stunning practices in slaughterhouses with high rates of stunning failures. The results of this study emphasise the need for further research and development related to optimal stun-to-stick intervals adjusted to the specific conditions of each slaughterhouse, establishing and implementing robust SOPs for stunning, monitoring, and maintenance of stunning equipment (e.g., CO_2 parameters and bolt lengths), along with recurrent training for slaughter personnel.

Data availability statement

The datasets presented in this article are not readily available due to GDPR and non-disclosure agreements between the slaughterhouses and SLU. All data required to replicate this work are provided (in aggregated form) in the article tables and figures. Requests to access the datasets should be directed to josefine.jerlstrom@slu.se.

Ethics statement

The animal study was approved by Swedish Animal Research Ethics Committee in Gothenburg. The study was conducted in accordance with the local legislation and institutional requirements. (Ethical approval number: Idnr 005587; Dnr 5.8.18-07913/2023).

Author contributions

JJ: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. CB: Conceptualization, Funding acquisition, Supervision, Writing – review & editing. AW: Conceptualization, Data curation, Funding acquisition, Methodology, Project administration, Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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III

Acta Veterinaria Scandinavica

BRIEF COMMUNICATION

Open Access

Traumatic injuries detected at slaughter in cattle: impact of production system and season on animal welfare and meat condemnation in Sweden

Josefine Jerlström[1*], Ann-Kristina Lind[2], Cecilia Lindahl[3], Charlotte Berg[1] and Anna Wallenbeck[1]

Abstract

The purpose of ante- and post-mortem inspections at slaughterhouses is to ensure that meat and other relevant food products of animal origin are safe for human consumption. However, these inspections can also be useful for detecting animal health and welfare issues. In cattle, traumatic injuries from on-farm incidents, transport or handling at the slaughterhouse are indications of both reduced animal welfare and increased risk of food waste, ultimately resulting in economic losses for both farmers and slaughterhouses. This observational study aimed to investigate the prevalence and seasonal variation of traumatic injuries in cows and heifers reared on organic and conventional farms in Sweden. The study includes slaughter remarks and condemnations from meat inspection data from 336,071 animals slaughtered between 2020 and 2022. Two types of injuries were analysed: "chronic traumatic injuries" (CTI) sustained on-farm and "acute traumatic injuries" (ATI) sustained during transport or at the slaughterhouse. Logistic regression models were developed to assess the influence of production system and season. Results show a higher prevalence of CTI in animals from conventional farms (9.8%) compared to organic farms (6.9%; $P < 0.001$), which may indicate that animals from organic farms are managed and handled in a way that makes them better prepared for challenges that they are later exposed to on-farm prior to slaughter. ATI were more frequent in animals from organic farms during the grazing period (interaction between production system and season: $P = 0.002$), which may indicate that animals from organic farms find the transition to the slaughterhouse environment more abrupt and stressful during the grazing period. Condemnations due to injuries were significantly higher for animals with CTI or ATI compared to animals without these specific remarks. These findings highlight the importance of pre-slaughter management, both on-farm and at the slaughterhouse, and slaughterhouse design in improving animal welfare and reducing food as well as economic losses associated with carcase condemnations.

Keywords Beef cattle, Carcass damage, Dairy cattle, Economic impact, Food loss, Lesions, Meat inspection, Organic

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Findings

Animal welfare, i.e. the subjective experience of the animal, biological function and ability to adapt to the environment in which it is kept [1], includes all aspects of the animal's life. Public interest in animal welfare has increased over the last decades [2, 3], including the welfare of animals at slaughter. In Sweden, around 400,000 cattle are slaughtered annually. Extensive research affirms

the relationship between pre-slaughter experiences, stress, animal handling, and meat quality. These factors include earlier human-animal interactions, transportation effects, time spent in lairage and facility design [4–9]. Accordingly, slaughterhouse staff observe differences in how animals cope and behave during handling at slaughter, which can be influenced by factors such as the on-farm production system (e.g. conventional vs organically certified farms), season (e.g. pasture vs indoor housing periods) and herd origin. All food-producing animals in Europe, including Sweden, are subject to official ante- and post-mortem (meat) inspections at slaughter [10]. At these inspections, the official veterinarian, employed by the Swedish Food Agency, may make decisions such as partial or total condemnation if the meat is deemed unfit for human consumption. A recent study found that the primary reason for partial condemnation of cattle carcases in Sweden was traumatic injuries sustained on the farm [11]. These types of injuries, as well as more recent bruises, are important indicators of poor animal welfare but also have financial consequences for both slaughterhouses and farmers, leading to part or whole carcase condemnations [5, 12–14]. Additionally, such condemnations contribute to food waste, as injured or damaged meat is excluded from the supply chain and deemed unsuitable for human consumption. This observational study aimed to investigate the prevalence and seasonal variation of chronic traumatic injuries (CTI) and acute traumatic injuries (ATI) (i.e. physical injuries, including bruises, fractures, cuts, and hematomas), among cows and heifers, reared on conventional and organic farms in Sweden. Older injuries occurring on the farm are classified as CTI, whereas ATI refers to more recent injuries sustained during transport or at the slaughterhouse.

Information on meat inspection data, i.e. slaughter remarks and carcase condemnation on cows and heifers of dairy and beef breeds slaughtered at Swedish slaughterhouses were provided by the cattle farmer's association Växa, which routinely collects information for the Swedish dairy and beef recording schemes. Two slaughter remarks of specific interest for animal welfare were identified, CTI and ATI, originating from routine veterinary post-mortem examinations of carcases conducted by the Swedish Food Agency. However, there are no precise guidelines in the inspection instructions for when an acute injury is considered to develop into a chronic one [15]. Only cows and heifers were included, as it is mandatory to keep animals of these categories on pasture during the vegetative season according to Swedish animal welfare legislation [16, 17], enabling assessment of differences between pasture and indoor seasons. The final data set included information on 336,071 slaughtered cows and heifers of both beef and dairy breeds slaughtered 2020–2022 (116,512, 106,390 and 113,169 in the year 2020, 2021 and 2022 respectively), representing 56.2% of all cows and heifers slaughtered in Sweden during the period [18]. Of these, 12.7% originated from farms that were organically certified according to KRAV's standards [19] (the main organic label in Sweden). Data editing, calculation of descriptive statistics and statistical analyses were performed using Statistical Analysis Software (SAS) version 9.4 (SAS Institute, Inc., Cary, NC). Differences in the prevalence of CTI and ATI between production systems and by season were analysed with logistic regression using PROC GLIMMIX, binomial distribution and logit link. The model included the fixed effects of the production system (organic, conventional), slaughter year (2020, 2021, 2022), slaughter month (12 classes, January – December), animal category (cow, heifer) and the interaction between the production system and slaughter month. Moreover, the model included slaughter weight as a continuous covariate (adjusting for the size of the animal including partial breed effects between heavier and lighter breeds) and the fixed random effect of slaughterhouse nested within slaughter year (including both effects such as management and size of the enterprise as well as geographic location).

In total, 9.4% of carcases from cows and heifers had the remark CTI (6.9% in animals from organic farms and 9.8% of animals from conventional farms) and 1.0% ATI (1.2% in animals from organic farms and 1.0% of animals from conventional farms). Carcase weight, conformation and fatness scores were numerically higher in animals originating from conventional compared to animals from organic farms (Table 1). The amount of condemned meat was higher in carcases with the remark CTI compared to carcases without this specific remark (mean 23.2 kg and 5.1 kg respectively: $P < 0.05$ with t-test). Similar results

Table 1 Carcase weight, conformation, and fat score in cows and heifers from certified organic and conventional farms

	Organically certified farms		Conventional farms	
	n = 42,517		n = 293,554	
	Mean	SD	Mean	SD
Carcase weight (kg)	305.6	52.62	318.1	56.55
Carcase conformation score[1]	4.3	4.89	5.0	5.48
Carcase fatness score[2]	7.0	2.14	7.6	2.28

SD standard deviation

[1] Conformation score 3 = P+, 4 = O-, 5 = O, 6 = O+, 7 = R- according to the EUROP carcase classification scheme, with higher scores for more developed muscles

[2] Fatness score 7 = "3-", 8 = "3", 9 = "3+", 10 = "4-", 11 = "4" according to the EUROP carcase classification scheme, with higher scores for more fat on the carcase

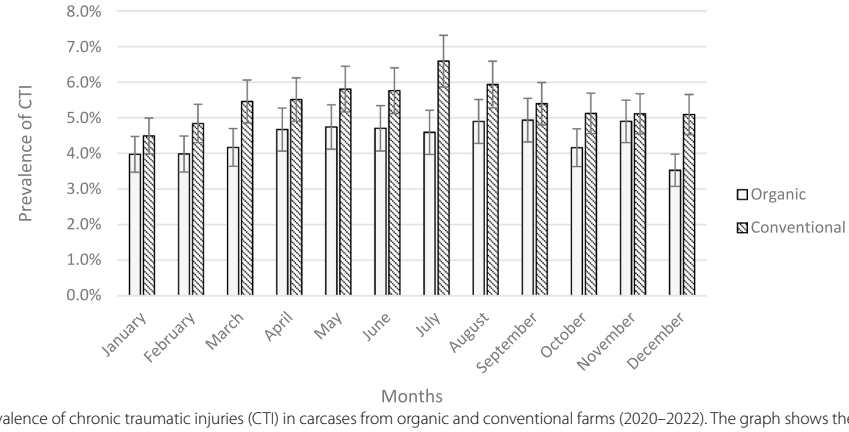

Fig. 1 Prevalence of chronic traumatic injuries (CTI) in carcases from organic and conventional farms (2020–2022). The graph shows the least square means (± standard error) of the slaughter remark CTI that occurred on-farm in carcases from cows and heifers slaughtered 2020–2022 originating from organic (n = 42,517) and conventional (n = 293,554) farms

were found for the remark ATI with an average of 15.1 kg vs. 6.7 kg respectively ($P < 0.05$ with t-test). This secondary finding of the present study confirms previous research, emphasising that injuries and bruises sustained during pre-slaughter and slaughter handling are not only indicators of poor animal welfare but also have economic implications for both farmers and slaughterhouses due to carcase condemnations [5, 20–22].

A lower proportion of cows and heifers from organic herds was identified with the remark CTI compared to those from conventional farms. This trend remained consistent across all seasons throughout the year ($F = 95.9$, $P < 0.001$; Fig. 1). Differences in management practices between conventional and organic dairy and beef farms in Sweden primarily relate to preventive animal health management (including parasite control), feed composition (notably the restriction on protein feed availability) and animal handling practices at the time of slaughter (Table 2) [19]. While access to pasture is a major distinction between conventional and organic farming in many countries, this is not the case in Sweden, where pasture access is mandatory for both beef and dairy farms [16, 17]. However, KRAV regulations impose stricter requirements regarding, for example, the minimum hours per day animals must spend on pasture and the minimum duration of the pasture season [19]. Regardless of production system, pasture season varies with climate and is thus the vegetative season across Sweden, with shorter seasons in the north and longer seasons in the south. This was partly adjusted for in the statistical analyses by including slaughterhouses nested within the slaughter year as a random effect. The difference in the prevalence of CTI between cows and heifers from organic and conventional farms (6.9% vs. 9.8%) may indicate differences in management and handling practices. Animals from organic farms might be better prepared to handle the on-farm challenges they face prior to slaughter.

The proportion of cows and heifers with ATI was significantly higher during the grazing period (i.e. when animals are kept on pasture, May – October, depending on

Table 2 Overview of selected slaughter regulations for KRAV certified, EU organic, and conventional farms (2022)

	KRAV-certified	EU-organic	Conventional
Free access to roughage	Yes	No	No[a]
Maximum transport 8 h	Yes	Yes	Yes
Use of electric prods allowed	No	Yes[b]	Yes
Stay overnight at the slaughterhouse	Yes[c]	Yes	Yes
Stunning prior to exsanguination	Yes	Yes	Yes

[a] Required only during the night

[b] Not allowed at loading or unloading

[c] Not more than 30% of the animals

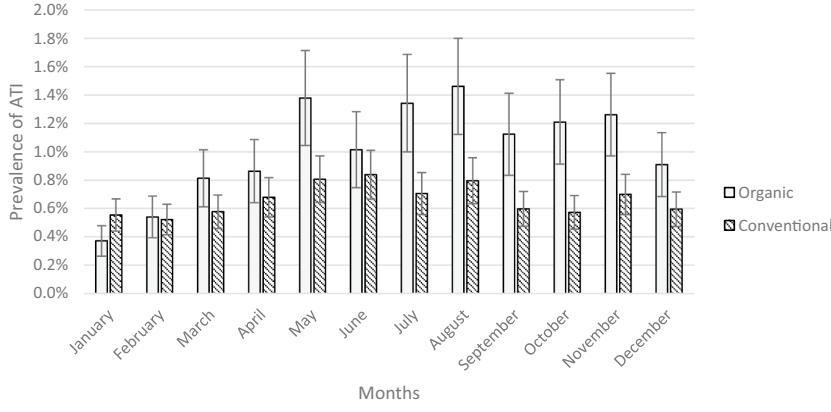

Fig. 2 Prevalence of acute traumatic injuries (ATI) in carcases from organic and conventional farms (2020–2022). The graph shows the least square means (± standard error) of the slaughter remark ATI that occurred either during transport or at the slaughterhouse in carcases from cows and heifers slaughtered 2020–2022 originating from organic (n = 42,517) and conventional (n = 293,554) farms

geographic location) for animals from organic farms, but not among animals from conventional farms (interaction between production system and season: F = 2.7, P = 0.002; Fig. 2). Animals from conventional farms, which are typically kept outdoors for fewer hours during the day (a minimum of six hours per day are mandatory), might find the transition to the slaughterhouse environment less abrupt and stressful as they spend more time indoors even during the pasture period, potentially explaining the differences in acute traumatic injuries. However, this observational study cannot establish any causal effects (e.g. animals staying overnight, the use of electric prods, etc.), thus further research is needed.

The findings of this observational study provide a starting point for discussions on optimising slaughterhouse facility design in order to prevent on-site injuries and improving pre-slaughter management practices at the farm level to reduce handling-related injuries, thereby enhancing overall animal welfare.

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These data have not been published previously.

Author contributions
Data was obtained by AW, AKL, CB, CL and JJ. The article was conceptualised by JJ, AW and AKL. The article was drafted by JJ, AW and AKL. Data editing and analyses were performed by JJ, AW and AKL. CB and CL reviewed and edited the manuscript. Funding was secured by AW, JJ, AKL, CB and CL. All authors have contributed, read and approved the final version of the manuscript.

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Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
This study was based solely on data routinely collected in the Swedish dairy and beef recording schemes and provided by Växa, thus the study did not require any official national or institutional ethical approval.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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Humane slaughter is essential to protect animals from unnecessary suffering. Thereto, slaughterhouse businesses are profit-driven and strive for efficient process flow. By combining animal science and production economics, this thesis maps key aspects of animal welfare during slaughter and assesses the economic relevance of animal welfare improvements for slaughterhouses' decision-making. Conclusions reveal that the primary motivations for animal welfare investments are reduced labour costs and improved productivity, and under simulated scenarios, animal welfare and economic outcomes are inextricably intertwined.

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