epa1341 Advanced System Dynamics

Case Description

Campylobacter spp. in Chicken Meat

The material for this case description is abstracted from the MSc. thesis of ir. Edien Rommens (Rommens, 2020), undertaken in partial completion of the degree of Engineering and Policy Analysis at the Delft University of Technology in 2020. Edien collaborated with food scientists from Wageningen University to produce the first synthesized simulation modelling study of the problem of campylobacteriosis infections. These infections can arise when people eat the meat of chickens infected with the campylobacter bacterium.

For the epa1341 Advanced System Dynamics course in the academic year 2020/2021, you are required to improve and/or extend the campylobacteriosis simulation model using the synthesized model of Rommens (2020) as your basis.

This assignment is to be executed in a small group. You are referred to the document "EPA1341 -Project Description – 31012021" and the information under the tab "Paper template, Checklists / Review criteria for the assignments, assessment Rubric" for precise specification of the requirements for each stage of the overall project assignment. An overview of the deadlines is provided in the document "EPA1341 Advanced System Dynamics 2020/2021 Schedule and arrangements".

Rommens, E.(2020). Infected by chicken meat? A System Dynamics perspective on the occurrence of Campylobacter in the chicken chain. Engineering and Policy Analysis MSc thesis, Delft University of Technology, Delft, the Netherlands. 130pp. http://resolver.tudelft.nl/uuid:a8bd14ae-30f8-471d-bb8b-56e4fffe136c

Introduction [Extract from introduction chapter of Romens (2020), so that you do not have to spend too much time searching for relevant literature]

Infectious diseases are currently one of the biggest global challenges (Van Der Meer, 2013). Major new threats appeared to the world like AIDS, SARS, and Corona virus, but also less threatening infections, such as infections caused by the Campylobacter bacteria. Campylobacter is a bacterium that can cause a human illness called Campylobacteriosis (Gölz et al., 2014). Campylobacteriosis is a collective name of infections caused by pathogenic Campylobacter species and is characterized by different mild symptoms such as fever, vomiting, watery or bloody diarrhea (Scallan et al., 2015). Campylobacteriosis is a global problem. The incidence of Campylobacter infections occurred in high-, middle-, and low-income countries (Hansson et al., 2018). As published by Skarp et al. (2016), human Campylobacter infections have been increasing in the past decade with poultry meat as the primary cause. Poultry encompasses chicken, turkey, duck, and laying hens (Skarp et al., 2016), of which chicken is the predominant species for meat production.

Foodborne illness is a serious public health concern and, according to White et al. (1997), raw chicken meat containing Salmonella or Campylobacter bacteria causes the largest number of foodborne illness cases. The number of cases of people getting sick of the Campylobacter is increasing (Gölz et al., 2014). In the European Union in 2009, 2,017,110 Campylobacteriosis cases were reported and this number increased to 2,147,790 cases in 2013 (Skarp et al., 2016). Consequently, public awareness of Campylobacter infections grows continuously (Gölz et al., 2014). With an incidence of approximately 55.5 cases per 100,000 population in the year 2012 (Authority et al., 2014), this disease is the most frequently reported foodborne illness in the European Union (EU). However, due to mild symptoms, most human clinical cases are not regularly published (Pezzotti et al., 2003) which leads to under-reporting. As appears from Gölz et al. (2014), it can be assumed that the actual incidences of Campylobacteriosis are eight up to 30-fold higher. Moreover, Campylobacter foodborne infection causes 8.4% of the global diarrhea cases (Igwaran and Okoh, 2019). The European Food Safety Authority (EFSA) estimated the cost of Campylobacteriosis to public health systems and lost productivity in the EU around EUR 2.4 billion per year (Gölz et al., 2014).

The EFSA estimated that poultry meat consumption accounts for approximately 50% to 80% of the Campylobacteriosis cases in the European Union (Skarp et al., 2016). Contamination of chicken by Campylobacter is widely accepted as a significant risk factor for human Campylobacteriosis (Lin, 2009). Poultry meat production and consumption are increasing globally. In 2023 the poultry meat industry is expected to be the largest meat sector by around 130.7 million tonnes of meat (Skarp et al., 2016). The Netherlands has always been a dominant force in the production and trade of poultry meat. The poultry industry is massive, efficient, and highly developed in the Netherlands making the Netherlands a country that is not only densely populated with people, but also with poultry (Leenstra et al., 2006). This creates problems with spatial planning, pollution, and it increases the risks of infectious diseases.

The control and, if possible, the prevention of Campylobacter in poultry meat is an important food safety issue, which can reduce the risk for humans to get infected (Lin, 2009). Different studies pointed out that the full elimination of Campylobacter in the chicken meat production process is hard for most countries (Gölz et al., 2014). The occurrence of the Campylobacter infections is often irregular (Blackall, 2017) and so far there is no explanation that can predict the presence of Campylobacter. This makes it difficult to understand the transmission events that result in human disease. Developing effective biosecurity measures, which are procedures used to prevent the introduction and spread of disease-causing organisms in poultry flocks, has been recognized as critical but complex (Newell et al., 2011). Numerous sources of contamination, which can differ among farms and seasons, are identified. From the article by Hansson et al. (2018), it is evident that knowledge is lacking about the transmission routes and the survival of

Campylobacter during the entire chicken meat production process. Different researches are focused on only one or two stages of the production process. To investigate the real effectiveness of the application of available current measures on reduction of Campylobacter infections, an overview of the entire production process is necessary. Pasquali et al. (2011) write that more scientific research is needed to investigate the real effectiveness of the application of available measures on reduction of Campylobacter infections. Proposed changes to industry practices on broiler houses or in slaughterhouses should be supported by robust research evidence to be acceptable (Newell et al., 2011). Also, earlier research on the Campylobacter problem is either qualitative or does not include dynamics over time (Bearth et al., 2014; Nauta et al., 2007; on Biological Hazards , BIOHAZ).

Different assumptions and boundaries are set to specify the scope of this research. In this research, the focus point will be the chicken meat production process. According to Nauta et al. (2007), the broiler chickens are generally regarded as one of the primary sources of the Campylobacteriosis. Therefore, control and prevention should aim at reducing Campylobacter infection at all stages of the chicken meat production process (Butzler, 2004). The Campylobacter case is a global problem, but in this research, the focus will be on the Netherlands. In the Netherlands, the incidence of Campylobacteriosis is estimated to be 80.000 cases per year (Doorduyn et al., 2010) and it is estimated that Campylobacter species infections represent at least one-third of the disease burden of all intestinal infections (Ruiz-Palacios, 2007). This represents around 5 percent of the total Dutch inhabitants. While the number of cases of Salmonella infections decreased the past decade, the number of Campylobacteriosis confirmed cases in the Netherlands remained at a constant level (Van de Giessen et al., 2006). According to Luangtongkum et al. (2006), it is evident that Campylobacter is highly prevalent in organic, free-range, and conventional poultry production processes. However, according to Newell and Fearnley (2003), the percentage of infected flocks is generally higher in organic and free-range flocks compared to the conventional flocks of chickens, because of both environmental exposure and the age of the birds at slaughter. These risks are not applicable to conventional chickens. Therefore, this research focuses on the conventional chicken meat production process.

The objective of this research is to understand the chicken meat production process and its uncertainties in the sources and transmission routes of Campylobacter. In order to do so, this research develops a model of the chicken meat production process from farmer to slaughterhouse. In this model, the most critical uncertainties are analyzed and different policies are introduced to show to what extent these may contribute to reducing the occurrence of Campylobacter in chicken meat.

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[Extraction from Chapter 1 of Rommens (2020) stops. The research questions etc. are not included here as the focus of the project assignment for epa 1341 is different]

4.3 Model Conceptualisation [Extract with small adaptations for readability from pg 22 onwards of Rommens (2020)]

The qualitative model is based on the chicken meat production process, which is shown in Figure 4.1 below ….. For this research, the model boundaries are set from the moment that the chickens are arriving in the broiler houses, until the moment that the chicken meat is produced in the slaughterhouses. These boundaries are chosen to cover all the different moments that Campylobacter bacteria can enter the chicken or chicken meat. The purpose of the developed model is firstly to get a more detailed overview of the chicken meat production process in the Netherlands and secondly to find out by using and testing different measures placed in different scenario's of the chain, what actions have the most significant impact and are recommended to reduce the amount of Campylobacter positive chicken meat.

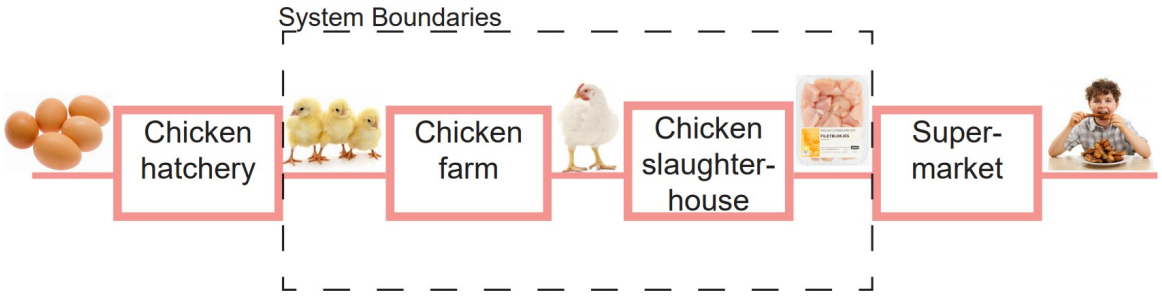


Figure 4.1: System Boundary of the chicken meat production process

In Vensim, which is simulation software for system dynamics models, a qualitative model is created based on the chicken meat production process. Figure C.3 in Appendix C shows the main stock-flow diagram of the model. The model starts with an incoming flow called Chickens arriving from hatcheries transported to broiler houses, which are chickens arriving in the broiler houses from the hatcheries when the chickens are around one day old. This flows end up in a stock called Campylobacter negative chickens in broiler houses. The chickens in the broiler houses can get colonized by Campylobacter. The part of the chickens that will be colonized over time, is controlled by the infection rate in broiler house and the infection rate after thinning. This part of the chickens will flow to the other stock on the right side of the model, which is called Campylobacter positive chickens in broiler houses, whereby the chickens are infected by Campylobacter in the broiler house. If the chickens are on the "right hand" side of the model, they cannot flow back. If they are infected, they will stay Campylobacter positive. The Infection rate on farmhouses and the infection rate after thinning are based on various other factors, which will be explained in subsections 4.3.1 and 4.3.2.

The duration of Campylobacter colonization in chickens has not been fully determined. Though, it is broadly acknowledged that colonization in chickens continues at least for the life span of a chicken (Newell and Fearnley, 2003). The life span of conventional chickens is less than 47 days. Based on various interviews[…] and according to Cawthraw et al. (1996), the Campylobacter infection spreads rapidly between the chickens. Within three days, up to 20.000 birds can become infected. Once Campylobacters have entered into the broiler houses all of the chickens become colonized within a few days (Rasschaert et al., 2007). In this model, the colonization between chickens in one broiler house is not explicitly modelled. Instead, the model is developed for the total amount of chickens in the Netherlands.

After five weeks, a part of the regular chicken flock will be caught by a catch crew, which is called "flock thinning". The term flock thinning applies to a situation in which a portion of chickens in a broiler house is removed for slaughter and processing, leaving the remaining birds to grow to average clearance age (Allen et

al., 2008). The Campylobacter positive and Campylobacter negative chickens that are caught during the process are placed on transport, which can be seen in Figure C.3. During the catching or so-called "thinning" process, the "left-over chickens" can become infected by the infection probability called Probability of infection after thinning. When the chickens become infected after this process, they will flow to the "Campylobacter positive" right part of the model. At the end of the rearing process, which is for the conventional chicken six weeks, all "left-over chickens" of the flock are placed on transport.

On transport, there also is probability that the chickens get infected. This infection flow is based on the probability called Transport infection probability. In section 4.3.3, a more in-depth explanation of this infection probability is given. Finally, the chicken flocks arrive in the slaughterhouses. From the stock called Campylobacter negative chickens in slaughterhouse, the chickens can flow into chickens getting infected during the slaughter process and Campylobacter negative chickens being slaughtered. According to interviewees […], the chicken flocks are being slaughtered in the order of how the chicken flocks arrive in the slaughterhouse. This means that when a positive flock of chickens arrive first in the slaughterhouse, they will be slaughtered first.

According toBiological Hazards (BIOHAZ) different steps of the chicken meat production process, which are primary production, after thinning, during transport, during slaughter and processing, offer options to control Campylobacter. Therefore the infection rates in these different processes are modelled and explained in more detail in the following subsections.

4.3.1 Conceptualization submodel 1: Primary production on farm

From the process described above it can be concluded that there are multiple sources and transmission routes for Campylobacter during the production process. Based on literature combined with the interviews, the main risk factors are identified in the primary production process.

Different risk factors are identified in the first part of the production process, which is the rearing of the chickens on farmhouses. Campylobacters are common in wild and domestic animals. The defecation of these animals consist Campylobacters which will stay on and around the farm site. It is important to minimize contamination of chicken rearing houses from such sources (Silva et al., 2011). As can be read in different interviews [Interview B.2.3] and in literature studies, (Magazine, 2017), the two main transmission routes of Campylobacter entering the broiler houses, are through insects or visitors and their equipment, which is shown in figure 4.3. Therefore the main infection rate Infection rate in broiler houses is split up into Insects infection subrate and human infection subrate, which are both colored in figure 4.4.

No direct contact between broiler flocks and animals outside the broiler house is possible, because the chicken meat production systems are closed. Although, indirect contact can be possible by flies that take up Campylobacter as they forage on fresh animal faeces (Hald et al., 2004). The study by Hald et al. (2004) has showed that flies are a significant threat of Campylobacter infection for chickens. Especially from April to October when insects are in season, they form a threat for infections. Hald et al. (2004) shows that flies enter broiler houses in large numbers through the ventilation systems, which will be working more often in summer- than in wintertime. This suggests that flies may be an important vector in summer. Besides flies, also other insects will transmit Campylobacter into the broiler houses. According to some of the farmer interviews [Interview B.2.11], insects such as beetles, are often found in the broiler houses.

In the model the factor Insects infection rate in broiler houses is influenced by the development rate of insects, probability insects entering the broiler house and probability that insects carry Campylobacter. This is shown in figure 4.4. Climate seasons are causing the seasonal activity patterns of living organisms (Wolda,

1988). In most regions of the world, the growing conditions for living organisms such as insects, generally overcome during specific seasons. To survive during unfavourable periods, many insects undergo a state of dormancy (Wolda, 1988). So if the temperature gets higher, the development rate of insects will increase (Tauber and Tauber, 1976), and the ventilator systems will start working. The combination of these two factors, let the insects infection rate increase. So when the temperature is higher, there are more insects, and these insects can easily enter the broiler houses when the ventilator systems are working [Interview B.2.11]. When the ventilator systems are working, the valves in the walls of the broiler houses will open wider. Through these valves, insects can enter the broiler house. However, insects do not only enter the broiler houses through the valves but can also enter them through crevices in the broiler houses [Interview B.2.11]. The insects infection rate is also dependent on Insects getting infected by vermins. This factor gives the probability of insects getting in touch with Campylobacter positive defecation of wild domestic animals.

Campylobacter can be found in standing waters or puddles on-farm sites, because they survive well in water (Newell et al., 2011). As can be read in the Interview with veterinarian 1 [Interview B.2.1], defecation of vermin will end up in mud and waters on the farm and will be an essential source for Campylobacters. When the temperature increases, more wild domestic animals will be around farmhouses. The level hygiene on a farm is a factor that can decrease the number of pests and vermins on a farm. When the farm is clean, the probability of Campylobacter infected vermin on farms will be low. The level of hygiene on a farm also influences the probability of walking through mud/water before entering the broiler house. When the farm is cleaned up, the probability of mud/water on the farm will be low. This will lead to a decrease in the probability of human physically carrying Campylobacter, which influences the human infection rate in broiler houses, as can be seen in figure 4.4. A second influence on this probability is the fact if visitors do follow the hygiene protocol [Interview B.2.4]. Prevention is essential to avoid spreading pathogens and other infections (PLUIMNED, 2019). If the total amount of visits increases, the probability of not following the protocol does increase. According to interviews with farmers, different farmers acknowledged that when they or other visitors need to visit the farm more often, they do not always follow the protocols anymore. The amount of visitors in a broiler-house is based on three different visitors called visits of the farmer, visits of the veterinarian and visits of other people. The visits of a farmer in his/her broiler houses and the probability of following the hygiene protocol are influenced by the temperature variable. If the temperature is higher, farmers are more worried about the health of their chickens and will visit their broiler houses more often. In summer the probability of switching clothing (part of following the protocol), will be lower. According to various interviews [Interview B.2.11], some farmers assumed that in summer, they do not wear their overalls but just their t-shirt and short pants.

According to Magazine (2017) drinking water could be a source for Campylobacter. Some studies isolated Campylobacter genotypes from the drinking system and then from subsequent flocks, which showed that water is not a significant source of Campylobacter in conventional chicken meat production systems. Also, feed and fresh bedding material for in the broiler houses (wood shavings), are not considered to be potential sources of Campylobacter.

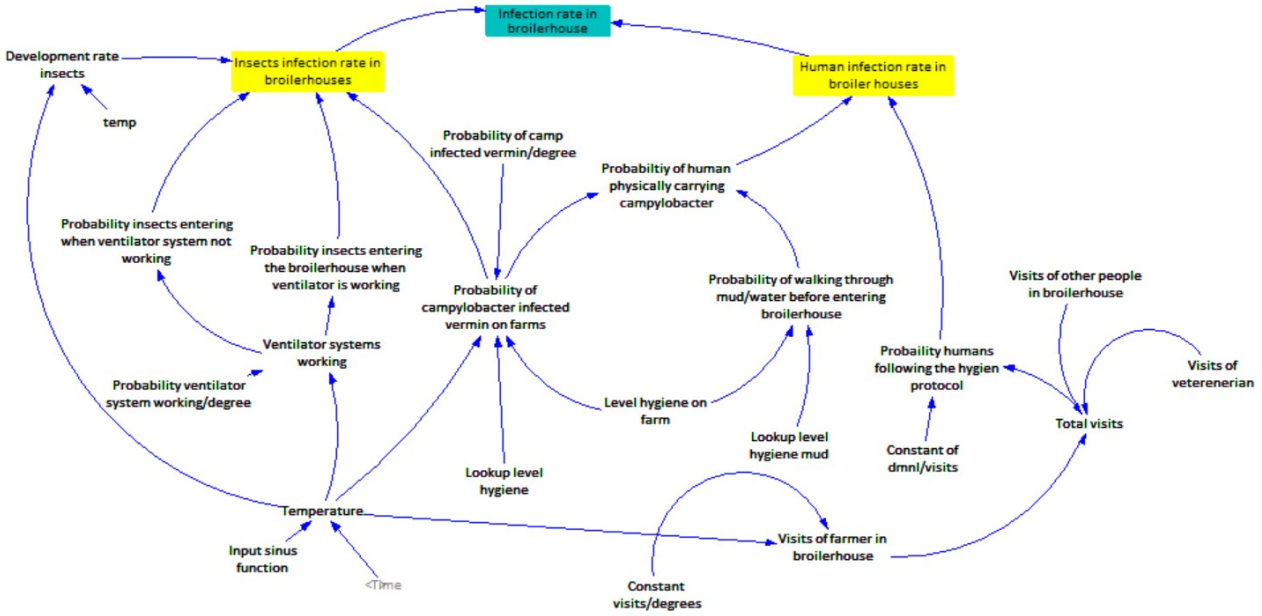


Figure 4.4: Conceptual model of infection rate in farmhouse

4.3.2 Conceptualization submodel 2: Thinning process

During the thinning or depopulation process, both the removed chickens and the remaining chickens can get infected. The sub-model called "thinning process" is focused on the infection rate after thinning, which can infect the remaining chickens. According to Allen et al. (2008) there is a probability that the Campylobacters may come from the boots, clothing, and hands of the so-called catching team, the transport crates, or forklift trucks. According to the interview B.2.9 the infection rate after thinning is based on the Catchers infection rate and the material infection rate. The catchers' infection rate is based on three different variables, which are Probability of getting infected by other farmhouse, probability of catchers getting in touch with Campylobacter on the farm and probability of catchers following the hygiene protocol. The probability if farmers already wear Campylobacter with them, is based on the infection rate in broiler-houses and the probability that the catching group arrives from another farmhouse. To get in touch with Campylobacter, the catching group will be seen as extra visitors, entering the broilerhouse at one point in time. So the probability of human physically carrying Campylobacter in combination with the amount of the catching group, will influence the probability of catchers getting in touch with Campylobacter positively. The amount of the catching group also affects the probability of infecting chickens by catch group. This factor also depends on the fact if the catching group follows the hygiene protocol.

In the EU, containers and trucks are always cleaned and disinfected before re-use for a different farm. However, many studies report that crates and boxed are still contaminated with Campylobacters after cleaning and disinfection (Rasschaert et al., 2020). Based on this, the Material infection rate will be different for different countries and different slaughterhouses. The use of containers contaminated with Campylobacter can possibly cause a scenario of partial depopulation. Campylobacters, which are present on the crates, will be introduced into the broiler house with a significant remaining part of the chickens (Rasschaert et al., 2020).

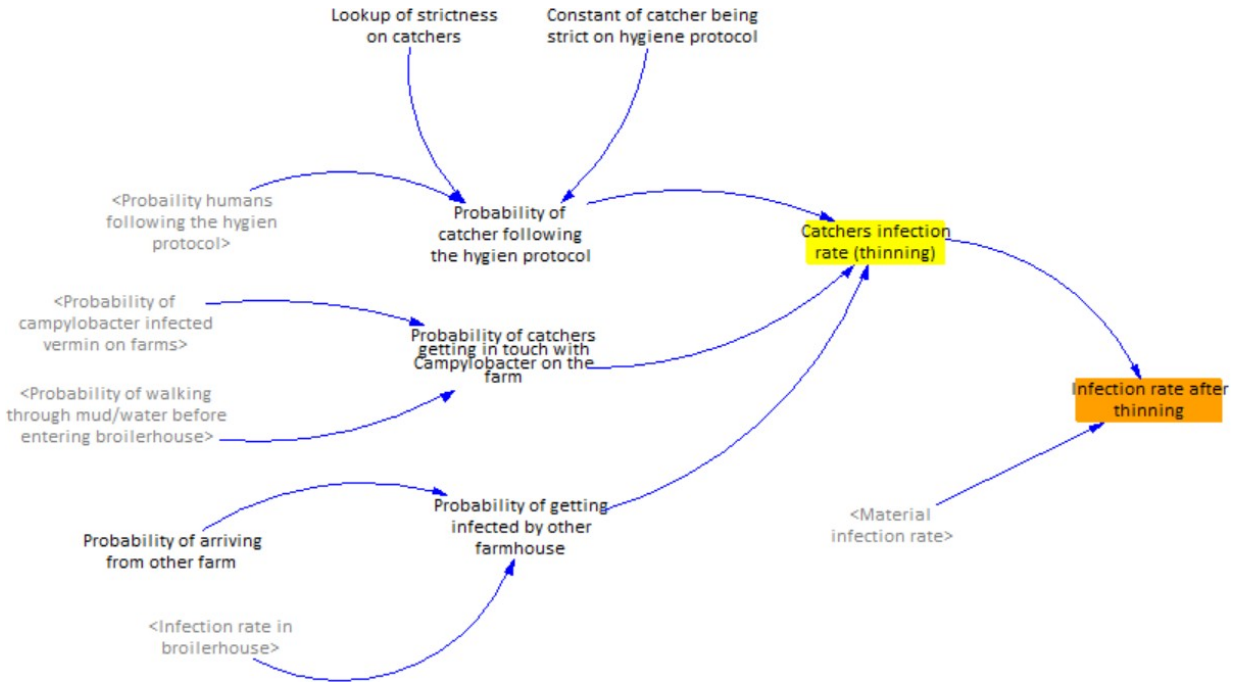


Figure 4.5: Conceptual model of infection rate thinning process

4.3.3 Conceptualization submodel 3: Transport process

The third submodel is developed to estimate the transport infection probability, which is the probability of chickens getting infected on transport to the slaughter houses. A significant correlation was found between the contamination of chickens and the faecal material of these chickens from the transport crates to the slaughterhouse (Rasschaert et al., 2020). In research for 14 flocks, the faeces in the crates were found Campylobacter positive, of which seven flocks were already Campylobacter positive during rearing. The other seven flocks were Campylobacter negative during rearing (Herman et al., 2003). Transport containers, even after the cleaning and disinfection process, can still contain various Campylobacters (Rasschaert et al., 2007). After transporting the flocks in containers, no significant intestinal colonization of the flocks by Campylobacters present in the transport containers is observed (Rasschaert et al., 2007), which means the infection probability on transport caused by material should be really small.

Besides the material infection rate, another factor that can influence the infection rate on transport is feed withdrawal time, which is the total time that chickens are deprived of food (Rasschaert et al., 2020). Insufficient feed withdrawal time may result in intestines still partially filled with feed and faeces.

During loading and transport of the birds, the animals may be subjected to stress due to crowding, motion, temperature fluctuations and food and water deprivation (Rasschaert et al., 2020). In stressed animals, the peristaltic movement of the intestines may increase, leading to more excretion of faeces and pathogens [Interview B.2.1]. This is shown in the model with the factor called Probability of excretion of faeces and pathogens. If this probability increases, this will also influence the material infection rate.

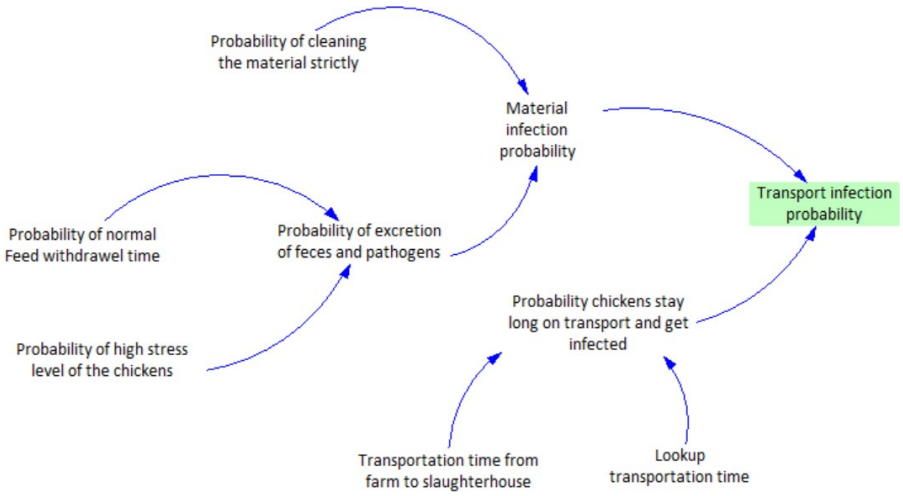


Figure 4.6: Conceptual model of transport process

4.3.4 Conceptualization submodel 4: Campylobacter in Slaughterhouses

According to (Herman et al., 2003) four of the seven slaughterhouses, which received Campylobacter negative chickens, were able to deliver them almost all as negative chicken carcasses. Although in two other slaughterhouses, all or nearly all the carcasses were contaminated with Campylobacter. In the slaughter process, it is crucial to take into account two contamination moments. The first one is the carcass contamination during slaughtering, which can occur during three different slaughter proccesses: scalding, plucking and evisceration (Rasschaert et al., 2007). An overview of these three steps in the complete slaughtering process is given in the figure 4.7 below. In the model, these three different moments are modelled as three separate probabilities which end up in one main factor, which is called probability of carcass contamination. When this happens, the gastrointestinal tract leaks Campylobacter-contaminated faecal material [Interview B.2.8]. The second one is the cross-contamination of previously slaughtered flocks or via the slaughter equipment. Therefore two different probabilities are given: Probability of contamination via the slaughter equipment and probability of cross-contamination of previously slaughtered flocks. These two form the Probability of cross contamination [Interview B.2.8].

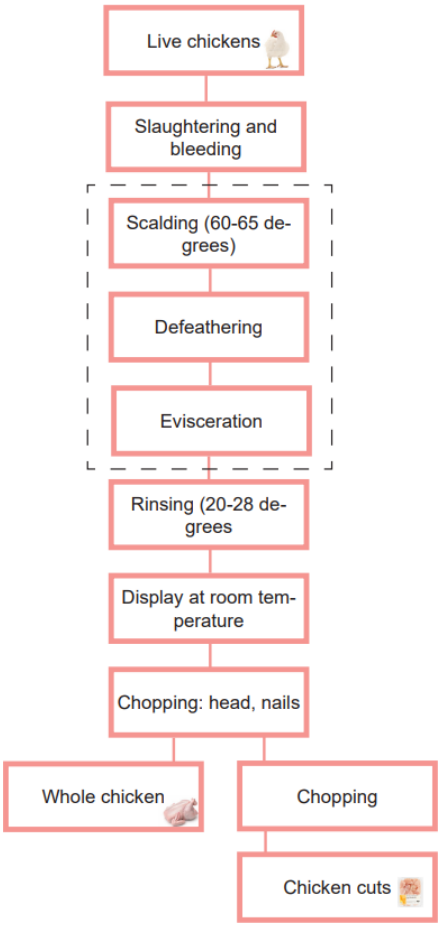


Figure 4.7: Production process in chicken slaughterhouses

During the different steps described in the figure above, Campylobacter contamination can occur from equipment, surfaces and water. Bacteria from the air and the environment in slaughterhouses can contaminate chicken meat (Rouger et al., 2017). The skin of poultry carcasses and cuts is directly in contact with air and equipment surfaces and so easily contaminated with Campylobacter (Rouger et al., 2017). At the slaughterhouse contamination could originate from other broiler flocks or it could be due to poor cleaning (Rossler et al., 2020). Therefore the Probability of poor cleaning is also integrated into the submodel and influences the probability of contamination via the slaughter equipment. The probability of poor cleaning is split up into probability of human working in the slaughterhouse strictly and probability of using the right water temperature.

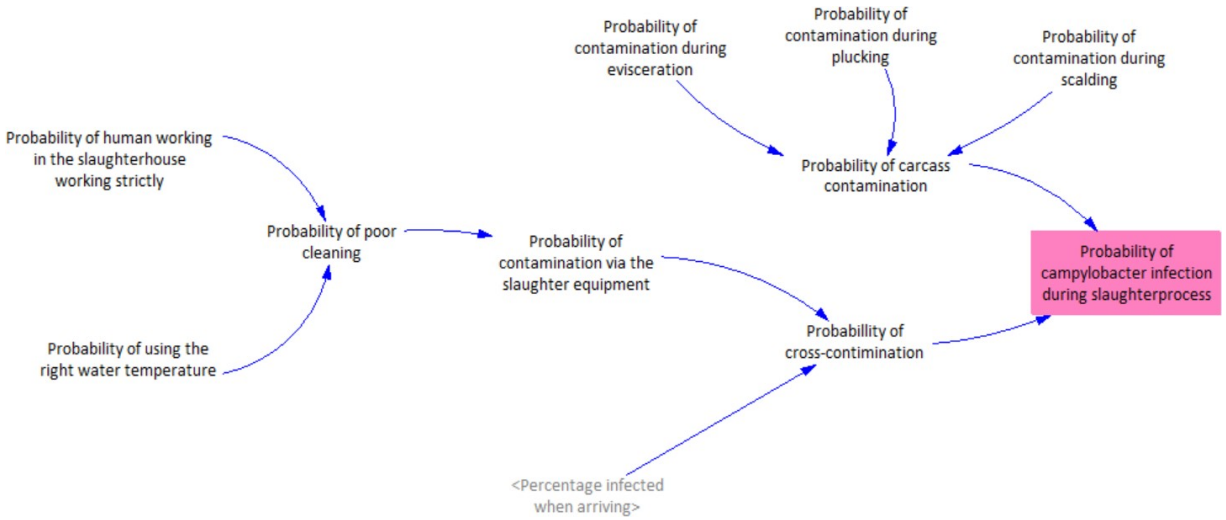


Figure 4.8: Conceptual model of slaughter process

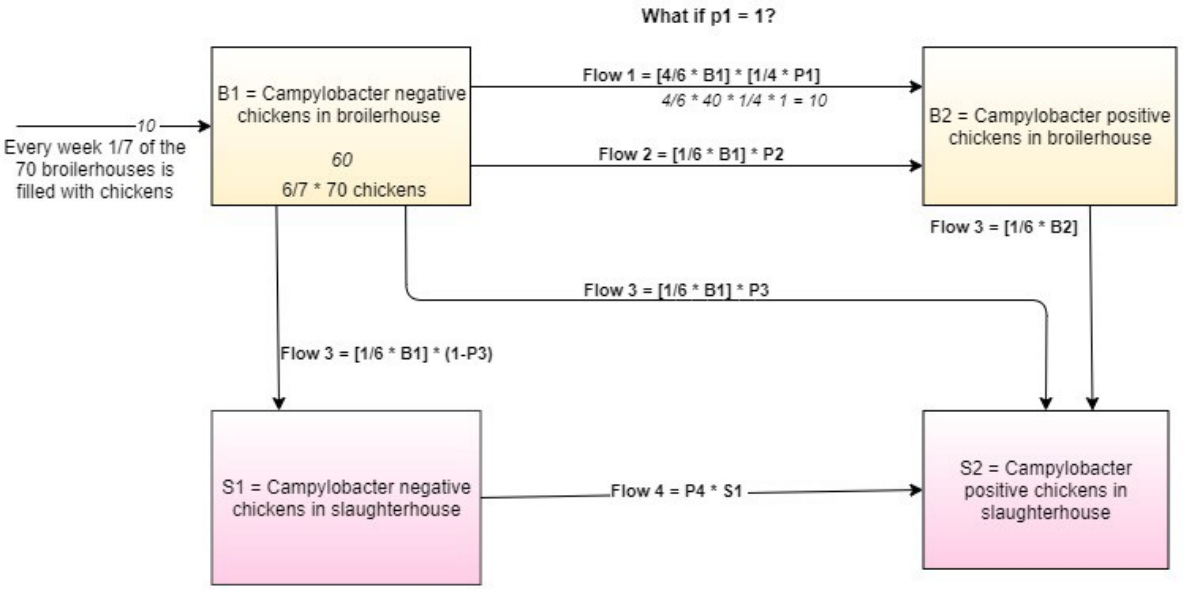
4.4 Model formalization

According to Pruyt (2013), the model formalization phase formulates an SD simulation model of the causal theory, which is developed in the model conceptualization phase. The formalization can be seen as the switch from a qualitative model to a quantitative model. In this section first, the details of the leading stock-flow structure will be elucidated, followed by the explanations of the equations and variables used in the different sub-models. In appendix C, an overview of the factors and its details (names, equations, units and references) is given.

4.4.1 Model formalization of the main model

The period for conventional chickens to grow up in a broiler house is six weeks. After these six weeks, the broiler house will be cleaned and will be prepared for new chickens arriving from hatcheries. The total duration of the process happening on-farm is seven weeks. For this model, the assumption is made that every week on 1/7th of the farms, new chickens arrive, on 1/7th of the farms' chickens are thinned out, and on 1/7th of the farms, the left-over (after the thinning process) chickens are caught by the catch crew to transport to the slaughterhouses. Every week 1/7th of the broiler houses will be empty. Therefore, the total occupancy is 6/7th of the total amounts of chickens that fit in the broiler houses in the Netherlands…..

In figure 4.10 an overview of the main stocks, flows, infection probabilities and explanations is given. The pink text shows what the probabilities and flows are called in the Vensim model.



Explanation of the probabilities

P1 = Probability chickens getting infected in broiler house = Probability of a chicken getting infected in broiler house during the 4 weeks the chickens is susciptible

P2 = Probability of infection after thinning = Probability of a chicken getting infected after the thinning process

P3 = Transport infection probability = Probability of a chicken getting infected during the transport process

P4 = Probability infection during slaughter process = Probability of a chicken getting infected during the slaughtering process

Explanation of the flows

Flow 1 = Chickens in broiler house getting colonized = The amount of Campylobacter negative chickens that get infected per week by the probability of getting infected in the broilerhouse. Every week 4/6th of the chickens will be susceptible to get infected in the broilerhouse. The probability happens over 4 weeks and therefore should be divided by 4 to determine the weekly probability.

Flow 2 = Chickens getting colonized after thinning process = The amount of Campylobacter negative chickens that get infected per week by the probability of a chicken getting infected after the thinning process. Every week 1/6th of the chickens which are in the sytem, is in week 6 and therefore the flow is multiplied with 1/6.

Flow 3 = Chickens getting infected during transport = The amount of Campylobacter negative chickens that is still negative but get infected on transport. The flow is multiplied with 1/6 to have the amount of transported chickens per week.

Flow 4 = Chickens getting infected during slaughter process =Every week 1/6th of all chickens in the system is in the slaughterhouse. During this process the chickens can get infected. This is shown by the equation of P4 * S1.

Explanation of the italic numbers

The Italic numbers are used as an example for the number of broiler houses in the Netherlands. So imagine every week, 10 broiler houses are filled with chickens arriving from the hatcheries. In total 60 of the 70 broiler houses in the Netherlands will be occupied with chickens. If the p1 = 1, every week 10 broiler houses will get infected due to p1.

Figure 4.10: Explanation of the different infection probability flows

As can be seen in figure 4.10 every week, new chickens will arrive from hatcheries to different broiler houses in the Netherlands, which will be 1/7th of the total occupancy of the broiler houses. The chickens coming from hatcheries transported to broiler house variable, therefore, is the complete number of chickens in the Netherlands at this moment divided by 7. This flow ends in the stock Campy negative chickens in broiler houses, which has five different outflows. The first outflow, flow 1, indicates the chickens in broiler houses getting colonized, which is influenced by the factor Probability of Campylobacter infection in broiler house (P1). Most flocks become infected only 2 to 3 weeks after the placement in the broiler houses, which is the so-called lag phase (Newell and Fearnley, 2003). The reason for this lag phase is not fully understood but may include immunity passed on from parent stock (Magazine, 2017). Therefore the chickens can only get

infected 4 out of the six weeks that they are in the broiler house, so in the equation, an extra factor of 4/6 is added in the model.

A second moment that the chickens can get infected in broiler houses is during and after the thinning process (flow 2), as can be seen in figure 4.10. After five weeks in the process, a part of the chickens will be caught to be transported to the slaughterhouses, which is assumed to be on average 30%, based on different interviews. The flow Chickens getting colonized after thinning process is influenced by P2, which is the probability chickens getting infected after thinning process. The dead chickens in broiler-houses are estimated by the multiplication of the chickens in broiler houses and the death rate in broiler houses. The death rate is the rate per cycle, and therefore this flow is divided by the total time of one period, which is six weeks. According to the European broiler regulations (2007), the chicken loss should be lower than (1 + 0.06* age of the flock)%. So when the flocks are around six weeks old, the percentage of chickens who die in the broiler-houses before getting slaughtered should be lower than 3.52% (Lourens and Steentjes, 2008). Based on this percentage and on the information obtained from the interviews which are summarized in the table B.1 below, the death rate in farmhouses is developed, which will be between the 2% and 3%. Every week in one-seventh of all broiler houses the chickens are placed on transport to be transported to the slaughterhouses. In the system, this is 1/6th of the total chickens as can be seen in flow 3 in figure 4.10. On transportation, chickens can get infected. In subsection 4.4.4, this infection process will be explained in detail. The flows are divided by seven because this is the total cycle time. So every week 1/6th part of chickens will be placed on transport. The negative chickens in the broiler houses can turn into positive chickens if they get infected during the transport process. The probability of getting infected during the transport process is based on different other variables and parameters which are explained in subsection 4.4.4. This flow ends in the same stock as the Campylobacter positive chickens transported, which shows the flow of chickens who were already infected in the broiler houses. Another part of the chickens will not get infected on transport, and this flow is estimated by multiplying the Campylobacter negative chickens and (1-probability of transport infection). This chicken flow is also divided by 6.

The chickens all end up in the slaughterhouse stocks. The Campylobacter negative chickens in the slaughterhouse can get infected during the slaughter process (flow 4) and are therefore multiplied by the probability of Campylobacter infection during slaughter process (p4). A more in-depth explanation of the infection in slaughterhouses is given in subsection 4.4.5. The chickens which are not getting infected are estimated by the multiplication of the negative chickens and 1-probability of Campylobacter infection during slaughter process. The stock of Campylobacter positive chickens arriving in the slaughterhouse has one outflow, which is called Campylobacter positive chickens being slaughtered per week. This outflow and the outflow of chickens turning positive during the slaughter process should be divided into the total of chickens being killed. The percentage of infected chicken meat will be the output of the model and will show per week what the rate of Campylobacter positive chicken meat is over time.

4.4.2 Formalization submodel 1: Infection rate in broiler houses (P1)

The infection rate in broiler houses is developed based on the insects infection rate in broiler houses and the human infection rate in broiler houses. The temperature has an influence on both of these factors. An explanation of the most important variables is given below.

Temperature

In the model, the factor Temperature shows the average temperature in the Netherlands at a certain Time, which is based on data [Maximum average monthly temperature in the Netherlands 2017]retrieved from

Statista (2017). This variable is dependent on the Time variable. The following sinus equation is therefore estimated, which is based on data retrieved from figure C.1:

$$Temperature = 13.45 + 8.45 * \sin(\frac{2 * 3.14}{52}) * (Time - 17)$$

Development rate of insects

The development rate of insects is based on temperature. According to Régnière et al. (2012) "The development rates of insects are calculated as the inverse of observed development time and are expressed as proportions of total stage duration per unit of time". Several studies tried to to quantify the influ- ence of temperature on insect development rates (Damos and Savopoulou-Soultani, 2012). Insects are slow developing in spring, but rapid developing in summer. This explains the fact that the growth and development rates increase almost linearly with temperature (Gilbert and Raworth, 1996).

This insect development rate is based on the following equation, which is retrieved on data from Damos and Savopoulou-Soultani (2012), which is shown in appendix C. By knowing different data points a linear equation could be developed.

$$Insect\ Development\ rate = 0.041 * Temperature - 0.0412$$

Insects infection rate in broiler houses

The insects' infection rate is, as can be seen in the conceptual model in figure 4.4, based on four different factors. Two of these factors are based on the fact if the ventilators systems are working. The Probability insects entering when ventilator systems not working is based on (1-ventilator systems working)*0.5. While the Probability insects were entering when the ventilator system is working is based on ventilator systems working*0.5. The number of 0.5 is chosen to show that insects will not always enter the broiler house through the ventilator systems. The factor ventilator systems working is based on the temperature. If the temperature is high, the probability that the ventilator system is working will be higher.

Visits of a farmer in broiler house

If the temperature increases, the farmer will visit the broiler house more often [Interview B.2.11]. The farmer visits his/her broiler house at least once per day, which is weekly visits in the model. When the temperature is high, the farmer will visit the broiler house around three times per day. These visits are also depending on if the chickens are sick, but this is not included in this model. The table 4.1 shows the numbers that are used for creating the following linear equation.

$$Visits\ of\ farmer\ in\ broiler\ house = 0.82 * T emperature + 2.8$$

For the directional coefficient of 0.82, a constant variable is created to show the visits per degree easily. In the table the on average minimum and maximum temperature are shown in the Netherlands. Also, themaximum and minimum visitors are shown, which numbers are based on assumptions obtained from the interviews.

Table 4.1: Visits of farmer in broiler house depending on the temperature

Factor	*Value*
Maximum visits of farmer in broiler house	21
Minimum Visits of farmer in broiler house	7
Maximum temperature	22
Minimum temperature	5

Probability humans following the hygiene protocol

The probability of visitors are following the hygiene protocol is depending on this model on the number of visits. From the interviews with different actors [Interview B.2.3 and B.2.11], it became clear that farmers become looser in following their protocols when more visits take place. A perfect example to illustrate this is based on the outside temperature. When the temperature increases, farmers will have to visit their broiler house more often to see if the chickens still are feeling well. When entering three times or even more the broiler house, people will quickly forget about switching clothing. In table 4.2, an overview is given of the numbers that are used to create the following linear equation to estimate the probability:

$$Probability\ of\ humans\ following\ the\ hygiene\ protocol = -0.029 * Visits + 1.16$$

For the number -0.029, a constant variable in the model is developed to show the decrease in probability per visit. The assumption is done that the probability of a visitor following the hygiene protocol is similar for all different visitors, such as veterinarians or family.

Table 4.2: The probability of humans following the hygiene protocol depending on the total visits

Factor	*Value*
Maximum visits/week	23
Minimum visits/week	9
Maximum probability humans following hygiene protocol	0.9
Minimum probability humans following hygiene protocol	0.5

Probability of Campylobacter infected vermin on farm

The probability of Campylobacter infected vermin on farms is influenced by two different factors, which are temperature and the hygiene level. A linear function is developed in which the probability is chosen as the dependent factor and temperature is the independent factor. The values determined to create this linear function are given in table 4.3. The level of hygiene is implemented in the so-called "B" value in the linear equation. When the level of hygiene is high, the "B" value will decrease, so the probability of vermin will be lower. When the level of hygiene is low, the probability of vermin will be higher.

$$Probability\ of\ Campylobacter\ infected\ vermin\ on\ farm = 0.03 * temperature - 0.05 + (LookupLevelHygiene"B")$$

Table 4.3: Infected vermin on farms depending on temperature and hygiene level

Factor	*Value*
Minimum temperature	5
Maximum temperature	22
Minimum probability of Campylobacter infected vermin	0.2
Maximum probability of Campylobacter infected vermin	0.9

A lookup function is used to change the level of hygiene on the farms. The table 4.4 below shows which values are used.

Table 4.4: Values used in lookup "level hygiene"

Hygiene level (0 = low, 4 = high)	*Value used in equation (B)*
0	0.2
1	0.18

2	0.15
3	0.1
4	0.05

Ventilator systems working

The factor ventilator systems working is dependent of the variable called temperature. The assumption is made, which is based on the conversations with the farmers that the ventilator systems are more often used when the temperature is higher. Based on this information the table 4.5 is created. Based on if the ventilator systems are working a probability is given to the "insects entering the broiler house" variable. If the systems are working the probability will be 0.6, and when the systems are not working, the probability will be 0.4. These numbers are close to each other because insects can also enter the broiler houses through different other ways, such as through crevices.

The equation to estimate the factor Ventilator systems working is the following:

$$Ventilator\ systems\ working = Probability\ of\ ventilator\ systems\ working\ per\ degree * T\ emperature + 0.04$$

Table 4.5: Ventilator systems working depending on temperature

Factor	*Value*
Minimum temperature	5
Maximum temperature	30
Minimum probability of ventilator systems working	0.1
Maximum probability of ventilator systems working	1

4.4.3 Formalization submodel 2: Infection rate after the thinning process (P2)

The second sub-model shows the factors which influence the infection rate after thinning. This infection rate is based on two infection rates which are called catchers infection rate (thinning) and the material infection rate. The material infection rate will be explained in the following submodel. For this model, the choice is made not to split up the percentage of chickens which are caught earlier. Because in 1/7th of the broiler houses will happen the thinning process (10 per cent of the chickens), and in another 1/7th of the broiler houses will the left-over chickens be caught (90 per cent). This means that every week 1/7th of the total of all chickens in the Netherlands is caught or 1/6th of all chickens in this system (100 per cent).

The catcher's infection rate is based on the multiplication of (1 - probability of catcher following the hygiene protocol) and the sum of the probability of catchers getting in touch with Campylobacter on the farm and the probability of getting infected by another farmhouse. The sum of these two probabilities gives the total probability that the catchers get in contact with Campylobacter. However, when they are wearing Campylobacter and they follow the protocol, there is a probability they do not transmit it into the broiler house. Therefore the sum is multiplied with 1 - probability of catcher following the hygiene protocol.

Probability of catcher following the hygiene protocol

The probability of catchers following the protocol is based on a lookup function which is called lookup of strictness on catchers and the probability humans following the hygiene protocol.

The assumption is made that the probability of catchers following the hygiene protocol is influenced by the probability of humans following the hygiene protocol. When in general, this probability is more significant,

the assumption is made that the farmer will be strict on the catchers following the protocol. Besides this, the probability of catchers following the protocol is also based on the strictness of the catchers on the protocol. If the catchers are strict on the protocol, the probability of following it will be higher.The table

4.6 shows the values that are used in the lookup function. All values are between 0.9 and 1 because the assumption is made that in general, the catchers will be strict on following the protocol and will often follow the protocol of the farmers.

Table 4.6: probability catchers following the hygiene protocol

Strictness of catcher on hygiene protocol (0 = low, 1 = high)	*Value used in equation (B)*
0	0.9
0.2	0.91
0.4	0.92
0.6	0.93
0.8	0.94
1	0.95

Probability of catchers getting in touch with Campylobacter on the farm

The probability of catchers getting in touch with Campylobacter on the farm is based on the multiplication of the two factors probability of Campylobacter infected vermin on farms and probability of walking through mud/water before entering the broiler house, which are in the first submodel. A multiplication of these two factors is necessary. People or catchers can walk through mud, which is not infected with vermin. The probability of then getting infected with Campylobacter is zero. Also, the mud can be infected with Campylobacter, but people do not walk through the mud. In this way, the catchers will also not get infected. The probability will then be zero.

Probability of getting infected by other farmhouses

The probability of getting infected by another farmhouse is based on the infection rate in broiler house from the first sub-model and the probability of the catch crew arriving from another farm. The assumption is made that the catch crew will come half of the time from another farm.

4.4.4 Formalization submodel 3: Infection rate on transport (P3)

The infection rate on transport is based on the multiplication of the material infection rate and the probability that chickens stay long on transport and get infected. The two probabilities are multiplied with each other to show the transport infection probability is depending on both. When the material infection probability is zero, the probability of chickens staying long on transport is negligible. When chickens stay long on clean transport, they cannot get infected. A lookup function is developed, which shows the time that chickens stay on transport and the probability the chickens get infected.

Within four hours after exposure to Campylobacters in naturally contaminated crates chickens became Campylobacter colonized. Another study showed that birds were transported in crates that were still harbouring Campylobacters after cleaning and disinfection. Although, those birds were not colonized. They were in the crates for about only two hours. Based on this information, the following lookup table is developed.

Table 4.7: probability chickens stay long on transport and get infected

Time on transport (1 hour = low, 8 hours= high)	*Probability of chickens getting infected*
1	0
2	0
3	0.01
4	0.02
5	0.03
7	0.04
8	0.04

The material infection rate is based on probability of cleaning the material strictly and the probability of excretion of faeces and pathogens, which is a multiplication of the probability of the stress level of chickens and the probability of a standard feed withdrawal time. To estimate both probabilities multiplications are used to show the dependence of the probabilities on each other.

4.4.5 Formalization submodel 4: Infection rate in slaughterhouses (P4)

The probability of Campylobacter infection during the slaughter process is based on the probability of carcass contamination and the probability of cross-contamination. Concerning Campylobacter and poultry slaughter, the available literature often showed common trends: reductions by scalding, instead increase by plucking, no changes or increases by evisceration, and decreases by washing and chilling (Rasschaert et al., 2020). Based on this information probabilities are assumed for the different factors which influence the probability of carcass contamination.

The three different probabilities are based on data which is retrieved from the article of Rasschaert et al. (2020). The mean increases (cfu/g) of Campylobacter after the specific steps are divided by the mean concentration on the carcass before the specific intervention step. In the table below is shown which values are used.

Table 4.8: Probabilities of contamination after processing steps

	Mean concentration on the carcass before processing step	Mean concentration on the carcass after processing step	Equation to estimate probability	**Used probability**
Scalding	3.2	1.8	(1.8-3.2)/3.2	-0.4375
Plucking	1.4	2.1	(2.1-1.4)/1.4	0.5
Evisceration	2.1	2.5	(2.5-2.1)/2.1	0.19

The probability of cross-contamination is based on the probability of contamination via the equipment multiplied with the percentage infected chickens when arriving in the broiler house, which value is based on different parameters from the primary stock-flow model. Multiplication is used. This can be explained by the example of a probability of zero of contamination via the slaughter equipment. If this probability is zero, cross-contamination will not be possible.

…

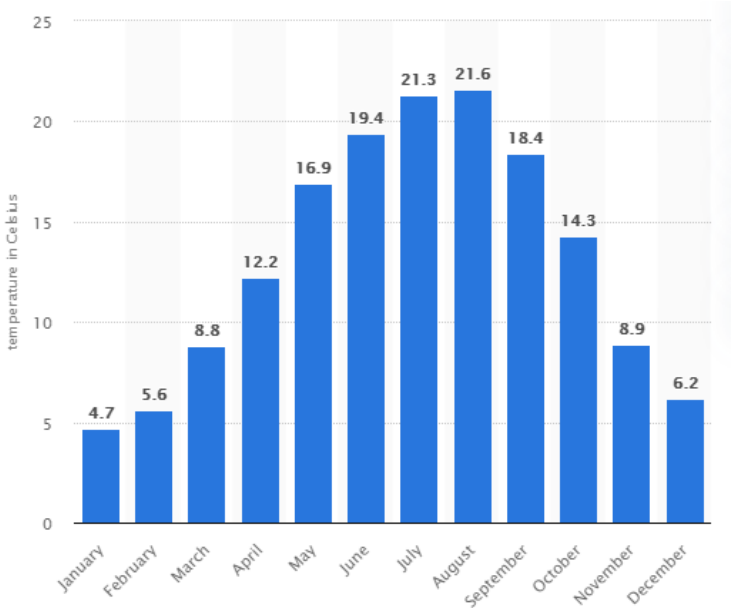
[End of extract from Chapter 4 of Rommens (2020)]

Details of the Model

[Extract from Appendix C of Rommens (2020)]

In the following appendix the details of the model are showed. For the main stock flow model and the various submodels, tables are created to show the values and number that are used. Also, the tables show the source on which the values and equations are based.

The temperature variable equation is based on the data from figure C.1. The development rate equation



is based on the linear equatiom from figure C.2.

Figure C.1: Maximum average monthly temperature in the Netherlands in 2017 Statista (2017)

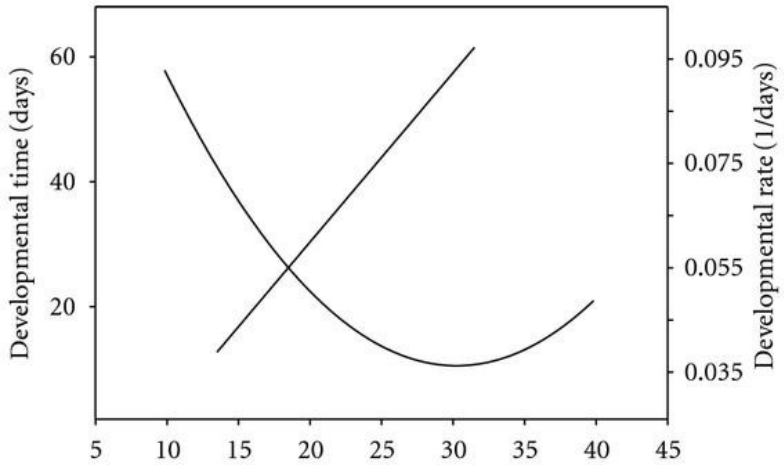


Figure C.2: Development rate of insects over temperature Damos and Savopoulou-Soultani (2012)

In figure C.3 the main stock flow model is shown and in the table below the details of the main stock flow model are shown.

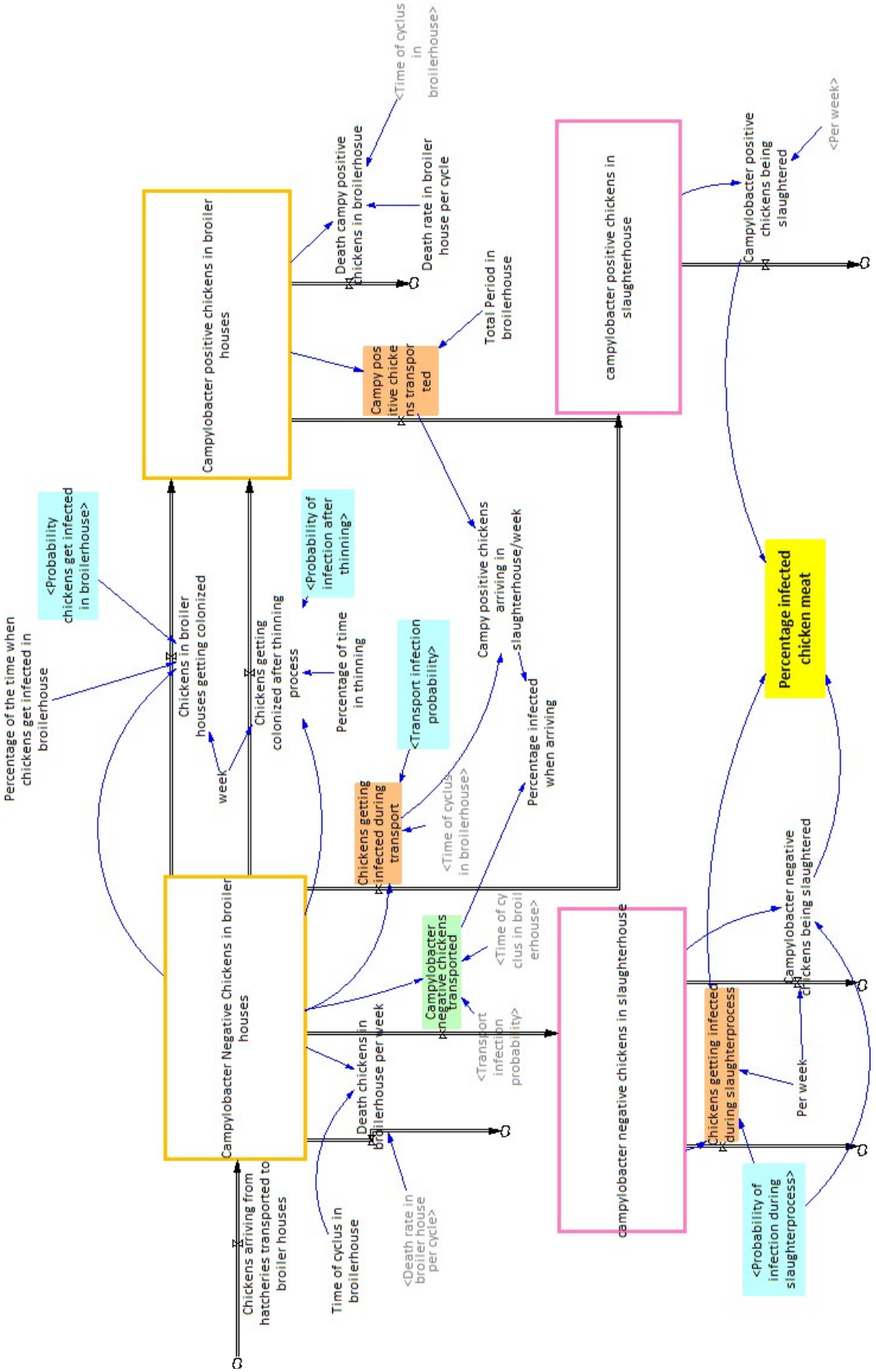


Figure C.3: Conceptual stock flow structure

Table C.1: Details of the stock flow model

Name factor	Units	Initial value	Equation	Source
Time of cyclus in broilerhouse	week	6	x	Interview Farmers
Chickens arriving from hatcheries transported to broiler houses	chickens/ week	x	(4.86843e+07*(6/7))/ Time of cyclus	CBS (2019)
Campy Negative Chickens in broiler houses	chickens	48684314* (6/7)	MIN(Chickens arriving from hatcheries transported to broiler houses-Campylobacter negative chickens not getting infected during slaughtering-Chickens getting colonized after thinning process-Chickens getting infected during slaughterproces-Chickens getting infected during transport-Chickens in broiler houses getting colonized-Chickens not getting infected during transport-Death chickens in broilerhouse per week , ((6/7)*4.86843e+07))	Wageningen University and Research (2020)
Death rate chickens in broiler houses	dmnl		0.02	Interview Farmers
Dead campy negative chickens in broiler houses	chickens/ week	x	(Campylobacter Negative Chickens in broiler houses * Death rate in broiler house per cycle)/ Time of cyclus	x
Chickens in broiler houses getting colonized	chickens/ week	x	(Campylobacter Negative Chickens in broiler houses * Probability of Campylobacter infection in broilerhouse * Possible part of the weeks of getting infected in broilerhouse)/Time of cyclus	x

Table C.1: Details of the stock flow model

Name factor	Units	Initial value	Equation	Source
Percentage of Time when chickens can get infected in broiler house	dmnl	4/6	(Campylobacter Negative Chickens in broiler houses * Probability of Campylobacter infection in broilerhouse * Possible weeks of getting infected in broilerhouse)/Time of cyclus	Interview Farmers
Chickens getting colonized after thinning process	chickens/ week	x	(Campylobacter Negative Chickens in broiler houses * Infection rate after thinning)/Time of cyclus	Own interpretation
Percentage of time after thinning	dmnl	1/6		
Campy positive chickens in broiler houses	Chickens	0	MIN(Chicken flocks getting colonized after thinning process+ Chickens in broiler houses getting colonized-"Campy positive chickens getting caught (thinning process)"- Campy positive dead chickens in broiler houses-Left over campy positive chickens getting caught, (6/7)*100000)	Own interpretation
Death Campy positive chickens in broilerhouse	chickens/ week		(Campylobacter positive chickens in broiler houses*Death rate in broiler house per cycle)/Time of cyclus	Own interpretation
Probability chickens get infected in broiler house (submodel)	dmnl	x	Insects infection rate in broilerhouses+ Human infection rate in broiler houses	Own interpretation
Chickens in broiler houses getting colonized	chickens/ week	x	(Campylobacter Negative Chickens in broiler houses * (Probability chickens get infected in broilerhouse)* Percentage of the time when chickens get infected in broilerhouse)/Time of cyclus	Own interpretation
Chickens getting colonized after thinning process	chickens/ week		(Campylobacter Negative Chickens in broiler houses * Infection rate after thinning)/ Time of being in broiler house	Own interpretation
Infection rate after thinning per cyclus	dmnl		"Catchers infection rate (thinning)"+ Material infection rate	Own interpretation

Table C.1: Details of the stock flow model

Name factor	Units	Initial value	Equation	Source
Chickens getting infected during transport	chickens/ week		(Campylobacter Negative Chickens in broiler houses* Transport infection probability)/ Time of being in broiler house	Own interpretation
transport infection probability	dmnl		Material infection rate*Probability chickens stay long on transport and get infected	Own interpretation
campy negative chickens on transport	chickens/ week		DELAY3((Campylobacter Negative Chickens in broiler houses*(1-Transport infection probability))/ Time of cyclus, 0.5)	Own interpretation
Chickens getting infected during slaughterprocess	chickens/ week		(campylobacter negative chickens in slaughterhouse *Probability of campylobacter infection during slaughterprocess)/Per week	Own interpretation
Probability of campylobacter infection during slaughterprocess	dmnl		Probability of carcass contamination +"Probabillity of cross-contimination"	Own interpretation
campy negative chickens being slaughtered	chickens/ week		(Campylobacter Negative Chickens in broiler houses/Time of cyclus)-Chickens getting infected during transport-Chickens getting infected during slaughterproces	Own interpretation
Campylobacter positive chickens being slaughtered	chickens/ week		Campylobacter positive chickens in broiler houses/Per week	Own interpretation
Init neg chickens	chickens		(4.86843e+07)*(1/7)	Own interpretation

The table below shows the details of the first submodel.

Table C.2: Details of submodel 1

Name factor	Units	Initial value	Equation	Source
Time	Week	x	x	Hald et al (2004)
Temperature per week	Degrees	x	13.45 +(8.45 * SIN(((2*3.14)/52)* (Input sinus function* Time-17)))	Statista (2017)

Table C.2: Details of submodel 1

Name factor	Units	Initial value	Equation	Source
Development rate insects	dmnl	x	MAX(0.041 * Temperature*(1/temp)-0.0412, 0.1)	Damos and Savopoulou-Soultani (2010)
Probability ventilator systems working/degree	dmnl/degree		0,042	Interview farmers
Ventilator systems working	dmnl	x	"Probability ventilator system working/degree" * Temperature + 0.04	Interview farmers
Probability insects entering when ventilator system not working	dmnl	x	(1-Ventilator systems working)*0.5	Interview farmers
Probability insects entering the broilerhouse when ventilator is working	dmnl	x	Ventilator systems working*0.9	Interview farmers
Insects infection rate in broiler house	dmnl	x	Development rate insects* (Probability insects entering the broilerhouse when ventilator is working+Probability insects entering when ventilator system not working)*Probability of campylobacter infected vermin on farms	Gilbert and Raworth, 1996
"Probability of camp infected vermin/degree"	dmnl/degree	x	0.03	Assumption
Probability of campylobacter infected vermin on farms	dmnl	x	"Probability of camp infected vermin/degree"* Temperature - 0.05 + Lookup level hygiene (Level hygiene on farm)	Assumption
Level hygiene on farm	dmnl	x		Assumption
Lookup level hygiene on farm	dmnl	x	[(0,0)-(10,10)], (0,0.2),(1,0.18),(2,0.15), (3,0.1),(4,0.05)	Assumption

Table C.2: Details of submodel 1

Name factor	Units	Initial value	Equation	Source
Lookup level hygiene mud	dmnl	x	[(0,0)-(10,10)], (1,0.8),(2,0.6),(3,0.4), (4,0.2)	Assumption
Infection rate in broiler house	dmnl	x	(Insects infection rate in broilerhouses+Human infection rate in broiler houses)	Assumption
Human infection rate in broiler houses	dmnl	x	Probabiltiy of human physically carrying campylobacter*(1-Probability humans following the hygien protocol)	Assumption
Probability of humans physically carrying campylobacter	dmnl	x	Probability of campylobacter infected vermin on farms* "Probability of walking through mud/water before entering broilerhouse"	Assumption
Probability of walking through water/mud before entering broilerhouse	dmnl	x	Lookup level hygiene mud (Level hygiene on farm)	Interview Farmers and own assumption
Visits of veterinarian	visits	x	1,000	Interview Farmers and Vetenerian
Visits of the farmer	visits	x	"Constant visits/degrees"* Temperature+2.8	Interview Farmers and Vetenerian
Visits of other people	visits	x	1,000	Interview Farmers and Vetenerian
Total visits	visits	x	Visits of farmer in broilerhouse +Visits of other people in broilerhouse+Visits of veterenerian	Interview Farmers and Vetenerian
Probability humans following the hygiene protocol	dmnl	x	("Constant of dmnl/visits"* Total visits)+1.16	Interview Farmers and Vetenerian
Constant of dmnl/visits	dmnl/visits	x	-0,029	Assumption
Constant visits/degree	visits/degree	x	0.82	Assumption

The table below shows the details of the second submodel.

Table C.3: details of submodel 2

Name factor	Units	Initial value	Equation	Source
Probability of Campylobacter infection after thinning	dmnl	x	("Catchers infection rate (thinning)"+ Material infection probability)	Interview catch group
Material infection probability	dmnl	x	Probability of excretion of feces and pathogens * (1-Probability of cleaning the material strictly)	Interview catch group
Catchers infection rate	dmnl	x	(1-Probability of catcher following the hygien protocol)*(Probability of catchers getting in touch with Campylobacter on the farm+Probability of getting infected by other farmhouse)	Interview catch group
Probability of catchers following the hygiene protocol	dmml	x	Lookup of strictness on catchers(Strictness of catcher on hygiene protocol)* Probability humans following the hygien protocol	Interview catch group and farmers
Lookup of strictness on catchers		x	[(0,0)-(10,10)],(0,0.9), (0.2,0.91),(0.4,0.92), (0.6,0.93),(0.8,0.94),(1,0.95)	Assumption
Strictness of catcher on hygiene protocol	dmnl	x	0.4	Assumption
Probability humans following the hygiene protocol	dmml	x	("Constant of dmnl/visits"* Total visits)+1.16	Interview catch group and farmers
Probability of campylobacter infected vermin on farms	dmml	x	"Probability of camp infected vermin/degree"*Temperature - 0.05 + Lookup level hygiene(Level hygiene on farm)	Interview catch group and farmers
Probability of waking through mud/water before entering broiler house	dmml	x	Lookup level hygiene mud (Level hygiene on farm)	Interview catch group and farmers
Probability of catchers getting in touch with Campylobacter on the farm	dmml	x	Probability of campylobacter infected vermin on farms*" Probability of walking through mud/water before entering broilerhouse"	Interview catch group and farmers
Probability of arriving from other farm	dmml	x	0.8	Interview catch group and farmers

Table C.3: details of submodel 2

Name factor	Units	Initial value	Equation	Source
Infection rate in broiler house	dmml	x	(Insects infection rate in broilerhouses+Human infection rate in broiler houses)	Interview catch group and farmers
Probability of getting infected by other farmhouse	dmml	x	Probability chickens get infected in broilerhouse* Probability of arriving from other farm	Interview catch group and farmers

The table below shows the details of the third submodel.

Table C.4: Details of submodel 3

Name factor	Units	Initial value	Equation	Source
Transport infection probability	dmnl	x	Material infection probability* Probability chickens stay long on transport and get infected	Interview Miriam
Material infection probability	dmnl	x	Probability of excretion of feces and pathogens * (1-Probability of cleaning the material strictly)	Interview Mirian
Probability chickens stay long on transport and get infected	dmnl	x	Lookup transportation time (Transportation time from farm to slaughterhouse)	Interview Catch Crew
Probability of cleaning the material strictly	dmnl	x	0.8	Interview Catch Crew
Probability of normal Feed withdrawel time	dmnl	x	0.2	Interview Catch Crew
Probability of high stress level of the chickens	dmnl	x	0.3	Interview Catch Crew
Transportation time from farm to slaughterhouse	dmnl	x	4	Interview Catch Crew
Lookup transportation time	dmnl	x	[(0,0)-(10,10)],(1,0),(2,0), (3,0.01),(4,0.02),(5,0.03), (6,0.04),(7,0.05),(8,0.06)	Interview Catch Crew

The table below shows the details of the fourth submodel.

Table C.5: Details of submodel 4

Name factor	Units	Initial value	Equation	Source
Probability of campylobacter infection during slaughterprocess	dmnl	x	(Probability of carcass contamination+ "Probabillity of cross-contimination")	Interview Slaughterhouse
Probability of carcass contamination	dmnl	x	Probability of contamination during evisceration+Probability of contamination during plucking+Probability of contamination during scalding	Rasschaert et al. (2020)
Probability of contamination during scalding	dmnl	x	-0,04375	Rasschaert et al. (2020)
Probability of contamination during plucking	dmnl	x	0,05	Rasschaert et al. (2020)
Probability of contamination during evisceration	dmnl	x	0,019	Rasschaert et al. (2020)
Probability of cross contamination	dmnl	x	Probability of contamination via the slaughter equipment*Percentage infected when arriving	Rasschaert et al. (2020)
Probability of contamination via slaughter equipment	dmnl	x	Probability of poor cleaning	Interview Slaughterhouse
Percentage infected when arriving	dmnl	x	"Campy positive chickens arriving in slaughterhouse/ week/(""Campy positive chickens arriving in slaughterhouse/week""+ Campylobacter negative chickens transported"	x
Probability of poor cleaning	dmnl	x	(1-Probability of using the right water temperature)* (1-Probability of human working in the slaughterhouse working strictly)	Interview Slaughterhouse
Probability of human working in slaughterhouse working strictly	dmnl	x	0.8	Interview Slaughterhouse
Probability of using the right water temperature	dmnl	x	0.8	Interview Slaughterhouse

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