A Model for Campylobacter Contamination in Chicken Meat Production Systems

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Abstract

Campylobacteriosis is the most reported zoonosis in the EU, and in the Netherlands, nearly 73,000 cases were estimated in 2019. Campylobacteriosis, a bacterial infection caused by Campylobacter ingestion, is societally costly and may lead to more severe sequelae. Campylobacter can be ingested via consumption of raw or undercooked chicken, and the systemic impacts of biosecurity measures to reduce Campylobacter contamination on farms and cross-contamination in slaughterhouses are not fully understood. Interviews with stakeholders in the chicken farming industry and literature review were conducted to construct a model of Campylobacter colonization in farm and slaughterhouse environments. Insects, transportation crates, farmers, and catchers were each identified as potential Campylobacter sources; four reinforcing feedback loops were also identified. Simulation results revealed that insect control can reduce the peak percentage of contaminated chickens from 54% to 43% and the peak percentage of contaminated neck samples of chicken carcasses from 12% to 10%. Farm hygiene and visitor control can reduce contaminated chickens to 48% and the contaminated chicken neck samples to 11%. Implementing all investigated interventions may reduce contaminated chickens to 36% and the contaminated chicken neck samples to 9%. These results show that implementing biosecurity measures will greatly reduce, but not eliminate Campylobacter contamination.

1. Introduction

Campylobacteriosis is the most reported zoonosis in the European Union (EU). Campylobacteriosis infections made up 69% of confirmed human zoonosis cases in 2018 (EFSA, 2014; EFSA & ECDC, 2019). EFSA estimated that there are approximately nine million zoonosis cases among EU residents each year at a cost of around 2.4 billion euros due to public health expenses and loss of productivity (EFSA & ECDC, 2013). In the Netherlands, the number of campylobacteriosis infections rose in 2018 and 2019, peaking at nearly 73,000 estimated cases after reaching its lowest recorded point since 2017 (Pijnacker et al., 2019).

In developed countries worldwide, up to 80% of campylobacteriosis cases can be attributed to poultry (Wagenaar et al., 2006). Approximately 60-80% of human campylobacteriosis cases in the Netherlands can be attributed to broiler chicken as a reservoir (Mughini-Gras et al., 2016). Chicken intestines provide ideal conditions for *Campylobacter* growth, reaching levels of around 10^9 colony forming units (CFU) per gram in the chicken caeca (Kuana et al., 2007). One infected chicken can spread *Campylobacter* to the rest of the flock within a few days, which makes it crucial to prevent *Campylobacter* spread on farms in order to prevent bacteria spread throughout the food chain (Lin, 2009; Mbabazi, 2011; Sibanda et al., 2018). Despite substantial efforts from regulatory institutions, national authorities, and the poultry production industry to control spread, campylobacteriosis remains the zoonosis with the highest incidence in the EU (EFSA & ECDC, 2019).

The inability to control the spread of *Campylobacter* arises from the bacteria's transmission cycle complexity (i.e., seasonality) and a lack of understanding of the underlying mechanisms of *Campylobacter* spread on farms (Rawson et al., 2020; Sibanda et al., 2018; Wagenaar et al., 2006). **Figure 1** shows typical sources of *Campylobacter* on a conventional chicken farm. Bacteria sources include the environment (insects, vermin, farm grounds, other farm animals), humans (farmers, veterinarians, poultry catch crew, and others), equipment (thinning and other farm equipment), water (puddles, ditches, and mud), or other chicken flocks (Agunos et al., 2013; Hald et al., 2008; Hertogs et al., 2021; Sibanda et al., 2018). These sources are not mutually exclusive and differ across farms and seasons (Chowdhury et al., 2012; Djennad et al., 2019). *Campylobacter* infection rates peak during summer months in Europe (Agunos et al., 2013; Newell et al., 2011; Rawson et al., 2020).

Furthermore, *Campylobacter* infections in chickens typically go unnoticed because they do not show symptoms. As a result, it is difficult to predict and prevent *Campylobacter* infection at the animal level (Agunos et al., 2013; Sibanda et al., 2018). Although various measures to control Campylobacter on chicken farms exist, such as those aiming at reduction of environmental exposure (e.g., biosecurity measures), increasing chickens' resistance to Campylobacter (e.g., vaccination), and at using antimicrobial alternatives to reduce and eliminate Campylobacter from colonized chickens (e.g., bacteriophage therapy), their impact on transmission factors is not yet fully clear and is difficult to quantify (EFSA BIOHAZ, 2020; Lin, 2009; Newell et al., 2011). Additionally, farmers have difficulty applying these measures while also meeting the high demands of other aspects of poultry farming (Jones et al., 2017). To address the complex problem of *Campylobacter* transmission on chicken farms, it is necessary to increase understanding of transmission mechanisms, and to propose, evaluate, and assure consistent implementation of measures.

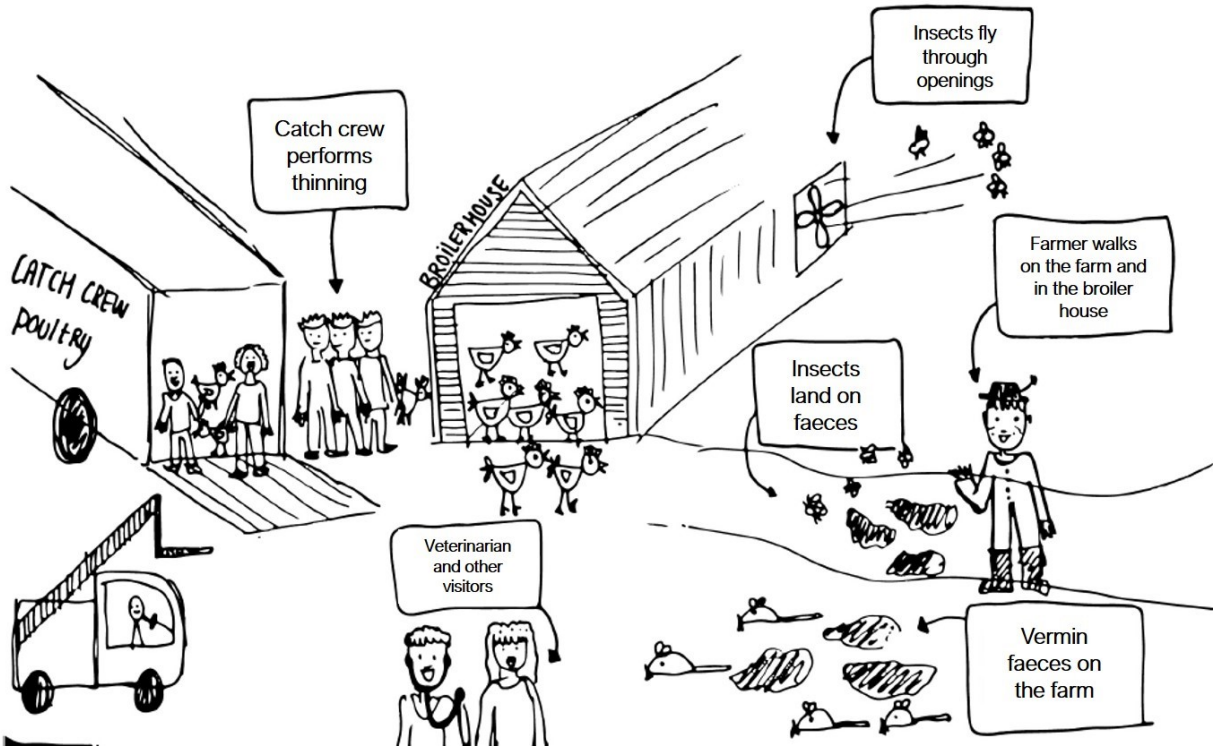

Figure 1: Typical sources of *Campylobacter* on a broiler farm

The European Food Safety Authority (EFSA) estimates that the public health risk from the consumption of broiler meat could be reduced by more than 50% if chicken carcasses are limited to containing less than 1000 CFU/g of *Campylobacter* on neck and breast skin samples (EFSA BIOHAZ et al., 2020). Since January 1, 2018, the European Process Hygiene Criterium has been implemented for *Campylobacter*. This criterium requires slaughterhouses to regularly test their flocks. Initial requirements restricted the proportion of positive samples (i.e., those with more than 1000 CFU/g) to 40%, with higher levels in violation of their initial policy (Cuperus et al., 2020). This policy is designed to become progressively stricter, reducing the proportion of allowed positive samples. By 2025, samples with more than 20% of specimens with high *Campylobacter* levels will be subject to corrective action (Cuperus et al., 2020).

Currently, existing research focuses on surveillance strategies and reactionary interventions; there are few rigorous policy analyses with large sample sizes available for guidance (e.g., EFSA BIOHAZ, 2020). Additionally, current analyses observe or model the impact of various isolated sources and measures on *Campylobacter* contamination in chickens. They do not capture the system-wide issue of chicken contamination by modeling the transmission mechanisms. Examples of research include measuring the impact of partial depopulation, i.e., flock thinning, (Allen et al., 2008), insects' and rodents' impact on disease spread (Allain et al., 2014; Hald et al., 2004), impact of ventilation systems (Romero-Barrios, Hempen et al., 2013) the presence of a separate anteroom or barrier in broiler houses (Høg et al., 2016), and acidification of drinking water and the use of antibiotics (Allain et al., 2014) on *Campylobacter* spread. Furthermore, current approaches in microbial risk analysis are based on Modular Process Risk Models (MPRM) (Nauta et al., 2012), where each step of the food chain is described using kinetic and/or probabilistic models. However, MPRM models are static and cannot easily incorporate dynamic

characteristics, such as seasonality, which is crucial to understand *Campylobacter* transmission (EFSA & ECDC, 2019), thus MPRM models are insufficient to model the dynamics within the system.

Persistently high infection rates of *Campylobacter* in chickens on Dutch broiler farms and their seasonal character prompted calls for investigation that would consider interactions among various *Campylobacter* sources on those farms, which requires uncovering feedback mechanisms within the system. Analysis rooted in a systems perspective, such as system dynamics (SD), and informed by stakeholders can address these needs. Therefore, we developed an SD model to aid in: 1) understanding the complex problem of *Campylobacter* prevalence on conventional Dutch broiler chicken farms; and 2) analyzing the effects of various interventions to reduce the rates of *Campylobacter*-contaminated chickens.

2. Methods

2.1. Model conceptualization

System dynamics models can help to clarify the complexity of a system of interrelated components, facilitate the communication of such complexity with various stakeholders, and analyse the impact of various interventions in a simulation setting (Sterman, 2000). To conceptualize the SD model of *Campylobacter* incidence on Dutch poultry farms, semi-structured interviews were performed with different stakeholders to understand the process of chicken meat production on farms and in slaughterhouses.

We interviewed 15 stakeholders in two phases. First, we interviewed five farmers, two slaughterhouse employees, one veterinarian, one poultry catcher, one employee of the Dutch Ministry of Agriculture, Nature, and Food Quality, and one employee of the Dutch Ministry of Health, Welfare and Sports. These initial interviews were summarized, and the information obtained from them was used to conceptualize the SD model. Second, we conducted six interviews with scientists who are experienced on the topic of broiler chicken *Campylobacter* incidence on farms and in slaughterhouses to validate the structure of the conceptualized model. The interviewees were shown various parts of the model and asked to state their opinion on whether the model represents real life, and if not, to give suggestions for improvement. The model structure was further modified based on these suggestions (see the supplementary document for interview questions). In addition to stakeholder interviews, a literature review was conducted to ascertain causal mechanisms related to *Campylobacter* spread on farms and in slaughterhouses.

2.2. Model formalization

The model was formalized to represent a situation on typical conventional Dutch chicken farms and slaughterhouses. **Figure 2** shows that a typical flock cycle on the farm lasts seven weeks. Each new flock arrives at the farm during the first week and lives in a broiler house on the farm for six weeks. Chickens are not susceptible to *Campylobacter* contamination during their first two weeks in the broiler house (Battersby et al., 2016; Lin, 2009). By the fifth week, the thinning process takes place, during which a portion of the chickens are captured and transported to the slaughterhouse. The remaining chickens are transported to the slaughterhouse during week six. In week seven, the broiler house is cleaned and prepared for the new flock. In slaughterhouses, slaughtering *Campylobacter*-negative chickens can still lead to positive neck samples due to cross-contamination from slaughtering equipment, while strictly-executed slaughtering of *Campylobacter*-positive chickens can lead to negative neck samples (EFSA, 2010; NEPLUVI, 2021).

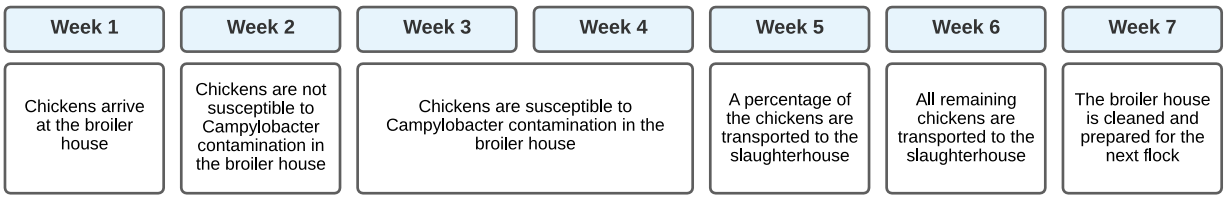

Figure 2: A typical life cycle of a conventional broiler flock on Dutch farms

Parameter data were obtained from literature and governmental reports (e.g., max development rate of insects) and interviews with five farmers. The remaining parameters were calibrated to historical data. The supplementary material contains an overview of all model parameters and their sources. The simulation model files are also included in the supplementary files to facilitate the reproducibility of this research.

2.3. Model testing and analysis

Model testing included model verification and validation based on guidelines set by Barlas (1996) and Sterman (2000). Model verification involved inspecting the variable equations and unit consistency (dimensional analysis) to uncover incorrectly coded variables. Model validation included empirical structure verification through expert interviews with eight farmers, two slaughterhouse employees, a veterinarian, a poultry catcher, an employee of the Dutch Ministry of Agriculture, Nature, and Food Quality, and an employee of the Dutch Ministry of Health, Welfare and Sports. Theoretical structure confirmation was performed to compare the form of the equations of the model with the relationships existing in the real-world system. Furthermore, extreme conditions testing was performed to evaluate the model equations, followed by the sensitivity analysis. Finally, the model was calibrated to reproduce baseline model behavior for two years, in line with historical data in **Figure 4** (see a list of calibrated parameters and details of the sensitivity analysis in the supplementary material).

Model analysis was performed using Vensim DSS (version 8.2.1) by exploring the outcomes of four intervention portfolios (see **Table 1**) of biosecurity measures, implemented after two years of baseline simulation. The impacts of the portfolios on percentages of *Campylobacter*-positive chickens delivered to the slaughterhouse and of *Campylobacter*-positive chicken carcass neck samples were projected for two years. Because the main dynamic behaviours happen in short cycles due to seasonality and as there is a lack of evidence for major long-term trend changes, we considered two years in our projections.

Table 1: List of model analysis portfolios and parameters

Intervention Portfolios	Parameter*	Baseline value	Intervention value
Insect control	probability of flies' ability to enter broiler houses when ventilation is working	0.5	0
	probability of flies' ability to enter broiler houses when ventilation system is not working	0.15	0
	probability of insects entering broiler houses through other openings	0.75	0
Thinning and transportation control	likelihood of catchers to follow hygiene protocols	0.6	1
	probability of normal feed withdrawal time	0.5	1
	probability of cleaning the crates adequately	0.8	1
Farm hygiene and visitor control	level of farm environment hygiene	0.9	1
	other external visitors to broiler houses	1	0
	human awareness personality traits	0.7	1
Total	All parameters from portfolios 1, 2, and 3 are adjusted to indicated portfolio values of parameters and simulated together.		

*All parameters are dimensionless with the range of zero to one.

3. Results

3.1. Model conceptualization

Figure 3-A shows the overall process flow of the model of *Campylobacter* contamination of chickens on farms and slaughterhouses. The flow (also called 'transition') *chickens arriving at broiler houses* represents the entrance of chickens to the farm and into the stock (also called 'state') of *Campylobacter negative chickens in broiler houses*. The chickens in the broiler houses can be colonized with *Campylobacter* and become *Campylobacter positive chickens in broiler houses* through two flows: *chickens getting colonized in broiler houses* and *chickens getting colonized after thinning*. The probability that the chickens will be colonized with *Campylobacter* in broiler houses depends on the probability of colonization of chickens by *Campylobacter*-carrying insects, vermin, and humans on the farm.

After five weeks on the farm, a percentage of the chicken flock will undergo thinning and be transported to the slaughterhouse (i.e., flows *transporting Campylobacter negative chickens* and *transporting Campylobacter positive chickens*). The remaining chickens can become *Campylobacter*-positive during the thinning process, which depends on the probability of catchers acting as vectors of *Campylobacter* for the remaining chickens or chickens contracting *Campylobacter* from dirty transportation crates. The remaining chickens will continue to grow until they are transported to slaughterhouses; some of them *Campylobacter*-negative (i.e., stock *Campylobacter negative chickens in slaughterhouse*), while others will be *Campylobacter*-positive (i.e., stock *Campylobacter positive chickens in slaughterhouse*).

Chicken flocks are slaughtered in the order of their arrival at the slaughterhouse. Therefore, when a positive flock arrives at the slaughterhouse first, they will be slaughtered first and may contaminate the slaughtering equipment with *Campylobacter*. Consequently, some *Campylobacter*-negative chickens can become infected through cross-contamination by *Campylobacter*-contaminated equipment. On the other hand, if the slaughtering process is executed in strict accordance with hygienic slaughtering practices, neck samples of chicken carcasses from *Campylobacter*-positive chickens can be *Campylobacter*-negative after slaughtering.

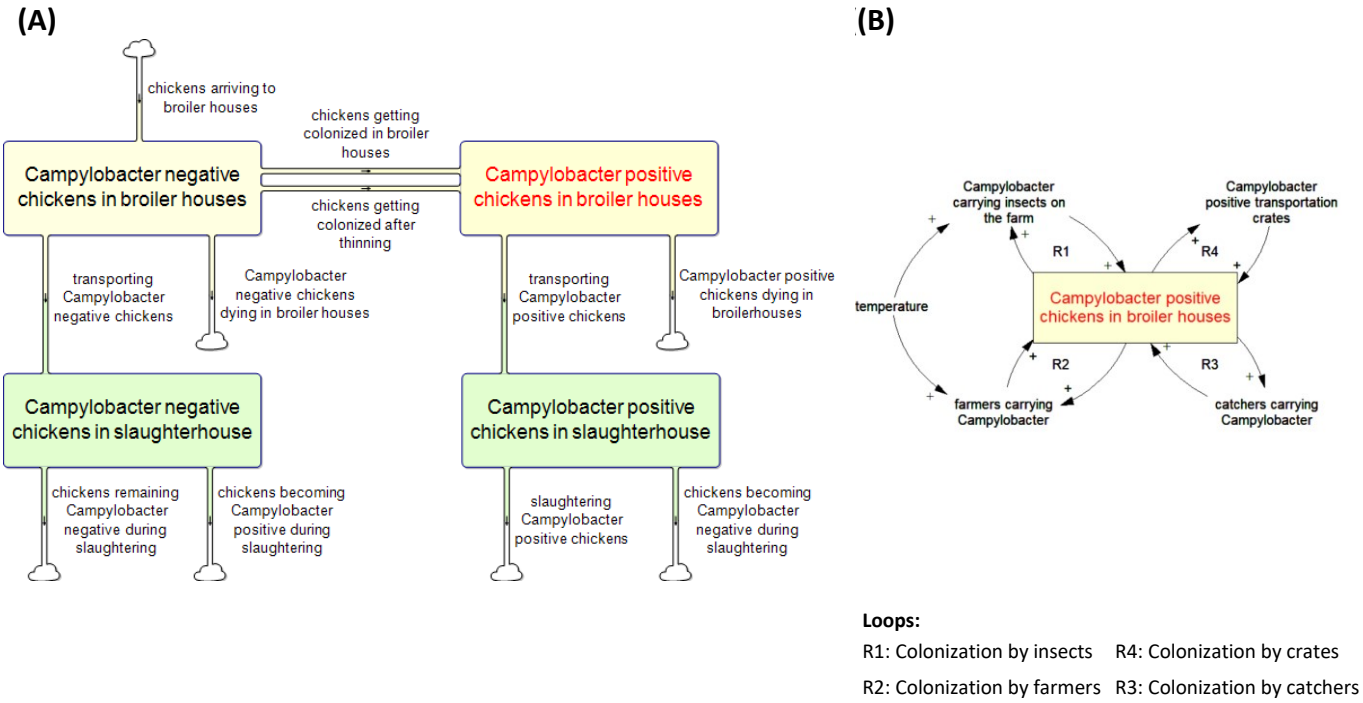

Figure 3: A) Stock and flow structure of the model. B) Feedback loops in the model.

Figure 3-B displays four feedback mechanisms that contribute to *Campylobacter*-contaminated chickens in Dutch broiler houses—these feedback mechanisms affect the flows between stocks shown in **Figure 3-A**. Feedback loop R1 represents the colonization of *Campylobacter* in chickens through bacteria-carrying insects on the farm; this happens when insects that carry *Campylobacter* enter the broiler house through various openings (e.g., ventilation, cracks in the walls). *Campylobacter*-negative insects can be colonized via chicken feces and carcasses and spread the bacterial infection to other chickens.

Feedback loop R2 shows that farmers can also spread *Campylobacter* to chickens, which occurs if they bring the bacteria into the broiler house (e.g., by walking through mud and puddles on the farm, by bringing contaminated tools from outside the broiler house) on their clothes and hands. The more *Campylobacter*-positive chickens present on the farm, the higher the chances are that the farmer will carry *Campylobacter* to another broiler house, if multiple exist on the farm.

Feedback loop R3 concerns the thinning process through which poultry catchers can spread *Campylobacter* from one farm to another. Therefore, the more farms with *Campylobacter*-positive chickens that catchers visit during one working day, the higher the chances are that they might contaminate *Campylobacter*-negative chickens on another farm.

Feedback loop R4 shows that transportation crates are also a fomite of *Campylobacter* contamination. *Campylobacter*-positive chickens can contaminate crates with *Campylobacter* during transportation from the farm to the slaughterhouse. Since the crates are not always properly washed, disinfected, and dried in the slaughterhouse, prior to being used in the thinning process on other farms, they can become a source of *Campylobacter*.

Finally, the temperature affects both farmers and insects. Higher temperatures in spring and summer lead to a higher development rate of insects, which slows down in autumn and winter months. Similarly, farmers visit the broiler houses more frequently in warmer months.

3.2. Model analysis

Baseline scenario: In the baseline scenario, 54% of chickens arriving at the slaughterhouse are *Campylobacter*-positive at peak, and 29% of chickens arriving are *Campylobacter*-positive at the end of two years. At peak, 12% of chicken carcass neck samples are contaminated, and at the end of two years, 8% are contaminated. Full results are presented in

Table *2*. Fit to historical data is shown in **Figure 4**.

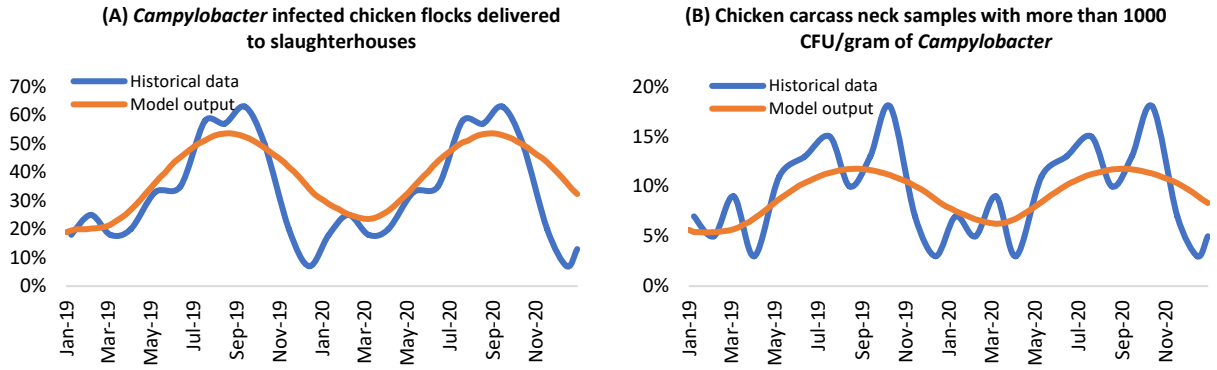

Figure 4: Model output fit to historical data at baseline of A) Campylobacter infected flocks delivered to slaughterhouses; and B) chicken carcass neck samples with more than 1000 CFU/gram of Campylobacter in the Netherlands in the year 2020 (NEPLUVI, 2021).

Intervention analysis: Table 2 presents the results of intervention analysis. The insect control portfolio had the strongest reduction in the percentage of *Campylobacter*-positive chickens arriving at the slaughterhouse, followed by the farm hygiene and visitor control portfolio, and then the thinning and transportation control portfolio (**Table 2** and **Figure 5**). At maximum, 43% of chickens arriving at the slaughterhouse were *Campylobacter*-positive in the insect control portfolio, 48% were positive in the farm hygiene and visitor control portfolio, and 53% were positive in the thinning and transportation control portfolio. When all portfolios are enacted at once, 36% of chickens arriving at the slaughterhouse are infected with *Campylobacter*, as compared to 54% at baseline.

Table 2: Intervention analysis

Intervention portfolios	Peak percentage of *Campylobacter* positive chickens arriving at slaughterhouse	Peak percentage of *Campylobacter* contaminated chicken carcass neck samples	Percentage of *Campylobacter* positive chickens arriving at slaughterhouse at the end of two years	Percentage of *Campylobacter* contaminated chicken carcass neck samples at the end of two years
Baseline	53.6%	11.8%	29.2%	7.6%
Insect control				
Eliminate insect entry through other openings	47.2%	10.8%	24.2%	6.5%
Eliminate insect entry through ventilation when ventilation is off	53.4%	11.7%	28.6%	7.5%
Eliminate insect entry through ventilation when ventilation is on	50.5%	11.3%	28.2%	7.4%
Total	42.6%	10.0%	22.1%	6.0%
Thinning and transportation control				
Maximum catcher hygiene	53.5%	11.8%	29.0%	7.6%
Maximum crate cleaning	53.2%	11.7%	28.6%	7.5%
Maximum probability of proper feed withdrawal time	53.4%	11.7%	28.8%	7.5%
Total	53.1%	11.7%	28.4%	7.4%
Farm hygiene and visitor control				
Minimize visits from non-farmers and non-veterinarians	53.5%	11.7%	29.0%	7.6%
Maximize farm hygiene	50.2%	11.3%	23.2%	6.3%
Maximum human awareness of hygiene protocols	51.6%	11.5%	25.9%	6.9%
Total	48.1%	10.9%	20.6%	5.7%
All portfolios	**35.6%**	**8.8%**	**13.9%**	**4.0%**

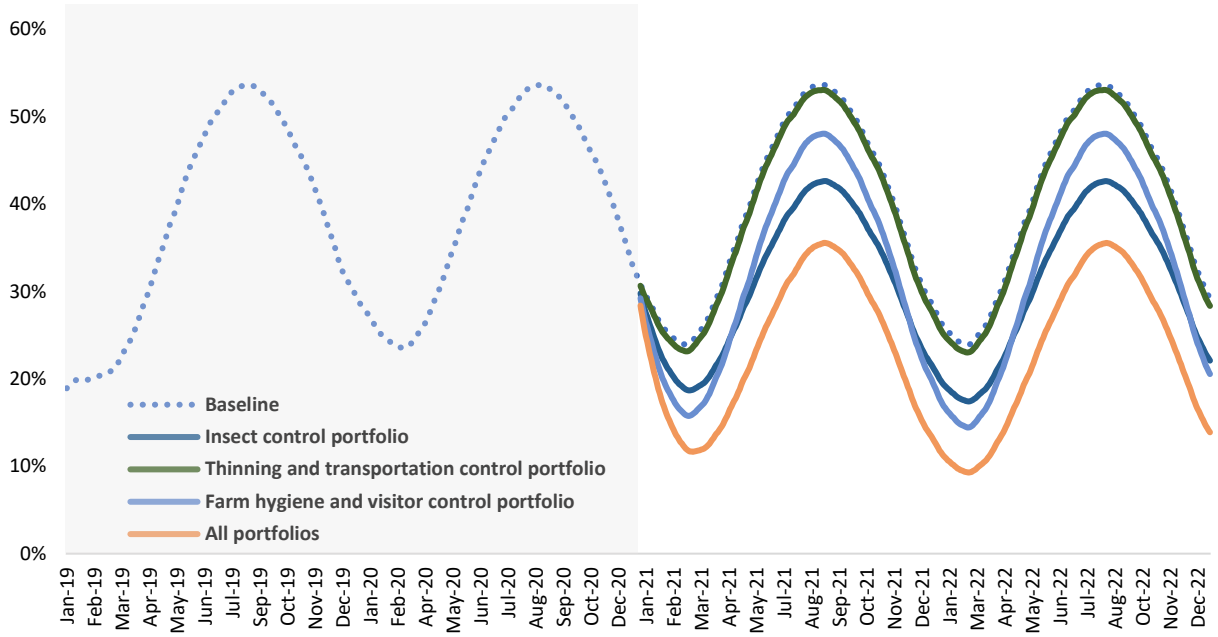

Figure 5: Results of the intervention portfolios analysis showing the percentage of *Campylobacter* positive chickens arriving at the slaughterhouse

Insect control had the strongest reduction in the percentage of contaminated chicken carcass neck samples, followed by farm hygiene and visitor control and then thinning and transportation control (**Figure 6**). At maximum, 10% is contaminated in the insect control portfolio, 11% is contaminated in the farm hygiene and visitor control portfolio and 12% is contaminated in the thinning and transportation control portfolio. When all portfolios are enacted, 9% of chicken carcass neck samples are contaminated with *Campylobacter*, as compared to 12% at baseline, which is a reduction of approximately 25%.

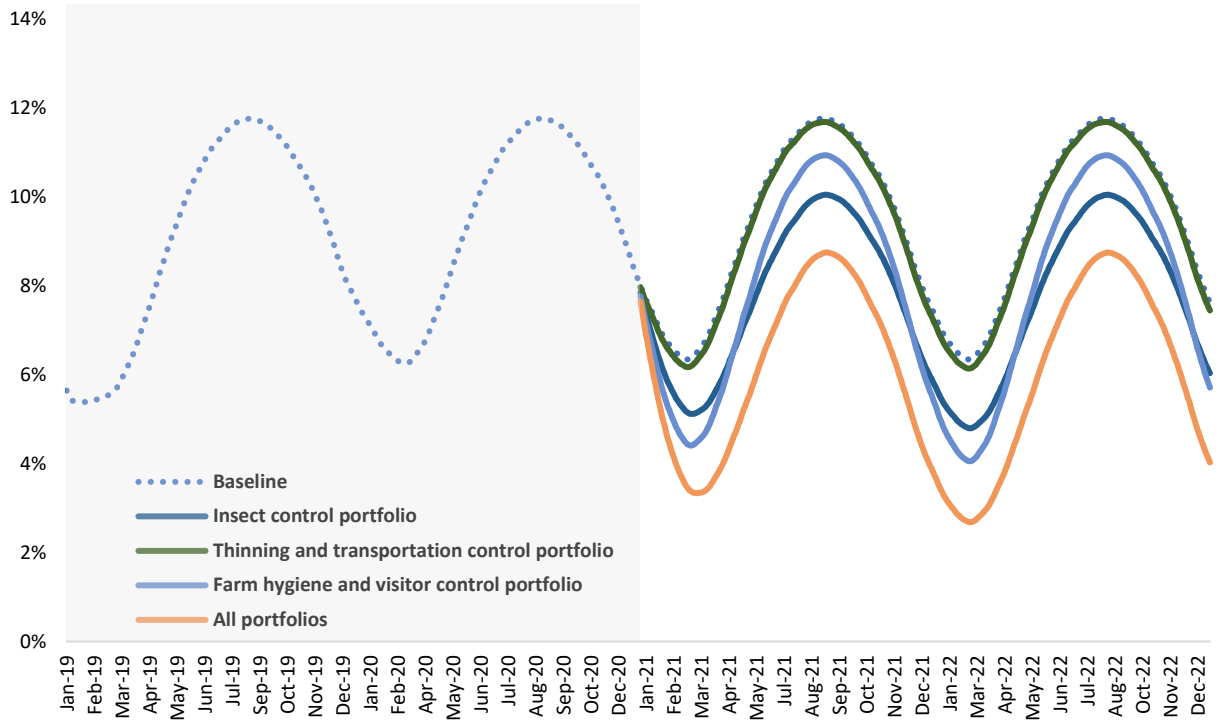

Figure 6: Results of the intervention portfolios analysis showing the percentage of *Campylobacter* contaminated chicken carcass neck samples

4. Discussion

We used system dynamics modeling to build and quantify a model of *Campylobacter* contamination in broiler chickens on conventional Dutch farms and in slaughterhouses. System dynamics is well-suited to model a problem where both quantitative and qualitative information must be considered and outcomes depend on the behavior of complex and interrelated systems (Sterman, 2000). The rising incidence of *Campylobacter* contamination in broiler chickens does not arise from a single behavior (or lack thereof), but rather the combination of multiple behaviors present in the farming sector (Newell et al., 2011). This interconnectedness within the system is reflected in the relatively modest reduction in colonized chickens and contaminated chicken carcass neck samples when one biosecurity measure is enacted, in contrast to the reductions achieved by combining measures into portfolios (see **Figure 5** and **Figure 6**, and

Table *2*).

We have built upon prior work on measures of *Campylobacter* reduction in the primary production of broiler chickens, which was predominantly focused on modelling parts of the *Campylobacter* contamination problem in isolation (e.g., EFSA BIOHAZ et al., 2020; EFSA, 2012), by presenting an overview of the feedback mechanisms in the primary production process. Furthermore, existing research did not include dynamics over time (e.g., Mughini-Gras et al., 2016 and Nauta et al., 2005). In this research, a qualitative approach of stakeholder engagement is combined with a quantitative approach to turn information into data. Specifically, the model was parameterized based on interviews with field experts and policymakers.

Importantly, we contribute potential policy portfolios that, if enacted, could sustain reduced *Campylobacter* contamination over time. We found that while interventions that control farm hygiene and visitors from entering the broiler house reduce *Campylobacter* contamination to some extent, interventions that prevent insects demonstrate the greatest reduction in the percentage of contaminated neck samples of chicken carcasses. Interventions focused on the strictness of catchers during thinning and hygiene of transportation crates only reveal minor reductions in the number of contaminated chickens and the amount of contaminated neck samples. These small effects may be due to the sub-model structure of the thinning process, which ultimately results in a small range of values of probabilities that chickens will be colonized after the thinning process is complete.

This work is subject to several limitations. First, we focused on the Netherlands due to the country's relatively high proportion of gastrointestinal illnesses caused by *Campylobacter*. Additionally, we only model conventionally raised chickens; free-range chicken farms slaughter chickens at a higher age and do not have a thinning process (van Horne, 2020). Further, the model parameters are based on qualitative information. Based on the interviews with different stakeholders, assumptions are made for the values of various model parameters. These uncertain parameters can lead to uncertain results for the percentage of contaminated chickens arriving at slaughterhouses and the neck samples of chicken carcasses. Moreover, in this research, the assumption is made that when one chicken is infected, the whole flock will be infected (Lin, 2009). These infection rates pertain to the individual chickens, but the infection probabilities in the broiler house and after thinning are employed as a probability for the entire flock getting infected.

Additionally, a chicken is assumed to be either Campylobacter positive or negative. In reality, amounts of Campylobacter on chicken samples are expressed in CFU/gram. According to a Process Hygiene Criterion (EU Commission, 2017), when chicken carcasses are contaminated with less than 1000 CFU/g after chilling, the test results are interpreted as satisfactory. In this research, more in-depth details about these numbers are not given, and the specific concentration of *Campylobacter* per gram of chicken is not estimated.

Finally, while we consider environment on the farm, we do not consider potential environmental factors beyond farm grounds such as the proximity of other farms and surface water (e.g., lakes and rivers). Potential relationships between environmental hygiene, proximity and corresponding impacts on *Campylobacter* spread on the farm could be explored in future research.

Despite these limitations, the current study provides a first systematic step towards better understanding the high rates of campylobacteriosis in the Netherlands. We elicited potentially interesting policies to reduce *Campylobacter*-infected chicken meat, including insect control, thinning and transportation control and farm hygiene and visitor control. Enactment of these policies could reduce the incidence of gastrointestinal illness in the Netherlands.

References

Agunos, A., Léger, D., Avery, B. P., Parmley, E. J., Deckert, A., Carson, C. A., & Dutil, L. (2013). Ciprofloxacin-resistant Campylobacter spp. in retail chicken, western Canada. *Emerging infectious diseases, 19*(7), 1121-1124. doi:10.3201/eid1907.111417

Allain, V., Chemaly, M., Laisney, M., Rouxel, S., Quesne, S., & Le Bouquin, S. (2014). Prevalence of and risk factors for Campylobacter colonisation in broiler flocks at the end of the rearing period in France. *British Poultry Science, 55*(4), 452-459.

Allen, V., Weaver, H., Ridley, A., Harris, J., Sharma, M., Emery, J., . . . Edge, S. (2008). Sources and spread of thermophilic Campylobacter spp. during partial depopulation of broiler chicken flocks. *Journal of food protection, 71*(2), 264-270.

Barlas, Y. (1996). Formal aspects of model validity and validation in system dynamics. *System Dynamics Review: The Journal of the System Dynamics Society, 12*(3), 183-210.

Battersby, T., Whyte, P., & Bolton, D. (2016). The pattern of Campylobacter contamination on broiler farms; external and internal sources. *Journal of Applied Microbiology, 120*(4), 1108-1118.

Chowdhury, S., Sandberg, M., Themudo, G., & Ersbøll, A. (2012). Risk factors for Campylobacter infection in Danish broiler chickens. *Poultry Science, 91*(10), 2701-2709.

Cuperus, T., Opsteegh, M., Wit, B., Gijsbers, E., Dierikx, C., Hengeveld, P., . . . van der Giessen, J. (2020). Surveillance zoönosen in vleeskuikens 2018-2019.

Djennad, A., Iacono, G. L., Sarran, C., Lane, C., Elson, R., Höser, C., . . . Semenza, J. C. (2019). Seasonality and the effects of weather on Campylobacter infections. *BMC infectious diseases, 19*(1), 1-10.

EFSA. (2010). Analysis of the baseline survey on the prevalence of Campylobacter in broiler batches and of Campylobacter and Salmonella on broiler carcasses, in the EU, 2008-Part B: Analysis of factors associated with Campylobacter colonisation of broiler batches and with Campylobacter contamination of broiler carcasses; and investigation of the culture method diagnostic characteristics used to analyse broiler carcass samples. *EFSA Journal, 8*(8), 1522.

EFSA. (2014). EFSA explains zoonotic diseases—Campylobacter.

EFSA, & ECDC. (2013). The European Union summary report on trends and sources of zoonoses, zoonotic agents and food-borne outbreaks in 2011. *EFSA Journal, 11*(4), 3129.

EFSA, & ECDC. (2019). The European Union one health 2018 zoonoses report. *EFSA Journal, 17*(12), e05926.

EFSA BIOHAZ, Koutsoumanis, K., Allende, A., Alvarez-Ordóñez, A., Bolton, D., Bover-Cid, S., . . . Hilbert, F. (2020). Update and review of control options for Campylobacter in broilers at primary production. *EFSA Journal, 18*(4), e06090.

EFSA Panel on Biological Hazards. (2012). Scientific Opinion on the development of a risk ranking framework on biological hazards. *EFSA Journal, 10*(6), 2724.

COMMISSION REGULATION (EU) 2017/1495, (2017).

Hald, B., Skovgård, H., Bang, D. D., Pedersen, K., Dybdahl, J., Jespersen, J. B., & Madsen, M. (2004). Flies and Campylobacter infection of broiler flocks. *Emerging infectious diseases, 10*(8), 1490.

Hald, B., Skovgård, H., Pedersen, K., & Bunkenborg, H. (2008). Influxed insects as vectors for Campylobacter jejuni and Campylobacter coli in Danish broiler houses. *Poultry Science, 87*(7), 1428-1434.

Hertogs, K., Haegeman, A., Schaumont, D., Gelaude, P., De Zutter, L., Dewulf, J., . . . Rasschaert, G. (2021). Contamination Sources and Transmission Routes for Campylobacter on (Mixed) Broiler Farms in Belgium, and Comparison of the Gut Microbiota of Flocks Colonized and Uncolonized with Campylobacter. *Pathogens, 10*(1), 66.

Høg, B. B., Sommer, H. M., Larsen, L. S., Sørensen, A. I. V., David, B., Hofshagen, M., & Rosenquist, H. (2016). Farm specific risk factors for Campylobacter colonisation in Danish and Norwegian broilers. *Preventive Veterinary Medicine, 130*, 137-145.

Jones, A. K., Cross, P., Burton, M., Millman, C., O'Brien, S. J., & Rigby, D. (2017). Estimating the prevalence of food risk increasing behaviours in UK kitchens. *PLoS One, 12*(6), e0175816.

Kuana, S. L., Santos, L., Rodrigues, L., Borsoi, A., Moraes, H. L. d. S., Salle, C. T. P., & Nascimento, V. P. d. (2007). Risk factors and likelihood of Campylobacter colonization in broiler flocks. *Brazilian Journal of Poultry Science, 9*(3), 201-204.

Lin, J. (2009). Novel approaches for Campylobacter control in poultry. *Foodborne pathogens and disease, 6*(7), 755-765.

Mbabazi, J. (2011). Principles and methods for the risk assessment of chemicals in food. In: Taylor & Francis.

Mughini-Gras, L., Penny, C., Ragimbeau, C., Schets, F. M., Blaak, H., Duim, B., . . . Mossong, J. (2016). Quantifying potential sources of surface water contamination with Campylobacter jejuni and Campylobacter coli. *Water research, 101*, 36-45.

Nauta, M., Jacobs-Reitsma, W. F., Evers, E. G., Van Pelt, W., & Havelaar, A. H. (2005). Risk assessment of Campylobacter in the Netherlands via broiler meat and other routes.

Nauta, M. J., Sanaa, M., & Havelaar, A. H. (2012). Risk based microbiological criteria for Campylobacter in broiler meat in the European Union. *International Journal of Food Microbiology, 158*(3), 209-217.

NEPLUVI. (2021). *Rapportage Campylobacter monitoring 2020 op Nederlandse vleeskuikenslachterijen*. Retrieved from

Newell, D., Elvers, K., Dopfer, D., Hansson, I., Jones, P., James, S., . . . Connerton, I. (2011). Biosecurity-based interventions and strategies to reduce Campylobacter spp. on poultry farms. *Applied and environmental microbiology, 77*(24), 8605-8614.

Pijnacker, R., Friesema, I., Mughini Gras, L., Lagerweij, G., Van Pelt, W., & Franz, E. (2019). Disease burden of food-related pathogens in the Netherlands, 2018.

Rawson, T., Paton, R. S., Colles, F. M., Maiden, M. C., Dawkins, M. S., & Bonsall, M. B. (2020). A Mathematical Modeling Approach to Uncover Factors Influencing the Spread of Campylobacter in a Flock of Broiler-Breeder Chickens. *Frontiers in microbiology, 11*, 2481.

Romero-Barrios, P., Hempen, M., Messens, W., Stella, P., & Hugas, M. (2013). Quantitative microbiological risk assessment (QMRA) of food-borne zoonoses at the European level. *Food Control, 29*(2), 343-349.

Sibanda, N., McKenna, A., Richmond, A., Ricke, S. C., Callaway, T., Stratakos, A. C., . . . Corcionivoschi, N. (2018). A review of the effect of management practices on Campylobacter prevalence in poultry farms. *Frontiers in microbiology, 9*, 2002.

Sterman, J. (2000). *Business dynamics*: Irwin/McGraw-Hill c2000.

van Horne, P. (2020). *Economics of broiler production systems in the Netherlands: Economic aspects within the Greenwell sustainability assessment model*: Wageningen Economic Research.

Wagenaar, J., Mevius, D., & Havelaar, A. (2006). Campylobacter in primary animal production and control strategies to reduce the burden of human campylobacteriosis. *Rev Sci Tech, 25*(2), 581-594.