INTRODUCING CULTIVATED MEAT TO THE DUTCH MARKET

A SYSTEM DYNAMICS MODELING APPROACH

Thesis submitted in partial fulfilment of the requirements for Master of Philosophy in System Dynamics from the University of Bergen.

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Abstract
The conventional production of meat proves to be unsustainable and is a big contributor to the greenhouse gas emissions in the Netherlands. As such there is a need for alternative more sustainable options. Cultivated meat, also known as lab-grown meat, seems to be a promising alternative. But the question remains how the introduction of cultivated meat impacts the market and how the system responds to its introduction. This research uses system dynamics as a modelling tool to explain the various mechanisms of the underlying structure which explores the introduction of cultivated meat to the Dutch market.

Naturally, there are delays in the market growth of a new product, especially considering the required technological advancements needed in the development of cultivated meat. When market share has grown it does have a significant effect on decreasing CO2eq emissions. Additional policies such as cattle restrictions and a meat tax can aid in accelerating and increasing the growth of the market share of cultivated meat. However, when the market share of cultivated meat increases, there are also several responses that can be perceived within the traditional meat industry.

Cultivated meat could potentially be a valuable alternative to traditional meat production. However, the introduction of cultivated meat could also invoke policy resistance as questions arises regarding the social and cultural feasibility of the various policies. Implementation obstacles with regard to these policies are not fully explored in this research and as such further research is warranted.

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Problem Background

Theoretical Background

What is cultivated meat and why does it have potential?

Alternatives to traditional meat production are needed as there are many concerns that the current food system brings along. One of these concerns is the unlikeliness that traditional animal agriculture is able to meet the increased protein demand caused by a growing population (Henchion et al., 2017). Furthermore, if animals are kept in close quarters, these can become a breeding ground for antibiotic-resistant bacteria and other diseases (Khanna et al., 2008; O'Neill et al., 2021). In addition to that, there are obvious ethical concerns regarding the welfare of the animals in the current system.

Another major concern is the substantial influence that livestock supply chains have on the environment (Lynch & Pierrehumbert, 2019). Animal agriculture is said to contribute 14.5% of all human-induced greenhouse gas emissions (Gerber et al., 2013). In 2013 Dutch pharmacologist Mark Post presented the first lab-grown cultivated meat burger at a press conference in London (Post, 2014). Over the last years, cultivated meat has been raised as a potential alternative to traditional meat production. Several studies indicate that the supply chain of cultivated meat products would emit fewer greenhouse gasses (Choudhury et al., 2020; Sinke & Odegaard, 2021). A preliminary life cycle assessment done by Choudhury et al. (2020) suggests that cultivated meat products could use 7-45% less energy and emit 78-96% fewer greenhouse gas emissions compared to traditional meat production. Ajena & Howard (2021) say that these stated emission calculations may be exaggerated as they expect the life cycle of cultivated meat products to be energy-intensive. Sinke & Odegaard (2021) predict that by 2030 cultivated meat could have a lower carbon footprint whilst also being cost-competitive with several conventional meat products as the cultivated meat industry becomes more efficient. They predict cultivated meat to reduce global warming impacts by 85-92% compared to conventional beef production if renewable energy is used in the production process of the cultivated meat products. Compared to chicken production, cultivated meat products would emit 17% less greenhouse gasses, and compared to pork production, a reduction of 52% is expected (Sinke & Odegaard, 2021).

Even though the introduction of cultivated meat products could potentially improve the mentioned concerns, it is a complex challenge to produce cultivated meat products that are scalable, high-quality and that can be produced at low-cost (O'Neill et al., 2021). The next section will go into more detail regarding the current status and obstacles of the production process of cultivated meat.

What has happened so far

After the first cultivated meat burger was presented in 2013, many companies were established in the pursuit to commercialize cultivated meat products (Choudhury et al., 2020). Currently Singapore is the only country to date that has already approved the sales of cultivated chicken bites, produced by the US company Eat Just, and are available in Singapore restaurant 1880 retailing at around $23 (Saleemuddin, 2021). In contrast, the burger developed by Mark Post in 2013, had an estimated costs of €250.000 (Saleemuddin, 2021). No cultivated meat company has formally applied for market authorization in the EU (Derbes, 2021).

It is clear that progress is being made regarding the production of cultivated meat products. However, there are still many challenges to overcome. One of these challenges is the scale of production. The growth medium that was used to produce the cultivated chicken bites for Singapore included foetal bovine serum (FBS), which needs to be extracted from foetal blood (O'Neill et al., 2021). FBS is expensive and contributes up to 80% of the production costs of cultivated meat products (Choudhury et al., 2020). Therefore, using FBS for large-scale meat cultivation is not viable. Additionally, obtaining FBS is not a slaughter-free process, defeating the purpose of developing slaughter-free meat. Finding an alternative to FBS is currently one of the main priorities of cultivated meat producers. Multiple companies have already indicated they are working with serum-free alternatives, including the Dutch company Mosa Meat, which was founded by Mark Post and whose products do not include any animal components (Butler, 2021). The company Eat Just, whose products are currently being sold in Singapore, are currently working with a plant-based serum for their next production line. This plant-based serum was not yet available when the Singapore approval process began in the previous years (Carrington, 2020).

There are companies that stated that 20,000 pounds of meat could be produced from a single cell sample (WhatisCultivatedMeat.com, 2022). However, this would require considerable technological progress in the next decade. There are several factors that influence the amount of meat that a cell sample can produce such as the type of cell, the growing conditions and the feed that is used as a growth medium (WhatisCultivatedMeat.com, 2022).

There are not only challenges in the production process. Another obstacle could be the level of consumer acceptance. This is discussed in the next section.

Consumer Acceptance

As mentioned before, the production process of cultivated meat products comes with its challenges. Research has also shown that consumer acceptance of these products could also prove to be a challenge when these products are made available to the market (Bryant & Barnett, 2018).

A common objective expressed by consumers is that cultivated meat is seen as unnatural. Some of the raised concerns indicate that they perceive that unnaturalness could potentially harm health and the environment (Holst, 2019). Other consumers believe that cultivated meat products are inherently unethical (Holst, 2019). However, in general consumers do believe that there are many benefits to cultivated meat products. In particular to animal welfare and the environment. They indicate that avoiding greenhouse gas emissions is seen as the most salient benefit (Holst, 2019).

Another study indicates that knowledge, perceptions and personal traits seem to be important elements of consumer acceptance. After sharing information about cultivated meat with participants, the number of consumers that indicated they were willing to try cultivated meat products increased from 23.9% to 42.5% (Pakseresht et al., 2022). Also, when researchers highlighted the benefits cultivated meat products could have, the acceptance level of the consumers increased (Bryant & Barnett, 2018). So, it will be important that the public is informed correctly about the impact of cultivated meat. Details about any personal benefits for the consumer is seen as the most effective type of information (Bryant & Barnett, 2018).

There are also many other more subtle questions that arise when it comes to consumer acceptance. For example, Sebo (2018) argues that identity will also influence the level of consumer acceptance. He argues that many consumers relate their gender identity, cultural identity and religious identity to their meat consumption. According to Bryant & Barnett (2018) cultivated meat is less appealing than eating plant-based meat. However, this depends on consumer preference. People who love meat indicate that cultivated meat is more appealing than plant-based meat (Bryant & Barnett, 2018).

At the moment, about 11% of consumers indicated that they are very interested in trying cultivated meat products, 66% indicate to be somewhat interested and 23% say they are not interested at all (Morach et al., 2021). When asked what could increase their interest, they indicated an improvement in taste and a more affordable price (Morach et al., 2021). Most studies agree with Morach (2021) that the most likely factors that will determine the level of consumer acceptance are driven by concerns about taste, price and safety (Bryant & Barnett, 2018; Holst, 2019).

When it comes to price, Specht (2020) predicts that cultivated meat would achieve price parity with traditional meat products once cultivated meat products can be produced free of animal derived components in the growth medium, as the growth medium is the biggest cost driver. According to Vergeer et al. (2021) price scenarios will develop from $22.421/kg to $6.43/kg when cultivated meat products are produced at an industrial scale. Ajena & Howard (2021) mention projections that assume price parity between conventional meat products and cultivated meat products by the early 2030s.

As the production of cultivated meat is a risky and long-term venture, a big quantity of funding is necessary (Treich, 2021). According to Treich (2021) governments play a central role in the funding for research and development of cultivated meat. This research is focused on the Dutch market. The Netherlands is the biggest meat exporter of Europe (CBS, 2021a) but is also one of the leading countries when it comes to the development of cultivated meat (Schouten, 2021). Therefore the decision was made to focus this research on the Netherlands. More about the Dutch government's involvement in the next section.

Government Involvement

In 2019 the highest Dutch administrative court found that the Dutch government was breaking EU law as they were not doing enough to decrease nitrogen in natural areas caused by farming and industrial activities (Levitt, 2021). Since then, the government has indicated more ambitious measures to reach certain climate goals. The Dutch government indicated that they are aiming to reduce CO_2 with 70% by 2035, 80% in 2040 and to reach climate neutrality in 2050 (VVD et al., 2021).

The Dutch government announced a €25bn plan that will be spend on radically reducing the number of livestock in the country (Levitt, 2021). The intention of this plan is to buy out livestock farmers on a voluntary basis. The expected results are a reduction of one-third of the number of livestock in the country in the next ten years (Levitt, 2021).

Simultaneously, the government is showing specific interest in cultivated meat as an alternative to make the agricultural sector more sustainable (Schouten, 2021). The minister of agriculture, nature and food quality called the development of cultivated meat as one of the most promising initiatives to get a more sustainable production and consumption of proteins (Schouten, 2021). She is currently collaborating with cultivated meat companies to further explore production opportunities and also indicates a willingness to subsidize these companies (Schouten, 2021). In April 2022 a combined investment of €60 million was made by the government in cultivated meat companies (Schuengel, 2022).

In March of 2022 the Dutch government approved the testing phase of cultivated meat products. Consumers could try a cultivated sausage or burger under safe conditions (RTLnieuws, 2022). In that same month, the minister of agriculture, nature and food quality also announced that an investigation will be started into the introduction of a meat tax (NOS, 2022). The investigation should provide information to what extent the meat tax would impact meat consumption of the Dutch population. However, not all political parties in the Dutch government support this initiative (NOS, 2022).

Agricultural Sector in the Netherlands

As mentioned in the previous chapter, the Dutch government is intending to make significant changes in the agricultural sector. The Netherlands is the biggest meat exporter of Europe, in 2020 the country exported 8.8 billion euros worth of meat, and this has caused the country to struggle containing greenhouse gasses due to an excess of farm animals (CBS, 2021a). The country has the highest density of livestock in Europe, more than 100 million in total. That is more than four times that of the UK or France (Levitt, 2021). Of the total Dutch earnings of meat sales, 60% comes from exported meat products and 40% is generated through domestic sales (CBS, 2021a).

In 2020, 85% of the exported meat was produced domestically and 15% was re-exported (CBS, 2021a). The total meat chain accounts for 1.1% of the Dutch GDP and the industry employs 1.3% of the total workers in the Netherlands (CBS, 2021a).

If cultivated meat is successfully integrated in the market, this may induce a costly transition for workers in the current animal farming sector (Bekker et al., 2017; Wilks & Phillips, 2017). According to Newton & Blaustein-Rejto (2021), the livelihoods of farmers who grow animal feed, the livestock farmers themselves and the meatpacking plant workers are most vulnerable. Another factor that influences this is how much of traditional agricultural products, such as vegetables, legumes, sugar etc., could be used to provide nutrients as a growth medium for cultivated meat (Treich, 2021). According to Sinke & Odegaard (2021), these products can be used but they require to be processed first in order to function as a growth medium for cultivated meat.
Government support will greatly help accelerating market transitions, and make it easier for farmers to adapt. As mentioned before, the government is already taking steps to adapt the animal agriculture in the Netherlands and is aiming to reduce the livestock with 30% by 2030 (Levitt, 2021). At the same time, a growing cultivated meat industry will also create jobs in various areas such as sales, regulation, distribution, quality assurance etc. (WhatisCultivatedMeat.com, 2022).

The introduction of cultivated meat will also have an impact on the land-use. As cultivated meat production is less dependent on weather conditions, facilities could be built almost anywhere (WhatisCultivatedMeat.com, 2022). According to Sinke & Odegaard (2021) cultivated meat would approximately take 17 times less land area to produce compared to beef cattle, 3.3 times less area would be needed compared to pork products and 2.5 times less land area compared to chicken products.

Market Projections Cultivated Meat

It is challenging to make predictions about the development of the market share of cultivated meat products because a lot of it depends on assumptions regarding matters like the scale of production, the level of costs reductions and consumer acceptance (Ajena & Howard, 2021). Butler (2021) predicts that by 2025 cultivated meat will have a market share of about 10% of alternative protein products. A report done by AT Kearney (2019) predicts cultivated meat to have a market share of 35% by 2040. They also mention that food experts predict that cultivated meat will likely coexist with conventional meat products and plant-based products for several decades (ATKearney, 2019).

Different research done by Tubb & Seba (2019) anticipate that the demand for cow products will fall by 70% by 2030 and by 80-90% in 2035. They predict the cattle industry to be effectively bankrupt by that point and expect other livestock markets to follow similar trajectories (Tubb & Seba, 2019).

Mestemacher & Welford (2022) envision that by 2040 cultivated meat will surpass the plant-based meat market with an estimated value of $630 billion vs $450 billion of plant-based products. The traditional meat market is estimated to decrease from approximately $1000 billion, measured in 2018, to $720 billion in 2040 (Mestemacher & Welford, 2022).

As can be seen, there are many different predictions, especially since there are still many uncertain elements when it comes to the development of the cultivated meat industry. Among other things, this research aims to investigate if the market projections mentioned above would be achievable for the Dutch market.

Research Objective

There are favourable market share projections for cultivated meat products. But there are still many uncertainties in this up-and-coming industry. This research aims to explore what happens when cultivated meat is introduced to the Dutch market and to identify several limits and opportunities to the growth of the cultivated meat market. To gain an understanding into these limits a system dynamics model will be developed that can provide insights in the dynamics originating from the process of introducing cultivated meat products to the Dutch market. The following research questions will be addressed.

Research Questions

1. What could be some unforeseen circumstances that could limit the growth of the market share of cultivated meat products in the Netherlands?
    a. How does the introduction of cultivated meat impact the traditional meat industry in the Netherlands and what are their dynamic implications?

2. What policy options for the Dutch government can be identified to optimize sustainable meat production?
    a. How do livestock restrictions influence the market share of cultivated meat products?
    b. What would the effect of a meat tax be on the growth of the market share of cultivated meat in the Netherlands?

3. What are insights into the feasibility of market share projections of cultivated meat products in the Netherlands?
    a. What effect does the introduction of cultivated meat products have on the greenhouse gas emissions of the meat industry in the Netherlands?

Methodology

The methodology used to carry out this research project is simulation modelling, more specifically system dynamics modelling. This chapter will give insights in the system dynamics methodology and will explain how that method is applied to this research project.

System Dynamics is based on principles developed by Forrester and studies the structural theory of dynamic systems (Forrester, 1961; Sterman, 2000). The method is used to build a simplified model of a real-world system to gain an understanding on how certain behaviour can emerge from that system (Sterman, 2000). System Dynamics is based on the hypothesis that the structure of a social system captured in the model is what drives the system behaviour over time. Additionally, the system structure is characterized by feedback loops of cause and effect and the delays between them. System Dynamics models not only reproduce and predict behaviour, but they also explain how behaviour is generated (Barlas, 1996).

Data Collection

A systematic literature review has been conducted for this research project. The data collected for this research has only been secondary data, no primary data collection was conducted. The secondary data was sought from scientific literature and from grey literature, including several governmental and commercial reports. For example, government reports gave insights into their funding intentions and statistics were used to provide insights into the current meat industry of the Netherlands. This data was used to conceptualize and formulate the model to visually represent the concepts established by the literature. Additionally, existing simulation models that were relevant to this research were also reviewed, such as the Bass diffusion model (Bass, 2004) that was adjusted and incorporated into the model. This approach was chosen to improve model confidence as it incorporates previously validated model components.

The secondary data was used to gain insights into the complex dynamics that relate to the introduction of cultivated meat products to the market. To conceptualize the model causal loop diagrams and stock and flow structures were used. Trough the incorporation of the data, a quantitative model was constructed which was analysed and tested to ensure the consistency of the theories.

Since primary data was not collected during the research process, a statement of ethics regarding collection, publication and protection of such data is not applicable. The data used for this research are all from publicly available sources.

Data Analysis Methods

The data was used to develop a stock and flow model. To gain confidence in this model structure, a model analysis was carried out. This analysis was based on internally generated simulations under specific scenarios. Various tests for model validation were carried out as well as sensitivity analysis and scenario analysis, where scenario runs with different levels of uncertainty and conditions were compared. Policy alternatives were also considered through parameter changes.

According to the guidelines of Barlas the tests that need to be performed to validate the model structure are behaviour tests, structure tests, and structure-oriented tests (Barlas, 1996). The purpose of the model analysis and validation is to get a deeper understanding of the model behaviour and to highlight leverage points and weaknesses in the model structure (Sterman, 2000). The results of the validation tests will be discussed in more detail in the model validation chapter.

Limitations of research design

The model does explore different policy options with regards to the introduction of cultivated meat to the market, however the main purpose of this research is not to suggest specific policies, but to research and analyse, in other words, to produce knowledge regarding a specific domain (Mayer et al., 2004). There are significant uncertainties and limitations in certain parameter values but also in several structural components of the model. These will be discussed in more detail in a later chapter that discusses the validation testing. In addition to that, the lack of field specific knowledge of the modeler also limits the ability to suggest certain policy recommendations. In the presentation of this report, these limitations are taken into consideration and will be referred to accordingly.

Chapter Conclusion

A more detailed overview and discussion of the model, model validation and the model simulation analysis can be found in the chapters below. The chapter model description will provide detailed descriptions of every sector of the system dynamics model that was developed for this research project. Additionally, an explicit documentation of the model according to Rahmandad & Sterman (2012) can be found in Appendix 1.

Model Description

This chapter will discuss the model made for this thesis in detail. First a conceptual model is presented with the use of a CLD that will discuss the main feedback loops. Then the model will be presented in detail sector by sector. Model boundary and major assumptions and basic model settings are discussed as well.

Conceptual Model

In this section a simplified version of the model is presented as a CLD. The main loops of the model will be discussed one by one. As the CLD portrays a simplified version of the model, there are structural elements not included in the CLD, resulting in some discrepancies with the actual model structure. A detailed description of the model will be provided later in this chapter.

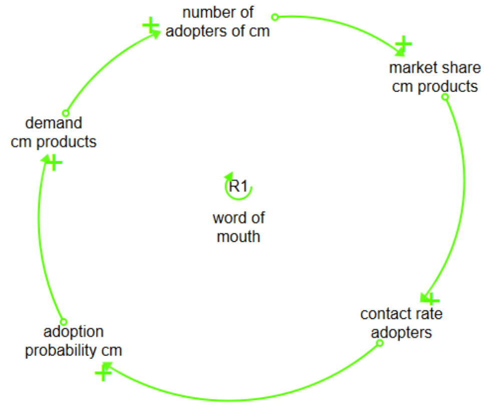


Figure 1: R1

Firstly, part of the model is based on the Bass diffusion model (Bass, 2004), this is represented as the reinforcing loop R1 from figure 1. This loop represents a word-of-mouth mechanism whereby, as the number of adopters of cultivated meat (cm) increases, the probability of getting in contact with an adopter increases too. This leads to a higher adoption probability of cultivated meat products. When the adoption probability increases, the demand for cultivated meat products increases as well, and this leads to an even higher number of adopters of cultivated meat products. That closes loop R1.

Next, another reinforcing loop, R2, can be introduced, starting off at the market share of cultivated meat products. If the market share of cultivated meat products increases, this means there will also be more consumption. If the consumption of cultivated meat products increase, there will be a need for more crops that can be used as a growth medium for the production of cultivated meat. If the need for these feed crops increases, the need for farmers that produce these crops also increases. As they increase, the production of cultivated meat will also increase which will lead to a higher market share of cultivated meat products.

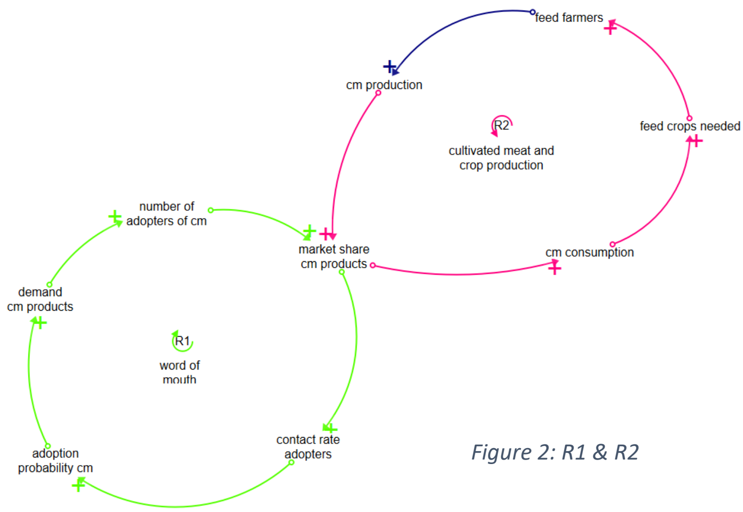


Figure 2: R1 & R2

Two more loops can be introduced now, B1 and R3 which can be found in figure 3. The first balancing loop B1, also starts off at the market share of cultivated meat products. If this market share would decrease, it is assumed that the government would invest more money to try and boost this market share. This would lead to more investments, that could be spend on trying to increase the knowledge of the public regarding cultivated meat. This is assumed to have a positive effect on the adoption probability of cultivated meat products eventually leading to more adopters, and a bigger market share. Reinforcing loop R3 follows a similar path as B1, the only difference is that it is assumed that as the market share of cm increases, there will be a higher number of private investments made in cm, as this becomes more profitable for them. With an increased number of total investments, it completes the loop along the same paths as B1.

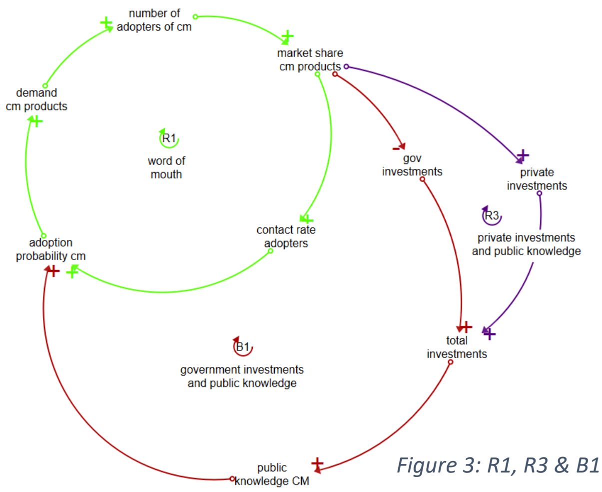


Figure 3: R1, R3 & B1

There are more loops originating from the investments that are made in cultivated meat. Similar to B1 and R3, another balancing and reinforcing loop are created as can be seen in figure 4. The polarity of these loops is once again influenced by the type of investment. Government investments would decrease with a growing market share, as private investments would increase.

The new loops, B3 and R5 represent the effect the investments would have on the price of cultivated meat products. R5 includes the effect of the private investments and B3 the effect of the government investments. If the investments would increase, it is assumed that the price of cultivated meat products can decrease, either through direct investments enabling producers to offer their products at a lower price even though the production costs stay the same, or indirectly, as investments could improve research and development, that reduce production costs. A lower price of cm will increase the attraction of the products, again leading to a higher adoption probability of cm and eventually to a higher market share.

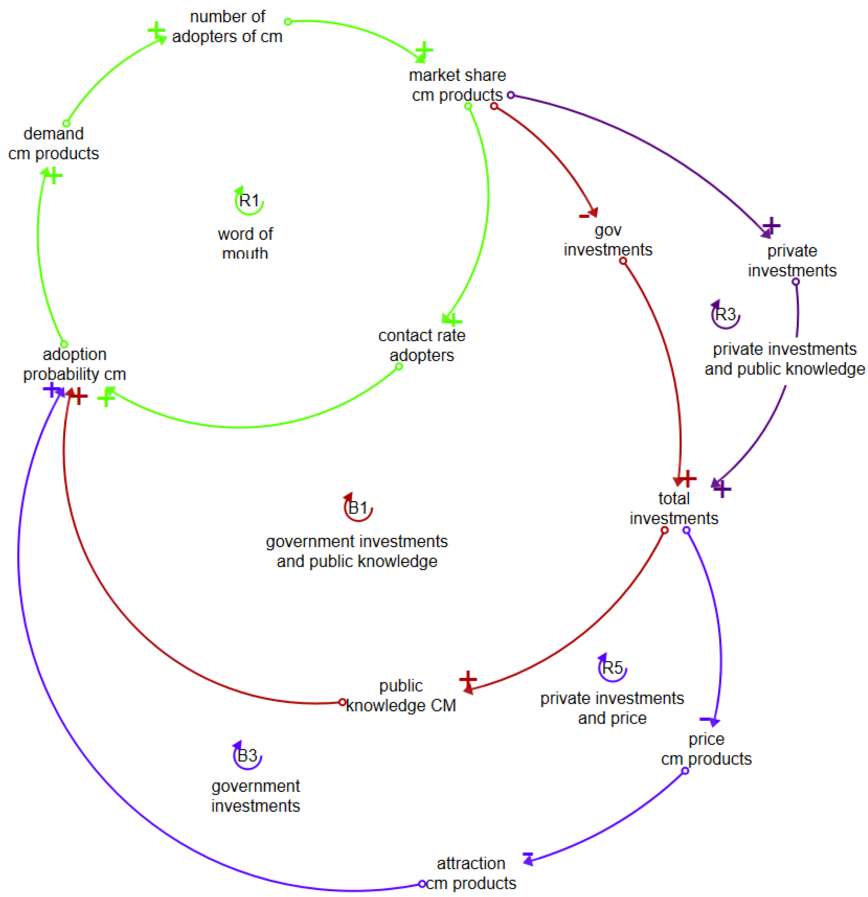


Figure 4: R1, R3, R5, B1 & B3

The investments being made in cultivated meat can also influence the production capacity. This is represented by loops B2 and R4 that can be found in the bottom right corner of figure 5. The consumption of cultivated meat is assumed to be restricted by the production capacity, therefore, both B2 and R4 connect to the previously discussed loop R2.

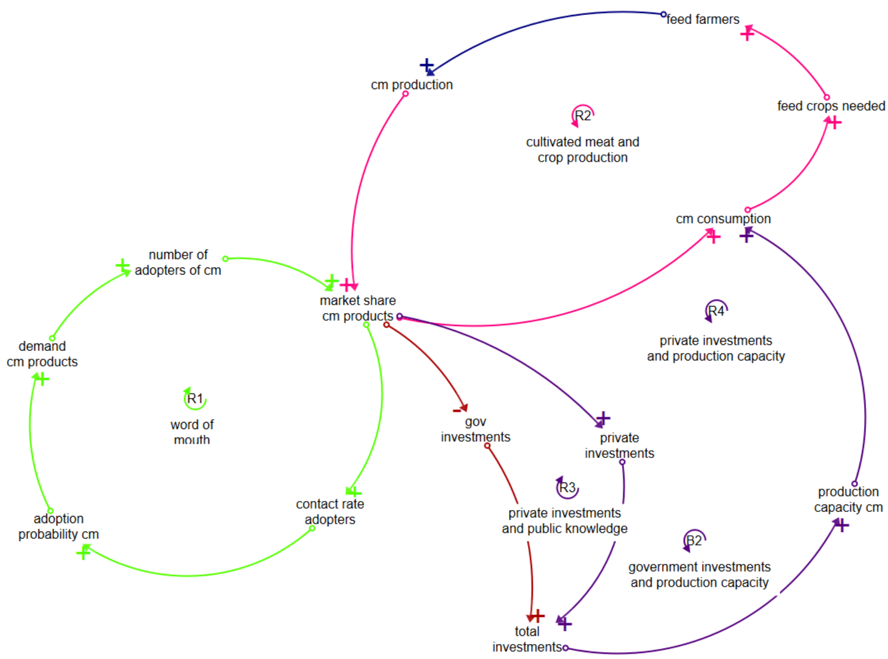


Figure 5: R1, R2, R3, R4 & B2

That same loop R2, is used again as part of the next two loops seen in figure 6. These next loops, B5 and B6 introduce meat production and land-use to the CLD. Firstly, consider the balancing loop B5 starting from cm production. If the production of cultivated meat increases, more agricultural land will be used, this means that less agricultural land will be available. If the available agricultural land decreases, so will the amount of feed farmers. When the amount of feed farmers decreases, so will the production of cultivated meat, closing the loop of B5.

Land-use is not only a restriction to cultivated meat, but also to traditional meat production. On the right side of Figure 6, the variable meat production can be seen. If the meat production increases, so does the agricultural land used. Again, if the land-use increases, the land availability decreases and thus so do the feed farmers. If the feed farmers decrease and are therefore not able to provide the food for the animals, the meat production will decrease which closes loop B6.

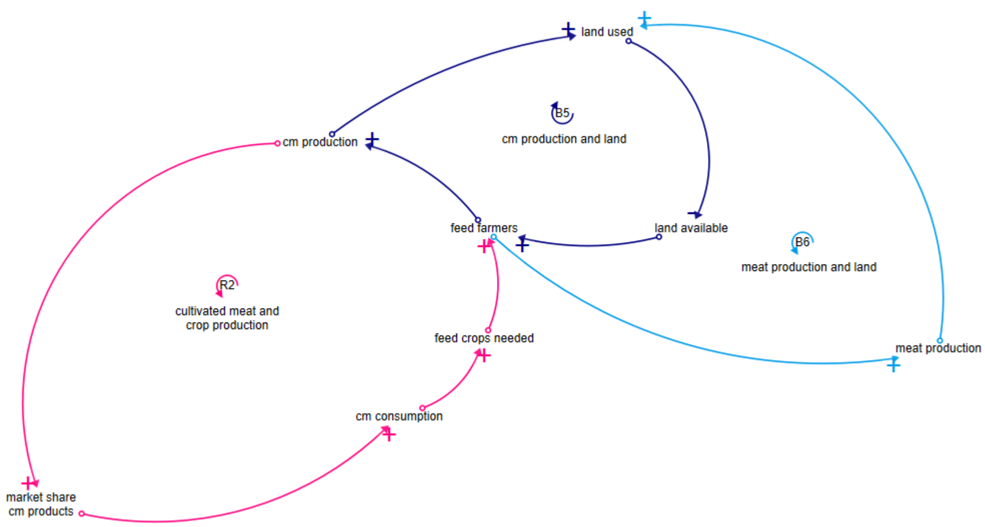


Figure 6: R2, B5 & B6

This leaves two main loops left to discuss to complete the CLD. One of these loops is the balancing loop B4, marked in yellow in Figure 7. Starting off at the market share of cultivated meat. When this cm market share increases, the market share for meat decreases and thus so does the meat consumption. When meat consumption decreases, so does the livestock and the livestock farmers. When the livestock farmers decrease, so does the meat production. As the demand for meat decreases, the price for meat also decreases in an attempt to become a more attractive option for the consumer. This lowering of the price of traditional meat, makes these products more attractive for the consumer, making cultivated meat relatively less attractive, so the attractiveness of cm products decreases as does the price of traditional meat products. This also decreases the adoption probability of cm products and therefore eventually will decrease the market share of cm products.

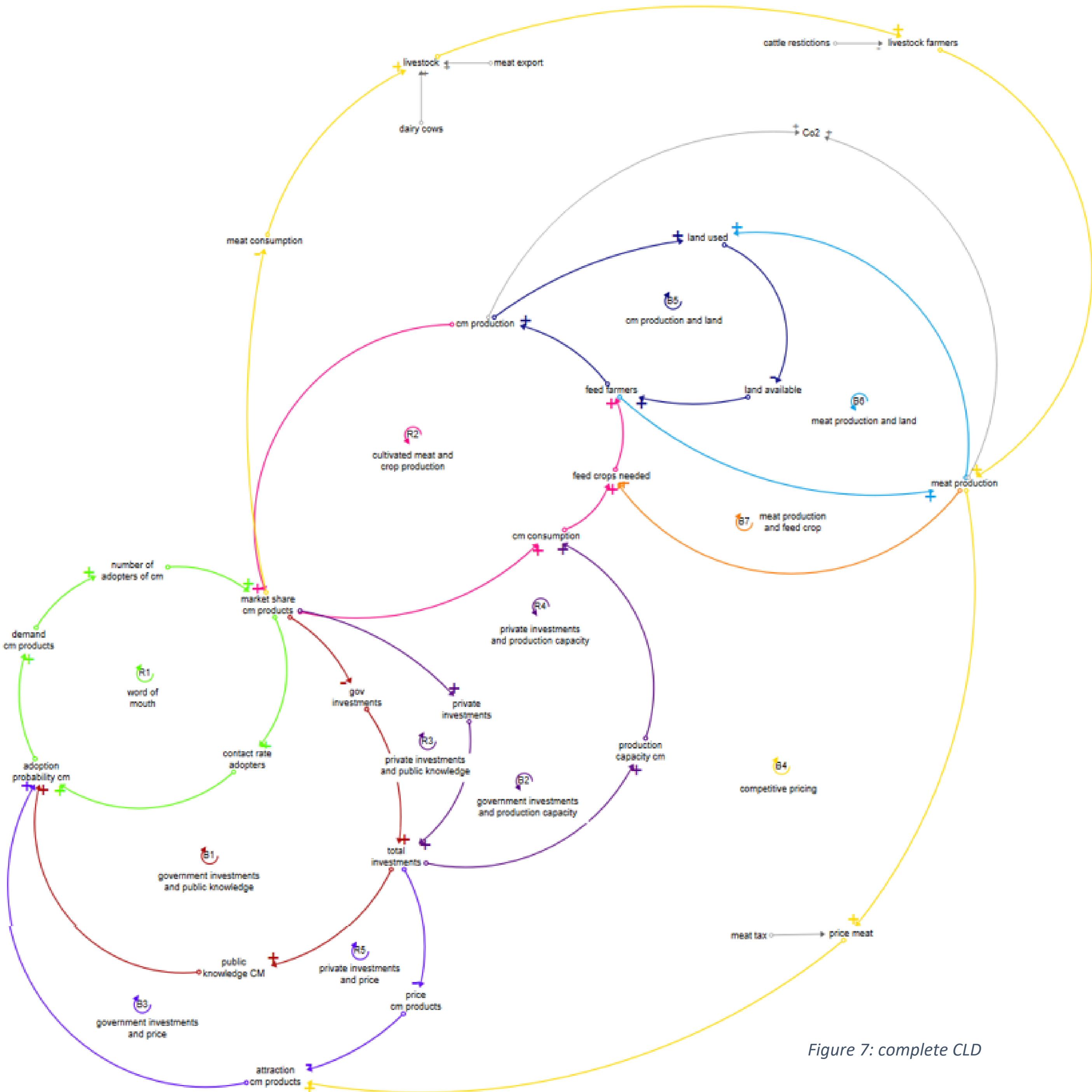


Figure 7: complete CLD

Finally, the orange loop B7. Starting off at meat production. If the meat production increases, so does the feed crops needed for the animals and therefore the feed farmers. When the feed farmers increase, so can the production for cultivated meat leading to an increasing market share of cm. When the market share for cm products increases, the meat consumption will decrease. Therefore, the livestock and the livestock farmers will also decrease leading to less meat production, closing the balancing loop B7.

Additionally, as can be seen, CO2eq emissions are not part of any of these main loops, however, they are a key variable in the model. Both cultivated meat production and traditional meat production add to the accumulation of the emissions, as shown by the links in grey.

After considering the main loops presented in the CLD, the next section will go through the model in more detail, discussing the structure sector by sector.

Detailed Model Structure

In this section the model structure is discussed sector by sector. Equations and graphical functions that need further explanation will be considered. More information can be found in Appendix 1 which includes the model documentation that addresses each individual variable separately.

Adoption Structure

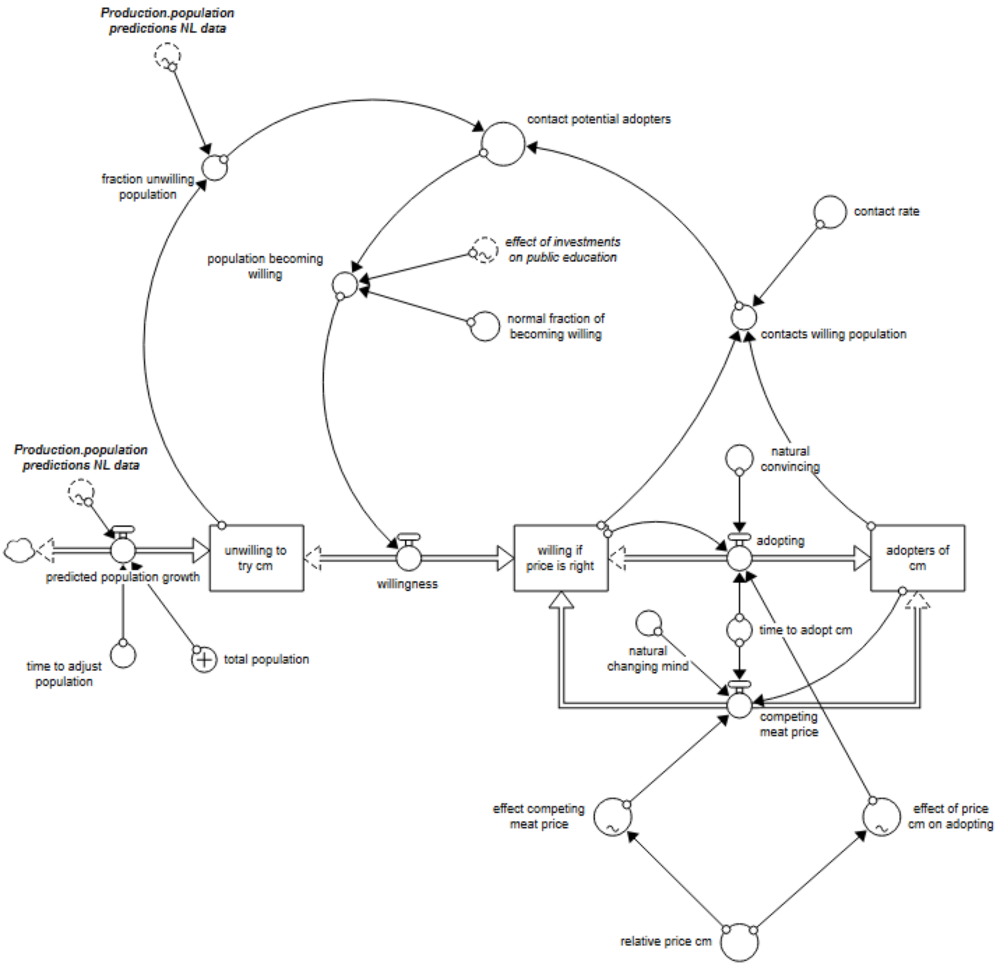


Figure 8: adoption structure

As mentioned previously, part of Bass adoption model was used to measure the development of adopters of cultivated meat. This structure takes the number of contacts with adopters and willing buyers in consideration, and can calculate the number of adopters by multiplying this with an adoption probability fraction. Some adjustments were made to the Bass structure to also take into consideration people who would be willing to try cultivated meat products but for whom those may be too expensive. Previous research indicated that price is one of the main consideration consumers have when making the decision to adopt (Bryant & Barnett, 2018; Holst, 2019; Morach et al., 2021). Therefore two price effect functions were included that influence the flows between the stock of people willing to buy cultivated meat if the price is right and actual adopters. The effect functions are based on the relative price of cultivated meat compared to traditional meat. The variable relative price is connected to these price inputs which will be discussed in the funding

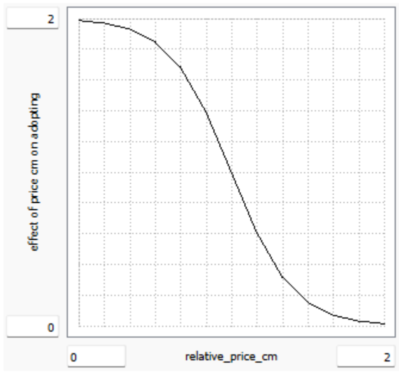


Figure 9: effect price cm on adopting

section. As can be seen in figure 9, as the relative price of cultivated meat drops when it becomes cheaper, it becomes more likely that people will adopt it. In contrasts, figure 10 shows the effect of people switching back to traditional meat products as the relative price of cultivated meat products increases. These effect functions are assumed to be s-shaped as there is a cap on the effect price can have. There are other considerations for adopting or not adopting to cultivated meat (Bryant & Barnett, 2018). Changes in price will not always alter those beliefs.

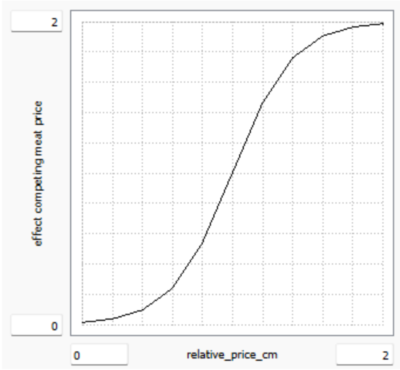


Figure 10: effect competing meat price

Another modification to Bass' adoption model is the inflow going into the stock of unwilling to try cultivated meat products. This inflow accommodates the effect of a growing population in the Netherlands. Finally, a last modification is the addition of an effect function that represents the effect of public education on the natural adoption fraction of becoming willing to adopt cultivated meat products. This variable will be discussed in the funding section of this chapter.

Market Share Structure

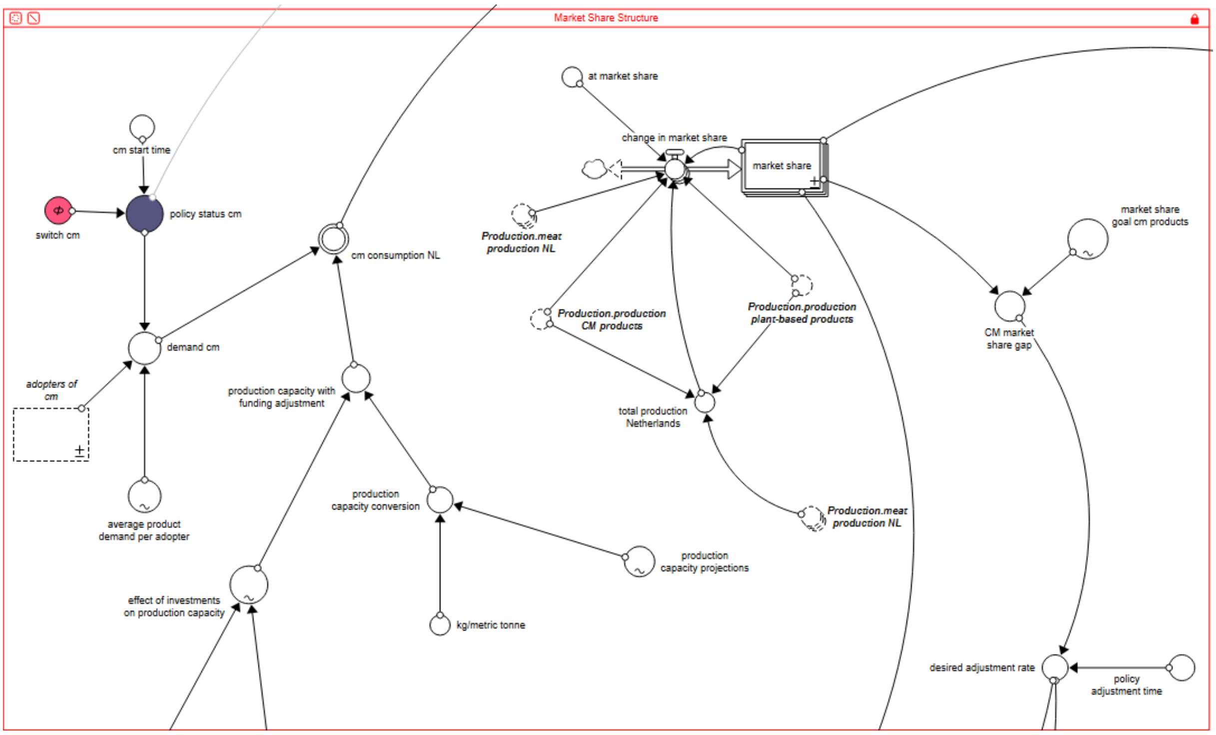


Figure 11: market share structure

Moving on from the adoption structure to the market share structure. As can be seen on the left side of figure 11, the stock of adopters as seen in the previous section is used to calculate demand. The demand for cultivated meat products is only activated when the policy status of cultivated meat is turned on, which is the case when the switch is activated and the start time of 2024 is passed. Another element needed for the calculation of the yearly demand for cm is the average products that are being purchased by each adopter. As can be seen in figure 12, it is assumed that this increases as adopters exchange more of their protein needs with cultivated meat products over time. As there is a limit to how much consumers would buy this variable is S-shaped.

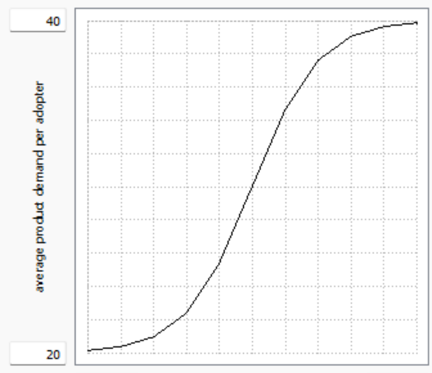


Figure 12: average product demand per adopter

The total yearly demand for cm is the adopters multiplied with the average kg of products each adopter purchases per year.

Moving on, the demand for cm products determines the consumption in the Netherlands. It is assumed that demand is met as long as production capacity is not exceeded.

Production capacity is based on projections from the Good Food Institute (GFI, 2021) and can be seen in figure 13. There are still many uncertainties regarding production capacity and therefore the accuracy of this variable would change as more research is done over the years. Investments can however influence these projections. A graphical function was added that represents the effect investments have on production capacity. This effect function can be found on the bottom left corner of figure 11.

As can be seen, consumption is not directly connected to the market share stock and flow structure. Consumption is one of the elements that is used to calculate the production of cultivated meat and production is used to calculate the market share. Not only the market share for cm has been calculated, but also the market share for traditional meat and plant-based meat through the use of arrays. The amount of production for each category is divided by the total production to calculate the market share. More on how the production is calculated in the section production structure.

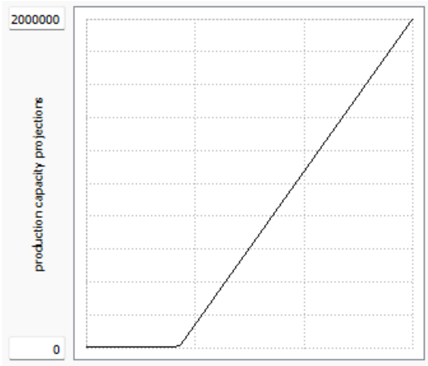


Figure 13: production capacity projections

Finally, as discussed in the CLD, market share influences both the private and government investments. This will be explained more in the next section regarding the funding structure. Figure 11, shows on the right side that there is a cm market share gap. This is the gap between the actual market share and the goal market share the government has, and this gap influences the government investments through the desired adjustment rate (which is the gap divided by a policy adjustment time).

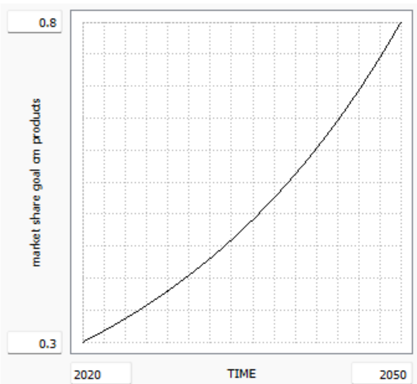


Figure 14: cm market share goal

The market share goal for cm can be seen in figure 14. As can be seen, the goal for the cultivated meat market share increases over time. Considering the significant effect of cultivated meat on the traditional meat industry, it is assumed that the Dutch government would like to make this transition somewhat gradually. However, as the government indicated they have strict goals for reducing emissions and becoming climate neutral by 2050 (VVD et al., 2021), the initial goal value is assumed to be relatively high at 0.3.

Funding Structure

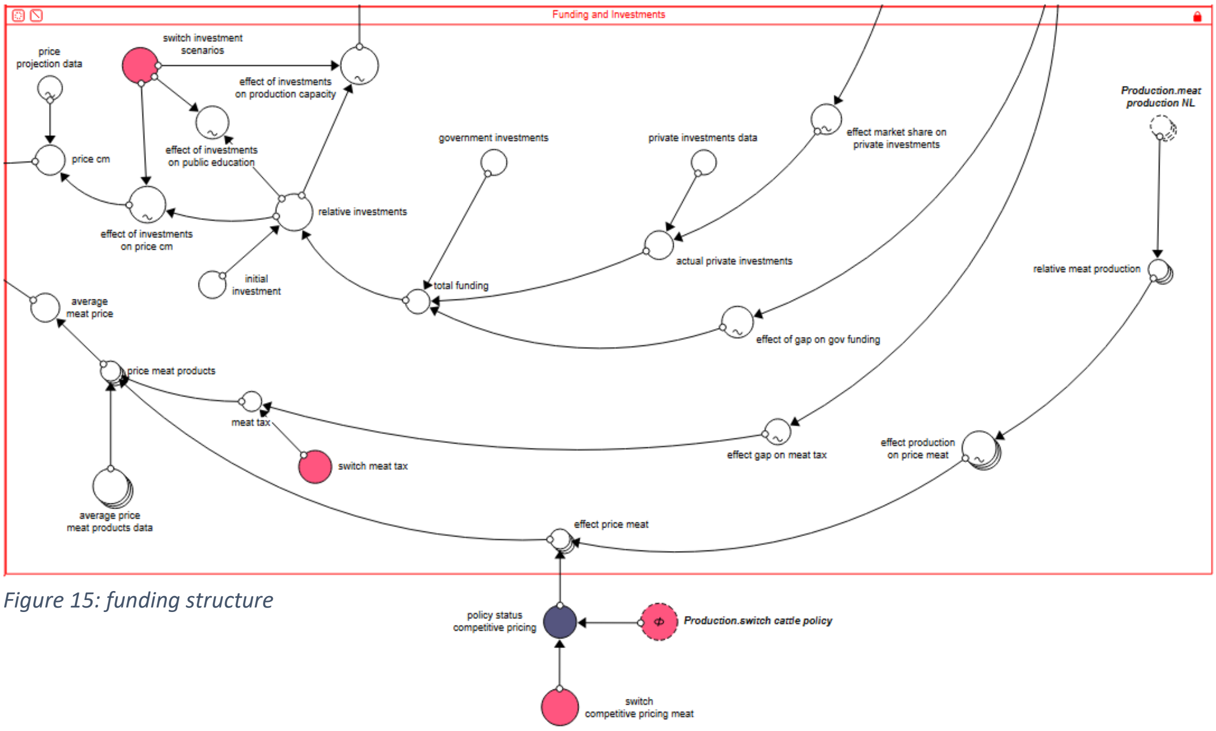


Figure 15: funding structure

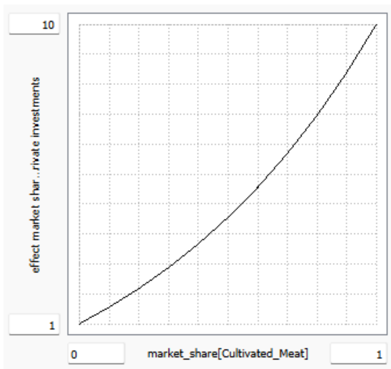


Figure 16: effect cm market share on private investments

Next up is the funding structure. As said before, the market share influences the investments, starting here with the effect on the private investments (variable can be found in figure 15, on the top right). It is assumed that the private investments would increase exponentially as the market share for cultivated meat increases because an increasing market share would increase the attractiveness to invest. This can be seen in figure 16. This effect function is then multiplied with the private investments that have already been made so far.

Now to calculate the total fundings, the government investments need to be included as well. As said before, these investments are influenced by a desired adjustment rate through the gap between the cm market share goal and actual market share. The effect is also assumed to be exponential here (figure 17), although to a lesser extent as the private investments and again is multiplied with an initial amount of government investments made up until 2021.

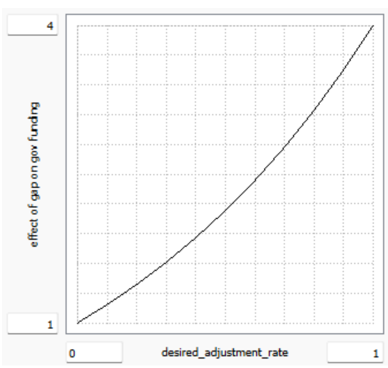


Figure 17: effect on government investments

These investments are combined, in the variable *total funding* and used to calculate the relative investments compared to the initial total investments. As can be seen, these relative investments feed into three graphical functions. Two of which were discussed previously, effect on public education and effect on production capacity. The other effect investments can have is on the price of cultivated meat. There is an investment switch added that allows for switching between these investment scenarios. All three investments could be selected, or each separately. Figure 18 shows the graphical functions of each investment effect.

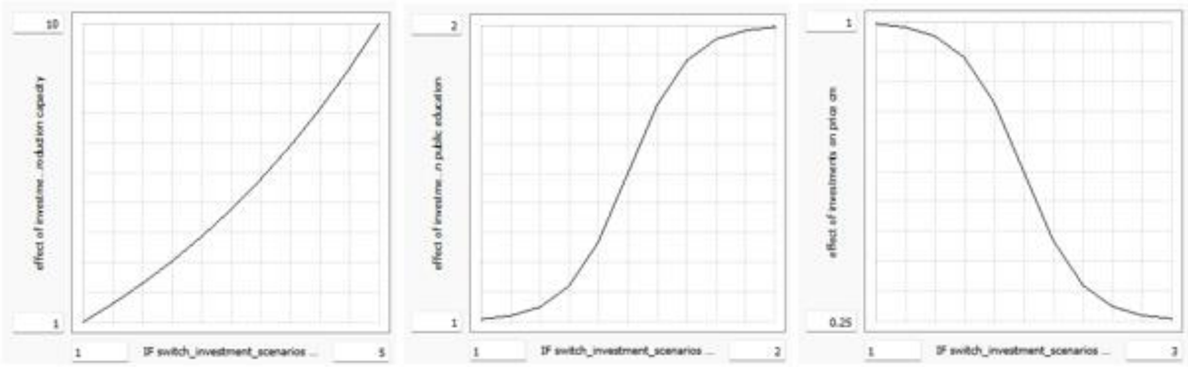


Figure 18: investment effects on production capacity, public education and cm price

The effect of public education and the effect on price are both used to influence the adoption structure. The effect of investments on price is multiplied with actual cultivated meat price projections made by Vergeer et al. (2021) to get the variable that represents the cm price. The price projections (figure 19) are already assumed to decrease over the years as research and development of the industry is progressing and the additional effect of the investments would amplify this effect.

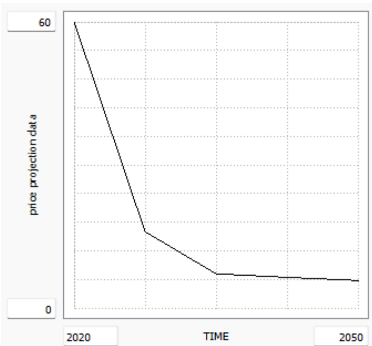


Figure 19: cm price projections

As said before in the section regarding the adoption structure, the relative price of cm will influence adoption. Therefore, the price development of traditional meat products is also portrayed in this sector as the bottom two loops from figure 15.

The price of traditional meat products can either be influenced by a policy from the government to introduce a meat tax, or from price changes made by a competing market. The desired adjustment rate, that was mentioned previously and is based on the market share gap, would also impact the extent of the meat tax policy. This effect is also assumed to be exponential, as the government would want to have a bigger impact through this tax if the gap itself is bigger. This possible meat tax policy was introduced to the model after it was previously suggested by the Dutch minister of agriculture as an option to explore (NOS, 2022). When the switch is turned on, this effect is multiplied with the average prices of traditional meat products.

When the switch is turned on, competitive meat prices are also taken into consideration. Meat production influences the prices of the products. Production for beef, pork and poultry is included in the model. More on how these are calculated in the section discussing the production structure. The price competition is introduced to the model with the use of another graphical function. This effect function ensures that the price for the meat products decreases as the meat production decreases. This can be seen in figure 20. The reasoning behind this drop in price is that as more consumers are opting for cultivated meat, the demand for traditional meat decreases. In order to stay competitive and an attractive option for the consumer, the price for meat products can be decreased. This effect is also multiplied with the average meat prices to get the variable *price meat products*. This is compared to the price of cultivated meat to get the variable *relative price cm* as discussed in the adoption structure section.

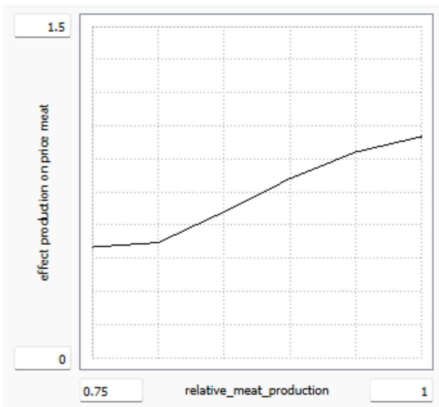


Figure 20: effect meat production on price

Production Structure

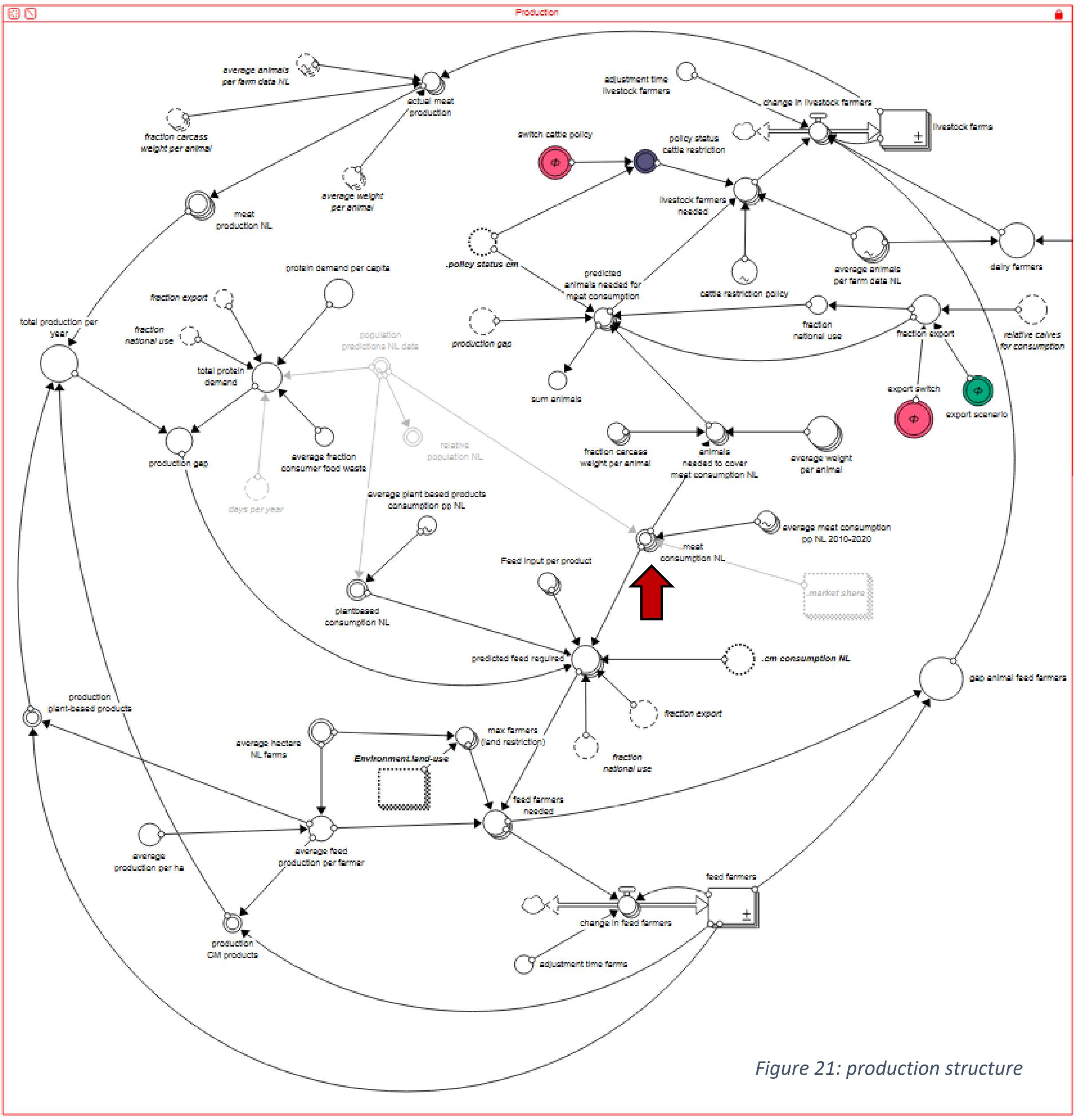


Figure 21: production structure

In this sector the production is calculated for meat products (beef, pork and poultry), plant-based products and cultivated meat products. In short, this sector uses consumption data – or in the case of cultivated meat, the consumption value that was calculated in the market share sector – and uses this information about consumption to calculate how many farmers are needed. With this number of farmers, the actual production they can produce is calculated.

To get orientated in this sector, consider the variable *meat consumption NL* at the red arrow in figure 21. This variable is calculated by multiplying the data for average meat consumption for beef, poultry and pork products per person per year in the Netherlands, with the population predictions and with the market share of meat products. This is done to adjust the meat consumption over time to a changing market share.

```
Equation
meat_consumption_NL[Farms] =                                   Apply To All
.market_share[Meat]*"average_meat_consumption_pp_NL_2010-2020"*population_predictions_NL_data
```

Moving upwards in figure 21, this consumption is used to calculate how many animals would be needed to cover this consumption by dividing the yearly kg of consumption with the average carcass weight of the animal. This is still the animals needed to cover only the consumption of the Netherlands. The next variable *predicted animals needed for meat consumption* includes the animals needed to cover export as well. The Netherlands exports 60% of all the meat that is produced in the country. This is considered our base-case scenario; however, the model allows for different export scenarios to be explored. A variable *production gap* can also be seen to link into *predicted animals needed for meat consumption,* this will be explained further down below.

Now again moving further up, to calculate how many farmers would be needed to cover these animals, data was used showing the average amount of animals per livestock farm in the Netherlands. This can be seen in the equation below for *livestock farmers needed.* What is also included in this equation is the policy for cattle restriction. As said before, the Netherlands has announced plans to significantly reduce livestock in the upcoming years (Levitt, 2021). When this policy switch is on, the average animals are multiplied with the variable *cattle restriction policy,* a graphical function which holds a value between 1 – 0.5 as can be seen in figure 22.

```
Equation
livestock_farmers_needed[Farms] =                              Apply To All
IF policy_status_cattle_restriction = 1 THEN
MAX(0, (predicted_animals_needed_for_meat_consumption/
average_animals_per_farm_data_NL*cattle_restriction_policy)) ELSE MAX(0,
(predicted_animals_needed_for_meat_consumption/average_animals_per_farm_data_NL))
```

There is one other element to consider before the livestock farmers in the Netherlands can be calculated. For beef products, it is assumed that the number of cow livestock farmers cannot go below the number of dairy farmers needed to cover diary consumption. Therefore, a MAX function was used in the inflow *change in livestock farmers* in the arrayed equation for beef. Finally, the livestock farmers are reliant on animal feed. More on this below.

The stock livestock farmers is multiplied with the average animals, and the average kg of meat products that would be produced per animal to get the meat production of the Netherlands including export.

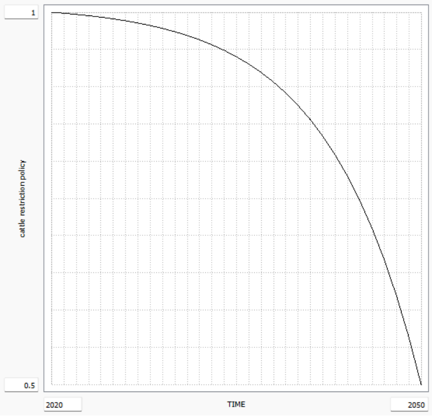
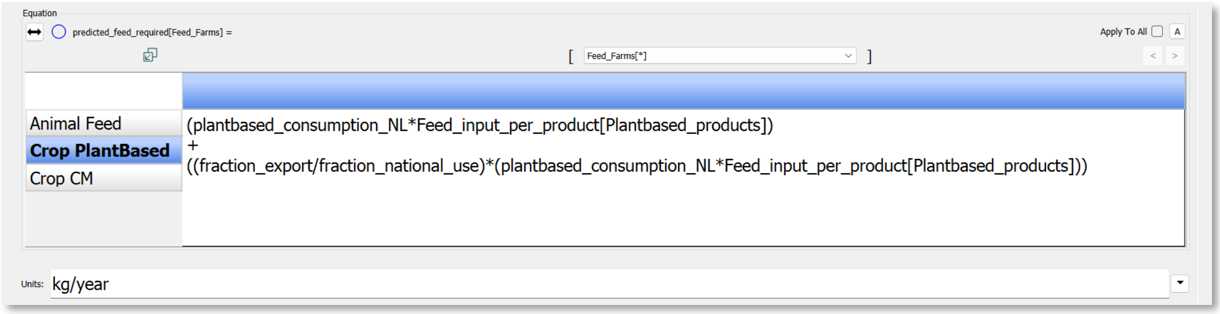


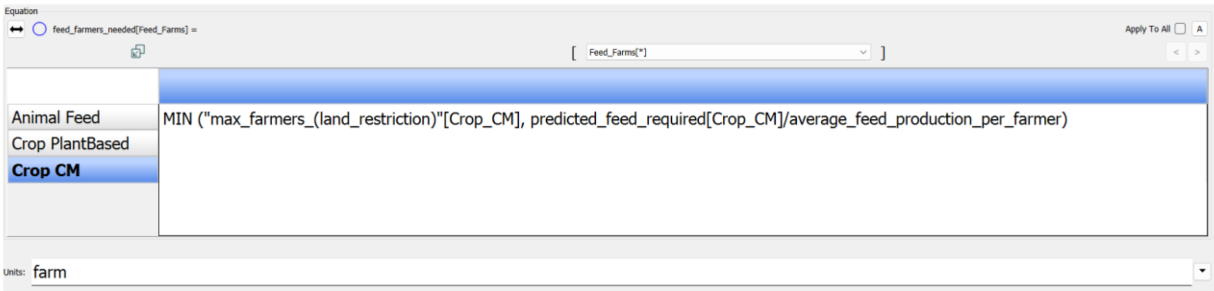
Figure 22: cattle restriction policy

Moving back to the variable *meat consumption NL* at the red arrow in figure 21. Following this variable down to *predicted feed required.* This variable is arrayed to include animal feed, crops needed for plant-based products and cultivated meat products. Data was used from Sinke & Odegaard (2021) that provided the amount of feed that was required to produce 1 kg of product. Also for cultivated meat products, traditional crops could be used as a growth medium (Sinke & Odegaard, 2021). The basic equation for this variable is the consumption of that product in kilograms multiplied with the feed required per kilogram of product, plus the added feed of what is required to cover export as well. The latter being the product of the previous equation with the fraction of export divided by the fraction of national use. This division would produce the value that is needed to include export. For example, if that national demand is only 40% of the total production, a multiplication of 1.5 would be needed to cover that other 60% of export (0.6/0.4=1.5). This can be seen in the below equation.



This equation is the same for animal feed, however for cultivated meat, there is another element added to the equation. If the production gap - the division between the protein requirement and the actual protein production - is below 1 (meaning there is more requirement than production) this gap will be compensated with cultivated meat products and the feed needed to cover this extra production is added to the cultivated meat formula. The production gap was previously seen to link into *predicted animals needed for meat consumption.* When the policy status for cultivated meat is off, it is assumed that this gap will be covered with traditional meat products so more animals would be needed which is added to the predicted animals variable.

Now as seen in the CLD, it is considered that land-use can restrict the production of feed crops. The amount of land that can be used per product is calculated in the environmental sector, described in the next section of this chapter. Having that amount of maximum land, the number of maximum farmers is calculated by dividing the land available with the average hectare of a farm in the Netherlands. This is incorporated in the variable *feed farmers needed (land restriction),* the equation for which can be seen below. As can be seen, a MIN function was used to either select the maximum number of farmers possible as dictated by the land, or number of farmers calculated according to the predicted feed that is required divided by the average feed production per farmer.



Feed farmers needed is used as input for the inflow *change in feed farmers* where the stock is subtracted from this variable and both are divided by an adjustment time. Additionally, the gap between *feed farmers needed* and the stock *feed farmers* is calculated by a division. If there are not enough feed farmers, this value is below 1 (it cannot go above 1 due to a MIN function). This is multiplied in the inflow *change in livestock farmers* to represent the restriction of animal feed on livestock farmers. To get the plant-based and cultivated meat production, the stock feed farmers, arrayed with the type of feed, is multiplied with the average kg of feed production per farmer.

Environmental Structure

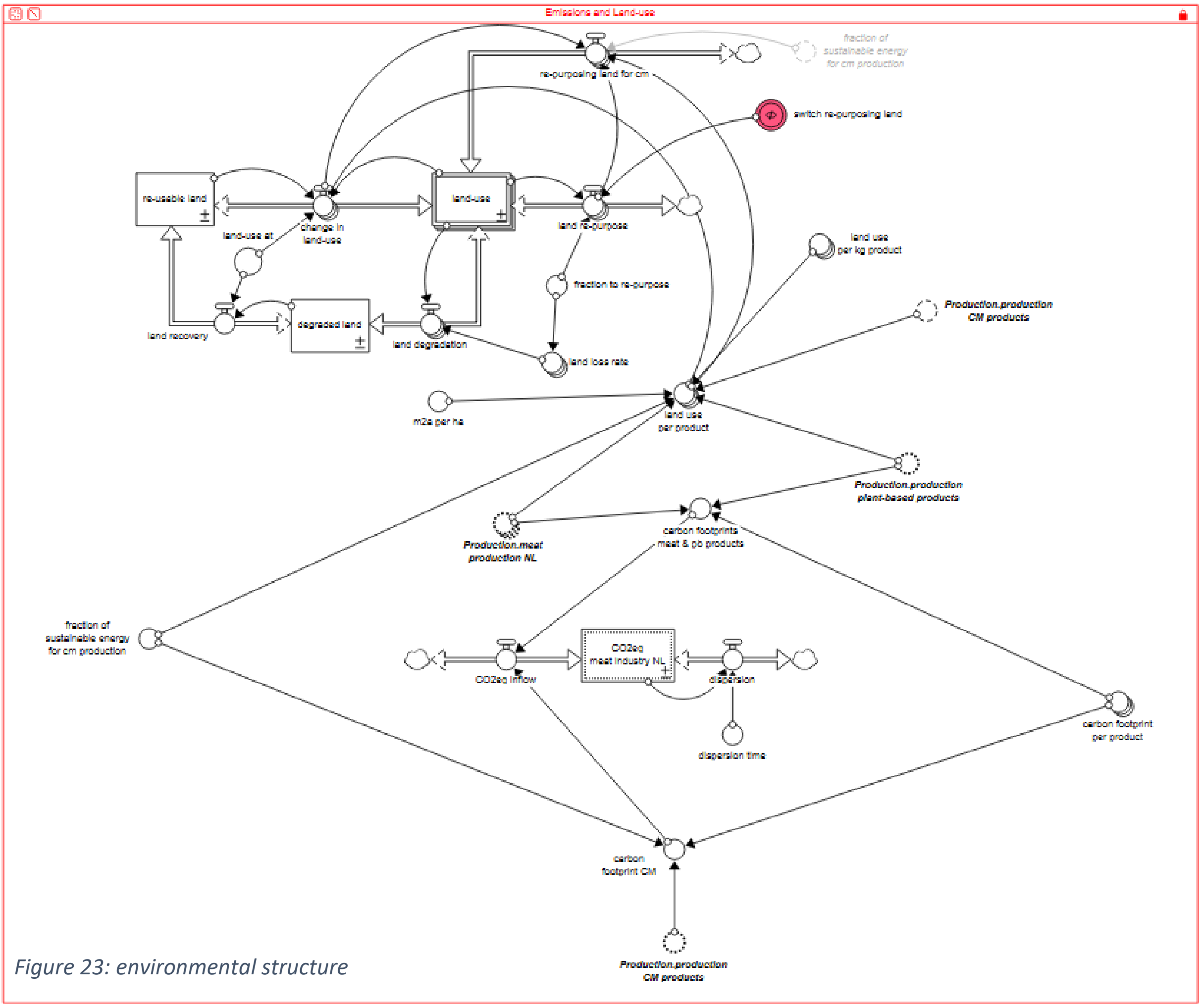


Figure 23: environmental structure

Finally, the environmental sector. This sector calculates two things, the CO2eq emissions and the land-use. Both are calculated using data from Sinke & Odegaard (2021), who provide the amount of CO2eq and land-use per kg of each product. These numbers are multiplied with the yearly kg of production for each product. In the case of CO2eq emissions, these numbers per product were combined and used as the inflow for the stock.

For land-use, the data provided was the number of hectares that is needed to cover the production of each product. However, there is a maximum amount of land available in the Netherlands that can be used for the production of meat and meat alternatives. This is contained in the stock and flow structure at the top of figure 23. The stock land-use continues to be arrayed according to each meat and meat alternative product. To ensure that there is enough land available for cultivated meat products, there is an option to re-purpose land from beef land to cultivated meat land. Beef is initially using a significantly higher amount of land, and is also the largest emitter of CO2eq. Therefore, when the switch is enabled, beef land can be re-purposed to as much land that is needed to cover the cultivated meat production.

Model Boundary

Table 1 portrays the model boundary and shows which key variables are included endogenously in the model, which are exogenous and which key variables were excluded from the model.

Table 1: model boundary

Endogenous	Exogenous	Excluded
Adopters cultivated meat	Export scenarios	Import of meat
Market share cultivated meat	Plant-based market growth	Policy resistance
CO2eq meat industry	Dairy production	Animal manure for fertilizer
Meat & alternatives production	Production capacity cm	Policy costs
Farmers meat industry		
Investments		
Agricultural land-use meat industry		

The import of meat and meat alternatives is not included in the model. Of course, imported products or raw materials play a significant role in the meat and meat alternatives industry. Since the focus of this research has been on cultivated meat, and as the Netherlands is one of the leading countries when it comes to the development of this product, it was assumed that the majority of the production could be domestically produced. However, to provide a more accurate picture of the meat and meat alternatives industry, this is recommended to be included in future iterations of this model.

As mentioned in the theoretical background, in the summer of 2022, there have been protests by farmers against the launch of a cattle restriction policy. A similar cattle restriction policy is included in the model, but no structure is added that reflects any policy resistance or social pressure on the government from the public.

There is also no structure that provides detailed insights in the costs of the proposed policies due to a lack of data or uncertainties regarding policy costs. Finally, an element that could affect crop production is the use of animal manure as fertilizer. For example, when livestock numbers decrease due to an increase in cultivated meat, there will also be less animal manure which could be used as fertilizer for other crops. All these key variables that are not included in the model structure could provide valuable insights and are encouraged to be included in future iterations of the model.

Major Assumptions

Aside from some variable assumptions that were mentioned in the detailed model structure section, there are some other major assumptions that were made in the process of the creation of the model.

A major assumption that was made is that the market share of plant-based meat alternatives will stay relatively constant throughout the whole simulation duration. It is assumed that people who would want to switch to a meat alternative, would opt for cultivated meat instead of plant-based meat, as cultivated meat should provide a closer substitute to traditional meat. Another element that influenced this decision was a news article was published earlier this year saying that the growth of the plant-based meat alternatives has been stagnating in the Netherlands (den Hollander, 2022). However, not enough data is available to assume that this would continue in the years to come and how it could affect the growth of the cultivated meat market share.

Another major assumption is that all the feed crops for cultivated meat products can be provided through traditional agricultural crops. Traditional crops can be used as a growth medium for cultivated meat after it is processed and converted to glucose (Sinke & Odegaard, 2021; Treich, 2021) as cultivated meat requires similar nutrients as animals do such as carbohydrates, amino acids, fats, vitamins and minerals (WhatisCultivatedMeat.com, 2022). However, it is not clear that all of the growth medium necessary for the production of cultivated meat products can be provided by traditional agricultural products. More research and innovation regarding the production of cultivated meat is necessary to provide clarity regarding this issue.

Finally, an assumption was made that the different product categories that are considered in the model are all similarly nutrient-dense, especially regarding protein levels. However, a kg of plant-based product might not be a perfect substitute for a kg of meat. Even though it is not expected that there are major inconsistencies between products, this would be a good addition to take in consideration for further iterations of the model.

Model Set Up

Basic Model Settings

The basic model settings that were used in this thesis are as follows:

- Start time: 2015 - for comparison with historical data
- Stop time: 2050 - roughly 30 years after the introduction of cultivated meat
- Time units: years
- Delta Time (DT): 1/32
- Integration method: Euler.

The model documentation is done according to the guidelines of Rahmandad & Sterman (2012) which can be found in Appendix 1 and in the Stella model that is attached to the thesis.

Chapter Conclusion

This chapter introduced the model that was made for this research thesis. The next chapter will analyse the validity of the model.

Model Validation

To gain confidence in the built model structure and its generated behaviour, the process of model validation is essential (Forrester & Senge, 1980). The results of the performed model validation are presented in this chapter. The guidelines and techniques of Barlas (1996) have been followed to carry out the model validation. The three types of validation tests that are identified by Barlas (1996) are: direct structure tests, structure-orientated behaviour tests and behaviour pattern tests. The validation tests have been carried out in that order and the results are presented below.

Direct Structure Tests

To validate the developed model, several tests have been performed. Firstly, direct structure tests have been done. According to Forrester and Senge (1980) the following tests are specified as direct structure tests: structure and parameter verification tests, direct extreme-conditions tests and dimensional consistency tests. These tests will be discussed below.

Structure Verification Test

A structure verification test is carried out to ensure that the model structure is consistent with knowledge about the real-world system (Forrester & Senge, 1980). The model structure is compared to the real-world system as it is portrayed in the literature (Barlas, 1996). This has been taken into consideration during the iterative modelling process throughout the development of the model structure. The model itself is grounded on existing literature and data. Of course, as described in the previous chapter, certain assumptions of the real-world system are also incorporated in the model. More details can be found in the model documentation in the appendix.

Parameter Verification Test

A parameter verification test has to be carried out to reflect if the parameter values represent the available knowledge of the real-world system. Continuously throughout the modelling process, parameter values were evaluated and compared to real systems. Forrester and Senge (1980) mention two elements of parameter verification: conceptual correspondence and numerical verification. Conceptual correspondence concerns whether parameters match elements of the structure of a real system and numerical verification regards whether or not the value of the parameter is within a plausible range. The conceptual and numerical verification are presented in more detail in the model documentation in Appendix 1. It is necessary to point out that the nature of the topic of this research brings along many uncertainties, parameter verification tests would need to be performed again as our knowledge grows over time. Any future iterations of the model would need to address any inconsistencies that are discovered as more research and information is known regarding cultivated meat. To assist in the understanding of the parameters that need additional exploration, structure-oriented behaviour tests are necessary and will be described in the next section.

Direct Extreme Conditions Test

The direct extreme conditions test is done to assess the equations of the model. The model should still be robust even under extreme conditions (Forrester & Senge, 1980). In the model, each equation has been tested to ensure that it responds appropriately to extreme inputs. For a few equations, MIN or MAX functions had to be employed to ensure that reasonable values were produced by the model structure. In addition to that, the bounds of table functions also ensured that no unreasonable values were produced. In a few cases, some changes had to be made to the input ranges of variables, for example to ensure that during the calibration process, the values could not accidentally go below zero.

Dimensional Consistency Test

The dimensional consistency test aims to ensure that the model uses consistent units of measurements without the use of scaling or dummy variables (Forrester & Senge, 1980). In the model used for this research all variables have consistent units of measurement and no dummy variables are used. All variables that were included in the model have a real-world meaning.

Structure-Oriented Behaviour Tests

Now several structure-oriented behaviour tests will be discussed. The following tests have been done and are described in this section: behaviour sensitivity, boundary adequacy and indirect extreme conditions

Behaviour Sensitivity

For a detailed sensitivity analysis please see Appendix 2. As expected, certain sensitive variables have been identified. Some variables should be sensitive, and are expected to be sensitive. This means they could potentially be good leverage points for policies to be introduced. Of course, sensitivity analysis will also assist us in identifying which variables need to go through further data collection (Barlas, 1996). The most notable sensitive variables are described here.

Firstly, some variable that proved to be sensitive, that were expected to be sensitive will be discussed. Several variables that had an effect on either the price of traditional meat products, or cultivated meat products turned out to be sensitive, such as *average price meat products data.* This was expected and this is an indication that investments and/or government subsidies being made into driving the price of cultivated meat products down will likely be effective. Other variables that are expectedly sensitive are the variables to do with the allocated land that is available for cultivated meat products, and the policy variable that represents cattle restrictions in the Netherlands. These policy opportunities will be further explored in the simulation analysis chapter.

There are also a few variables that are not sensitive, that were expected to be. Most notably the effect of investments on production capacity. The model suggests that the production capacity would continuously exceed the demand, and its restrain on the model is therefore weak. More research is necessary to determine more accurate projections of the production capacity and its effect on the production of cultivated meat products. Similarly, the effect of public education also proved to be insensitive and more research is also required in this area to give insights on the extend of the effect of public education.

Finally, there are also variables that are sensitive, and were based on assumptions and calibration. Most notably the variables representing the adoption fractions between the consumers who would be willing to buy cultivated meat products if the price is right, vs the adopters. These variables, called *natural convincing* and *natural changing mind,* were calibrated to match the projected market share of cultivated meat. Both graphical functions *effect competing meat price* and *effect of price cm on adopting* also turned out to be sensitive, and are based on assumptions as well. To quantify variables like this better, future research is necessary. This is also the case for the variable that represents the average product demand per adopter per year. This is, as expected, a sensitive variable and affects the market share of cultivated meat significantly. This variable is also calibrated and also requires more data to be accurately quantified.

This model is a first iteration on a topic that has many uncertainties regarding future development. The sensitivity analysis highlights this for several variables. Again, a detailed sensitivity analysis can be found in Appendix 2.

Boundary Adequacy

According to Forrester and Senge (1980) this boundary adequacy test is concerned with the model structure that is (and is not) included in the model and whether or not that boundary is appropriate to answer the proposed research questions. To answer this, the purpose of the model needs to be considered. The model aims to explore what happens when cultivated meat is introduced to the Dutch market and to identify any limits and opportunities that could affect the market introduction of cultivated meat products. The bass diffusion model (Bass, 2004), was used to visualize the development of adopters of cultivated meat products in the Netherlands, which translated to a certain market share of these products. In addition to that, multiple feedback loops were identified that would in turn also affect that market share, including several possible policies options. The boundary is therefore determined to be adequate. As the cultivated meat industry develops over time and new policy opportunities might occur, the boundary test will need to be re-examined.

Indirect Extreme Conditions Test

Similar to the direct extreme conditions test, the indirect extreme conditions test evaluates how the model performs under extreme conditions. For indirect extreme conditions test, the model as a whole is considered. An example of what was tested as an extreme condition in the model was the consideration of the market share of cultivated meat products without new adopters of cultivated meat. The market share did not pick up which was the expected behaviour of the model.

Behaviour Pattern Tests

Behaviour pattern tests aim to make comparisons between the behaviour that the model produces and behaviour of a reference mode, when available (Barlas, 1996; Sterman, 2000). This helps to determine if a model and its behaviour are similar to expected behaviour and therefore if the model output is reliable.

Firstly, the model aims to match market projections for cultivated meat. Market projections from AT Kearney (2019) indicate that by the year 2040, the market share of cultivated meat products has reached 35%. As seen in figure 24, the model output is able to reproduce that projection.

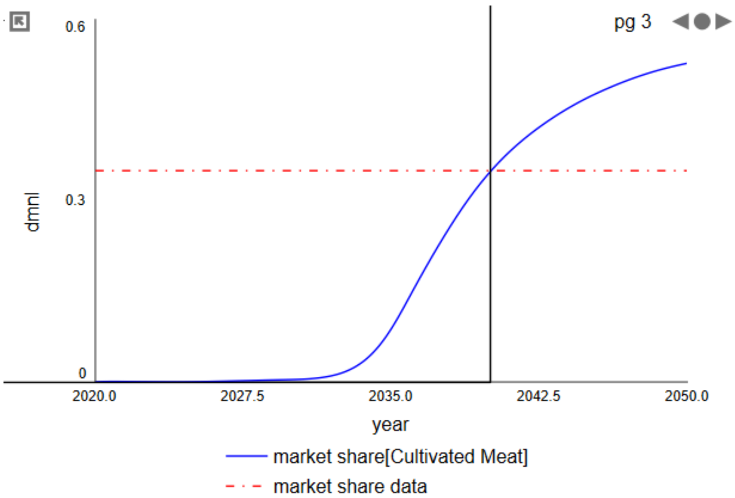


Figure 24: market share reference data

Note, the model behaviour produced in figure 24, is not the base scenario of the model, but the scenario with the cattle restriction policy enabled. These scenario comparisons and their behaviour will be discussed in more detail in the chapter simulation analysis. An additional note, market projections for future years vary significantly as they are dependent on an abundance of elements.

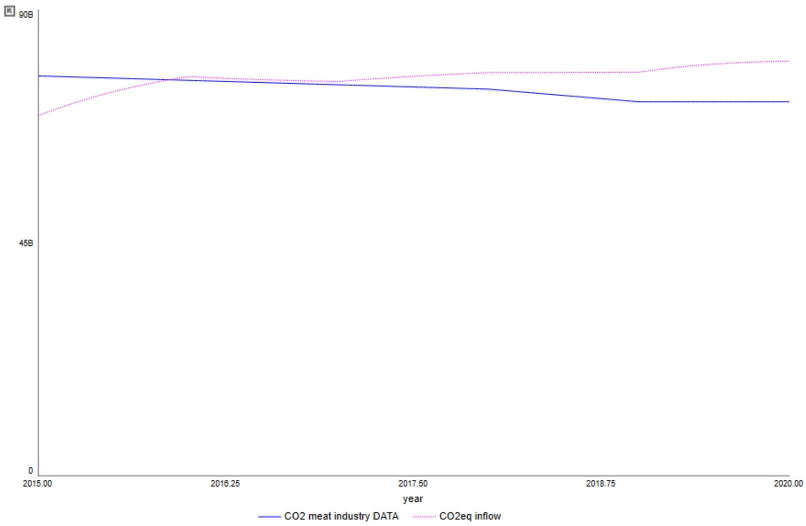


Figure 25: CO2eq reference data

Figure 25 shows historical data of CO2eq produced by the meat industry from 2015 to 2020 (in blue) and the produced model output of CO2eq, of course, without the inclusion of cultivated meat products. As can be seen, there are slight discrepancies between the two. Most likely this is because of the use of different data sources and what statistics would be included in each source. Concerning the meat industry for example, there can be various inconsistencies such as the inclusion of fish or dairy products. As the model behaviour and the reference behaviour are moderately similar, the uncertainties are tolerated, however, additional data and information can improve the model output to reach better estimates in new iterations of the model.

Validation Reflection

Model validation allows for confidence to be built in the model and results of the validation tests indicate that the model is significantly robust and behaves logically. There is a moderate amount of uncertain parameter values and assumed table functions, some of which also proved to be sensitive. However, this validation process is crucial to form an understanding of what variables might prove to be weaker links in the model structure and will aid to improve the model in future iterations.

Model Simulation Analysis

Chapter Introduction

This chapter will compare several scenarios and discuss what loops or structural elements are causing what behaviour. The scenarios that will be discussed are; a base scenario, an optimistic scenario, a scenario where land is restricted for cultivated meat, a scenario where there is no cultivated meat introduced to the system and finally a comparison of different export scenarios.

Base Run

This first scenario is considered the base run. In this scenario, cultivated meat is enabled as well as other factors that are expected to be included in normal market conditions, such as competitive pricing and land re-purposing. It is assumed that export will continue to be 60% versus 40% of products that are sold domestically.

Figure 26 and 27 show the development of the market share of cultivated meat, the livestock farmers and the CO2eq development for the base scenario. As can be seen in figure 26, it takes time for the market share of cultivated meat to take off, but then around the year 2032 it starts growing exponentially. This can partially be attributed to the reinforcing loop R1 that incorporates the word-of-mouth adoption development. This growth eventually slows down as the majority of the population has become an adopter. As there is still a significant production of traditional meat products, the market share will not exceed 40%. This value also depends on the amount of cultivated meat products versus other meat products an adopter would consume, as research by AT Kearney (2019) predicts that cultivated meat and conventional meat products will likely coexist for several decades. However, this division of product demand per adopter is currently an assumed variable in the model as the data is still uncertain about these projections. Future iterations of the model will take updated research regarding this in consideration.

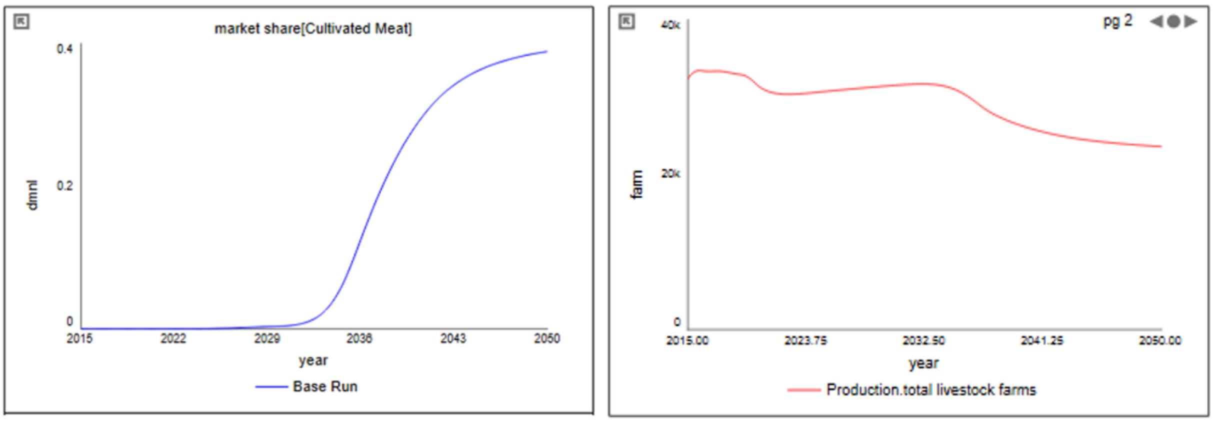


Figure 26: base run - market share cultivated meat & livestock farmers

On the right side of figure 26, the number of livestock farmers in the Netherlands can be seen. From 2015 until 2020, this value is based on historical data. From 2020 onwards, it can be seen that there is a slight increase in the amount of livestock farmers. This is because the market share of cultivated meat is still low, and the majority of the (growing) popuatlion is still consuming meat. As of 2035, the amount of livestock farmers decreases as the market share of cultivated meat increases.

Next in figure 27, the development of CO2eq can be perceived. Again, the behaviour shown from 2015 until 2020 is caused by historical data. From 2022 onwards an increase in emissions can be perceived. An explanation for this is an increased total production of meat and meat alternative products in the Netherlands. Mostly this is due to the production being adjusted to population predictions. Only when the market share of cultivated meat really picks up, the CO2eq emissions decrease as cultivated meat production emits less CO2eq compared to most traditional meat products.

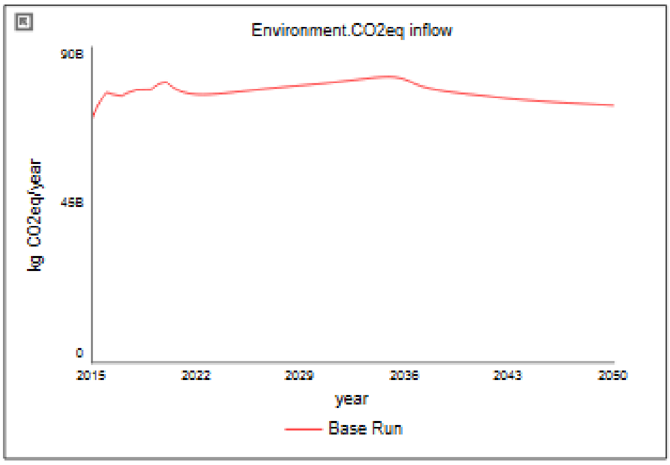


Figure 27: base run - CO2eq

In figure 28, the base scenario is compared to different investments scenario. In the base run, it is assumed that the government and private investments are equally divided between the investment options; increasing production capacity, increasing public knowledge through education campaigns and reducing the price of cultivated meat products. As can be seen in figure 28, the effect of price reductions produces the same behaviour as the base run, whilst investments being made in production capacity or public knowledge have a much weaker effect.

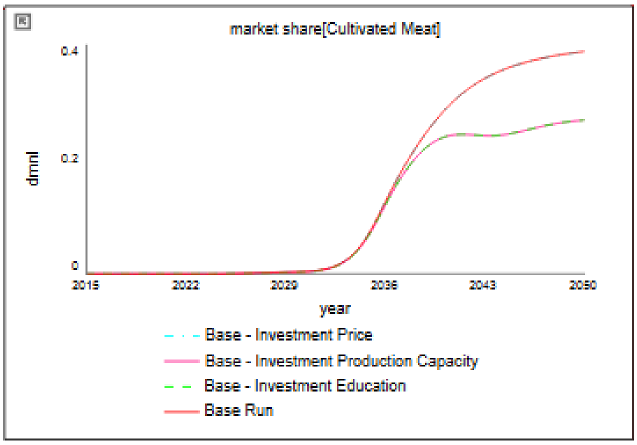


Figure 28: investments scenarios

Therefore, it is clear that the price loops R5 and B3 are stronger compared to the other investment loops. The effect of a reduced price of cm impacts the willingness of the consumers to adopt and more adopters leads to a higher market share.

Considering the loops R3 and B1 including public education, it can be detected why the effect of the increase of public education is not strong. As said before, these are two contradicting loops, reacting oppositely to market share developments. Initially, as the cultivated meat market share is low, B1 will have a stronger effect compared to R3. When market share picks up, there will be more private investments, and as there is a bigger share of private investments compared to government investments, the increase of total fundings will be higher when R3 is strongest and market share of cultivated meat has already started developing. This means that by the time the total investments are of a significant amount that they could have an impact on the adoption probability through education and knowledge about cm, the majority of the population would already have been convinced to become an adopter.

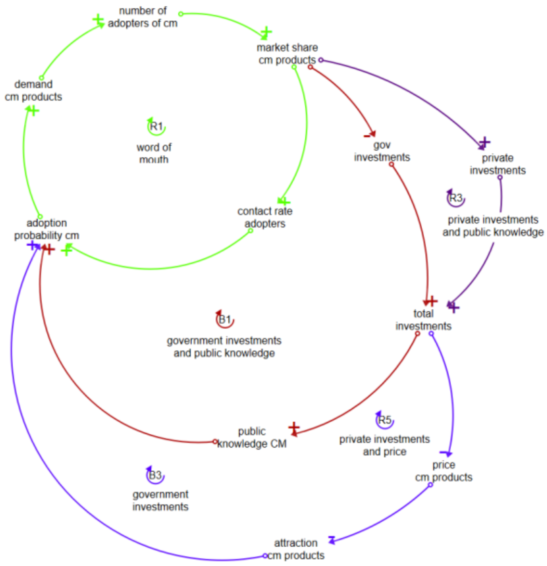


Figure 29: investment loops

Therefore, in the model, the effect of investments in public education seem to have a low impact.

As mentioned before, the data regarding production capacity are still uncertain (GFI, 2021). The reason why the effect of production capacity is insignificant is due to the data developments of production capacity. Production capacity exceeds the demand for cultivated meat, even in the base scenario, therefore extra investment in increasing production capacity will not affect the market share development. In reality, especially when the cultivated meat industry is still young, investments in production capacity might have a significant impact. More data is needed to represent this more accurately in the model.

A final thing to consider is the total production of meat and meat alternatives, this can be seen in figure 30. Up until 2034 a slight but steady increase in total production can be perceived, due to a growing population. After 2034 the production increases with a more considerable amount. This is caused by the increase of cultivated meat consumption and production. This is undesirable, as there would be an overproduction of meat and meat alternatives. Additionally, there would be a bigger effect in the reduction of CO2eq if there was no excess production. As described in the previous chapter, the loop B4 indicates that when cultivated meat increases, traditional meat decreases in order to prevent overproduction. However, there are delays in the model, for example, it takes time to decrease the number of livestock farmers and their production. Therefore, the decrease of traditional meat production does not happen as fast as preferable. Eventually, when the traditional meat production has decreased enough, and the CM production will increase decreasingly, the total production per year will start to decrease again from the year 2041 onwards.

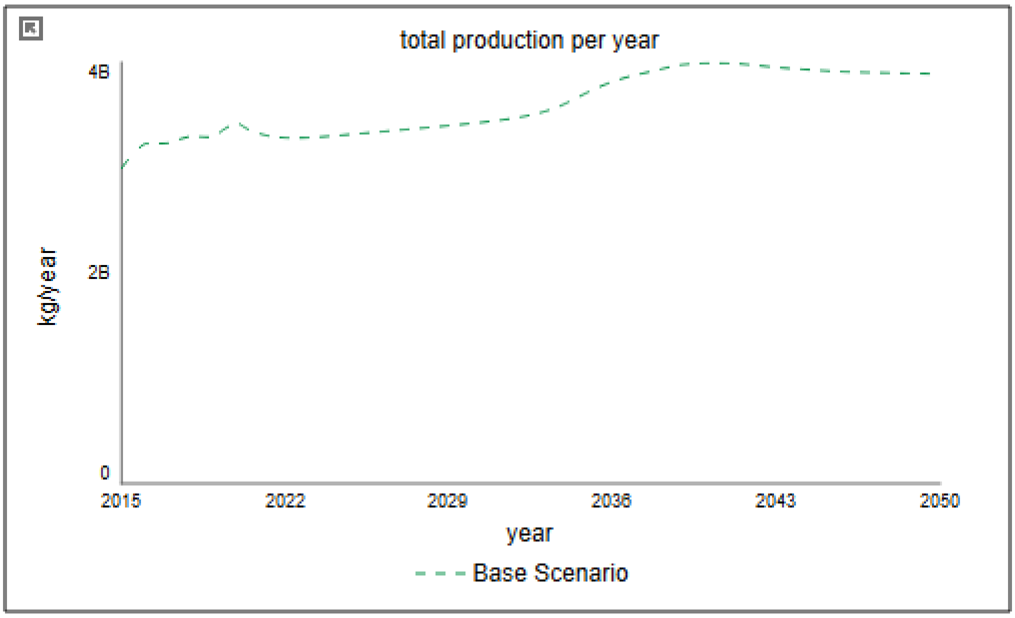


Figure 30: total production base run

Optimistic Scenario

This section will compare the base scenario to the most optimistic scenario for the market share of cultivated meat products. Two other government policies are enabled in this scenario. A cattle restriction and a meat tax are introduced. Figure 31 portrays the market share for both the base and the optimistic scenario.

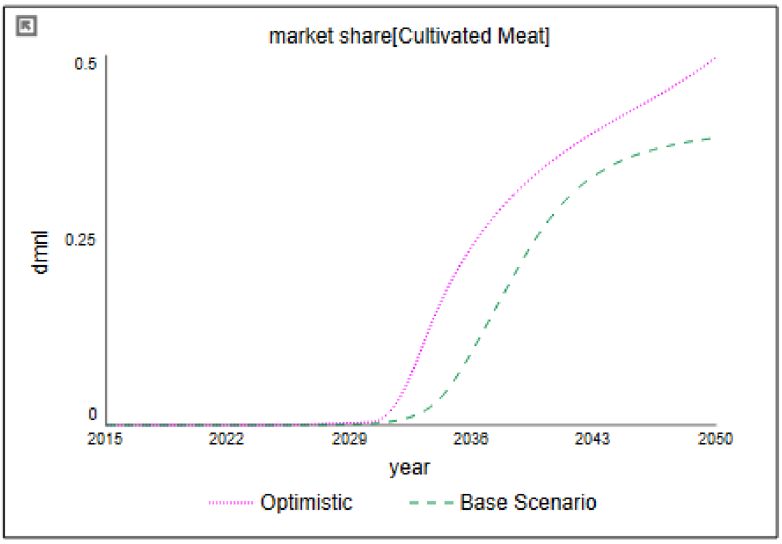


Figure 31: optimistic vs base

As can be seen, there is an increase in the market share. The loop that is causing this change in behaviour is the balancing loop B4 that includes meat production and the price of meat. The balancing effect of this loop was as follows: when more cultivated meat is produced, the demand and therefore meat production would decrease and as a reaction to this decrease in demand, the meat prices would decrease to make conventional meat a more attractive option and less consumers would adopt to cultivated meat products. Now what these two policies do is decrease the strength of this loop. The cattle restriction policy does this through an exogenous effect on the meat production while the meat tax only effects price. Now that that balancing loop is weakened, the reinforcing loop R1 including the adoption structure gains more strength and the market share increases.

Figure 32 considers both policy options separately, to consider if when both cattle restriction and the meat tax are enabled, if this would have an amplified effect on the system.

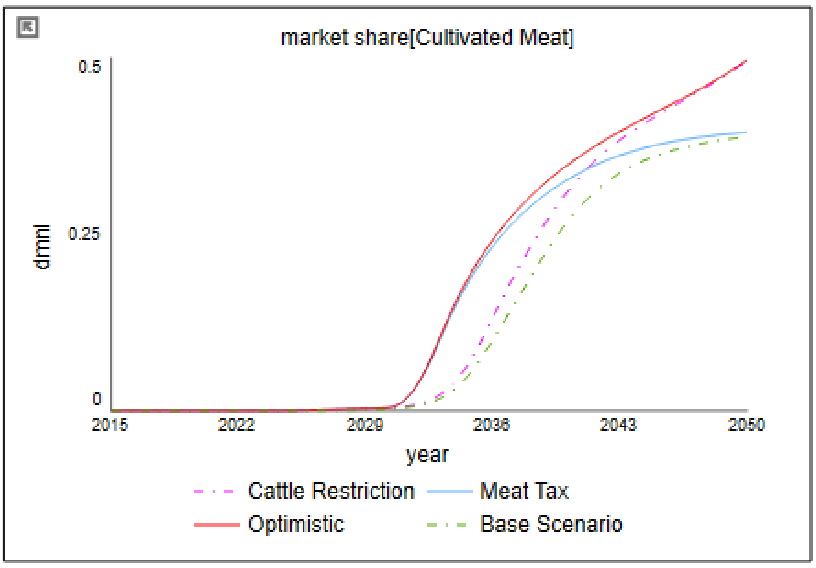


Figure 32: meat tax vs cattle restriction

As can be seen, both policies have a different effect. Interestingly, the meat tax policy alone does not increase the market share higher than the base scenario. What the meat tax does is make the price of meat more expensive, therefore making cultivated meat a more attractive option, increasing the adoption fraction. The stock *willing if the price is right,* is depleted faster as people become adopters. This has an effect on the market share which gets picked up a few years prior to the base scenario, as can be seen in figure 32.

Looking at the cattle restriction policy, the market share does go beyond the maximum market share reached in the base scenario. This is because meat production is directly affected. The cattle restriction reduces the amount of cattle, livestock farmers and therefore the meat production. As mentioned before, the model includes a production gap, so as meat production decreases, this production will be substituted by cultivated meat products, thus increasing its market share. Also, as the cattle restriction gradually increases its effect through the graphical function in the variable *cattle restriction policy* (figure 33), the behaviour of the market share of cultivated meat increases increasingly.

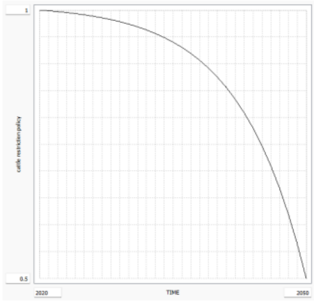


Figure 33: cattle restriction policy

Figure 32 indicates it is not the case that the policies are amplified by each other. In the optimistic scenario, both effects are combined, the market share takes off a few years prior to the base scenario and the market share increases overall, however, they are not amplified when enabled together.

Figure 34 shows the yearly CO2eq rate and the total livestock farmers in both the base scenario and the optimistic scenario. The market share for cultivated meat increases, and starts at an earlier time. As the market share is calculated by comparing the production of each meat and meat alternative, and the CO2eq is also calculated by the production values, it can be seen that CO2eq also starts to decrease at an earlier time and decreases increasingly. Livestock farmers shows a similar trajectory.

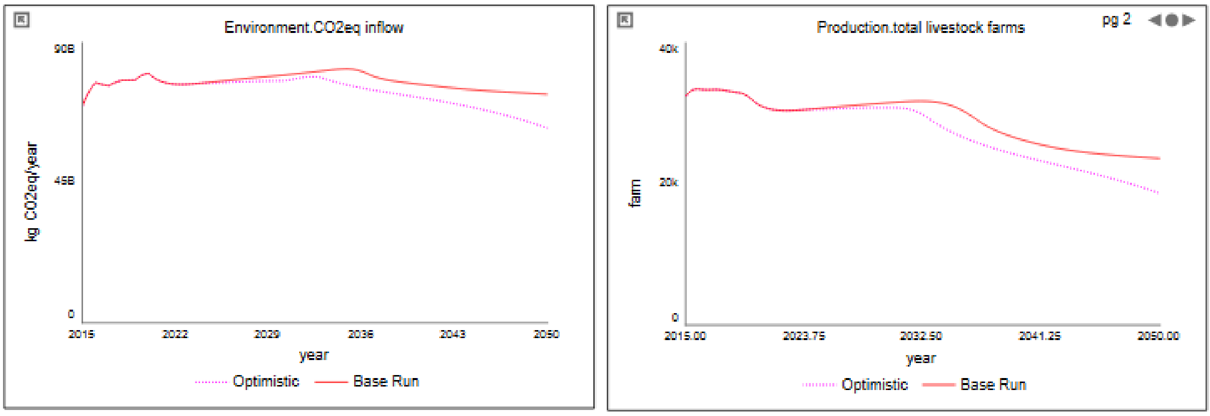


Figure 34: optimistic vs base - CO2 & livestock farmers

Finally, figure 35 compares the base and optimistic scenario with and without competitive pricing for meat products enabled. As can be seen, the competitive prices do not seem to have a big impact on the system. Why is this the case? In these scenarios, this is caused by loop B4 (competitive pricing) and R5 (private investments and price). B4 is the loop that includes meat production which affects the price of meat. R5 is the loop that includes the market share of cultivated meat which influences the private investments, which influences the price of cultivated meat. The price projections of cultivated meat can be found in figure 36. As can be seen, it is projected that there will be a steep decrease in the years 2020-2027 and that from 2035 onwards, the price will stabilize at approximately €6, - per kg (Vergeer et al., 2021). The loop R5 would contribute to a lowering of this

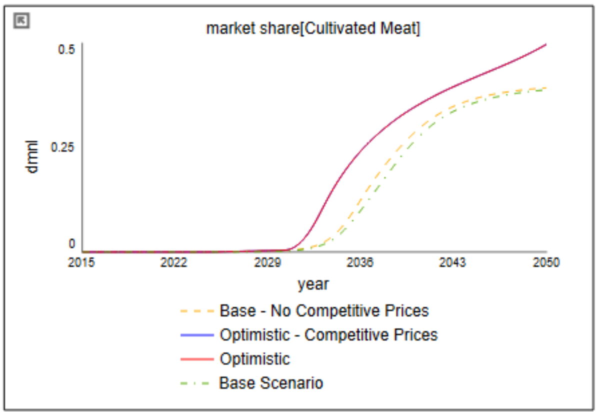


Figure 35: competitive pricing

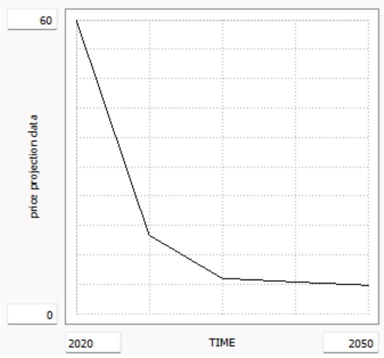


Figure 36: price projections cultivated meat

price, in particular as of 2030 onwards because that is when the production and therefore market share of cultivated meat takes off, which would increase the private investments and therefore decrease the price of cultivated meat further. In addition to this, in the loop B4, the price of meat is reactive to the meat production (which reflects the demand). So only when the meat production is already decreasing will the price react. By that time, the loop R5 has a more dominant effect, ensuring that the relative price of cultivated meat is always lower compared to the average price of traditional meat products.

Land Restriction

As mentioned in the base scenario section, land repurposing is enabled in the base run. It would make sense that this is possible in a real-world scenario. As a reminder, land-use is one of the balancing loops that could restrict the production of cultivated meat. This is shown as loop B5 in figure 37.

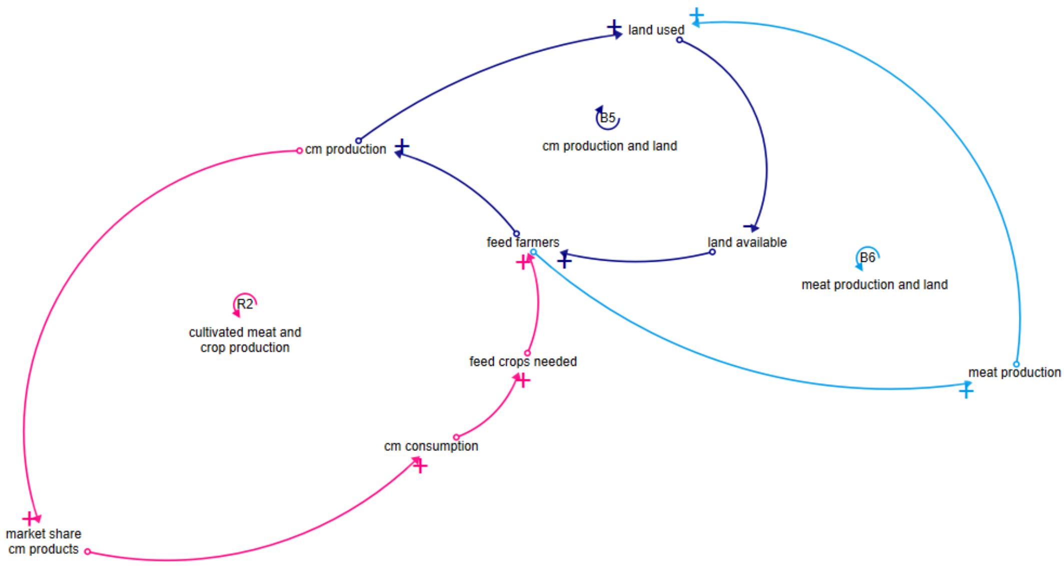


Figure 37: land restriction loops

If this policy of land repurposing is turned off, it means that the land-division as it initially is, will stay the same over the time horizon, only changing when the land degrades and then revives, so the new land can be redistributed again. This process takes a few years though. As the majority of land available to sustain the meat industry is already in use, it would restrict the growth of the cultivated meat industry significantly as there would be not enough available land left. This is confirmed by figure 38 and indicates that land could be a consequential element to the success of the cultivated meat industry. In the scenario where land repurposing is turned off, cultivated meat would only reach a market share of 4%, even in the most optimistic scenario.

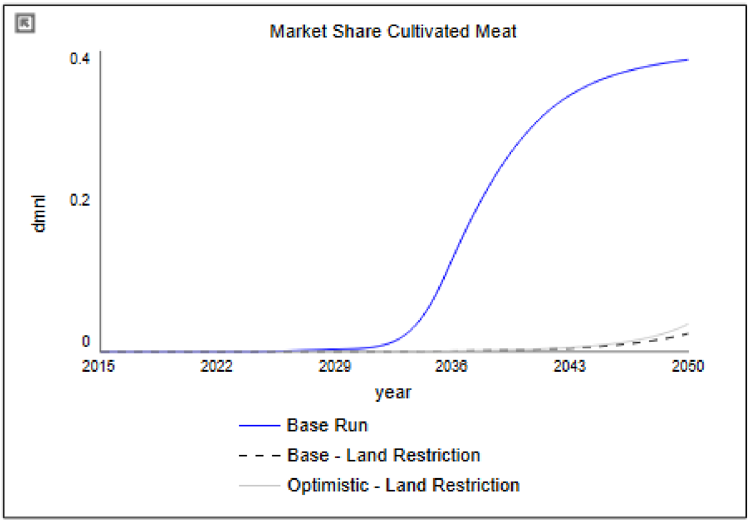


Figure 38: market share - land restriction

As is expected, when market growth of cultivated meat is stunted, there will be a higher production of traditional meat and compared to the base scenario there will be a higher amount of CO2eq emissions. However as can be seen in figure 39, the scenario where land repurposing is off under otherwise the most optimistic settings, indicates that it would actually have a substantially lower amount of CO2eq emissions. This seems counterintuitive. The reason the model is producing this behaviour in this scenario is because in the most optimistic scenario, the cattle restriction policy is enabled affecting loop B4 that is concerned with meat production. This means that the number of cattle is considerably reduced, and therefore less meat is produced, this is visualized in the right graph of figure 39. Of course, when there is less production, CO2eq would decrease. However, a production gap would occur between the amount of protein that is actually produced and the amount of protein that is necessary to cover both the consumption needs of the Dutch population and export. In our optimistic scenario, this gap would be filled with cultivated meat products. However, as cultivated meat is restricted in this scenario because of land, the gap is not being filled. So, either export would have to be decreased in reaction to the cattle restrictions, which would hurt the Dutch economy, or protein products would have to be imported. As said before, the model does not take import into account. Therefore, the behaviour produced for the optimistic land restriction run in the CO2eq graph of figure 39, is technically correct, but it is not necessarily an attractive scenario.

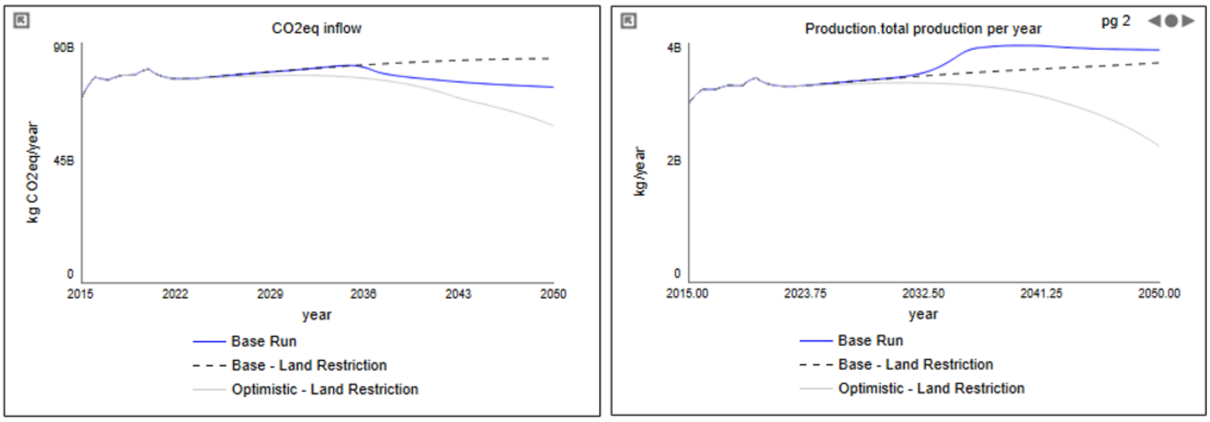


Figure 39: land restriction and CO2eq

No Cultivated Meat

The next scenario shows what happens to the system when no cultivated meat is ever introduced. As cultivated meat is essentially a policy option itself, comparing it to a scenario without it being introduced could provide interesting insights. The loop that is cut in this scenario is loop R2, as can be seen in figure 40 as cultivated meat consumption is considered to be zero. Of course, this also influences loop B4, the loop including traditional meat consumption and production. There will be no competition from cultivated meat products, the loop will lose strength so the meat production will not be impacted the same as in the base run.

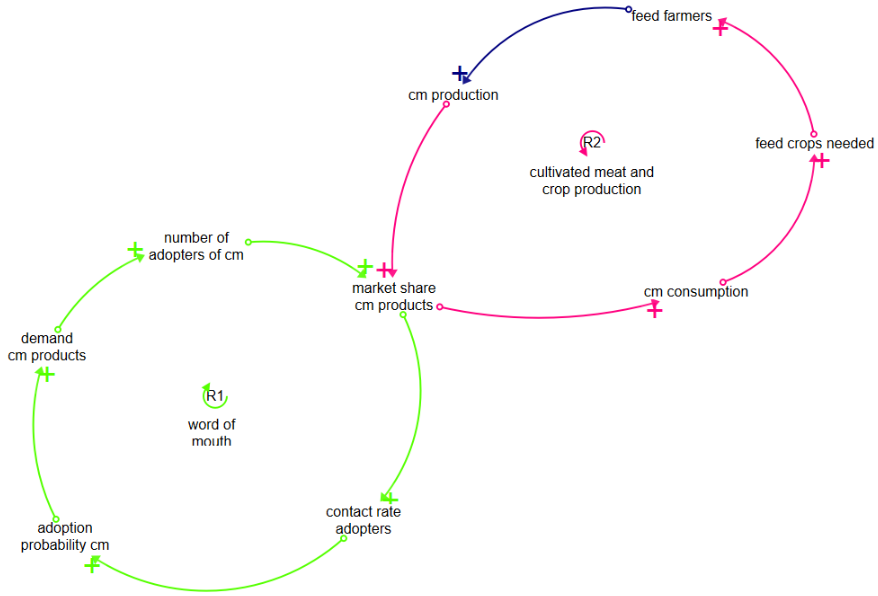


Figure 40: loop R1 & R2

Firstly, consider the CO2eq emissions and total production in figure 41 below. As can be seen, when there is no cultivated meat introduced to the system, the production of traditional meat products and plant-based products is expected to increase steadily according to a growing population. Note, as export is considered to be a set proportion of the production, as the Dutch population increases, the export also increases proportionally. With this production increase, the CO2eq also increases in a similar way. Compared to the base scenario, even though there would be an increase in total production, due to cultivated meat products, the CO2eq would still be lower in the base run. This is because the emissions from traditional meat are higher per unit compared to the emissions from cultivated meat.

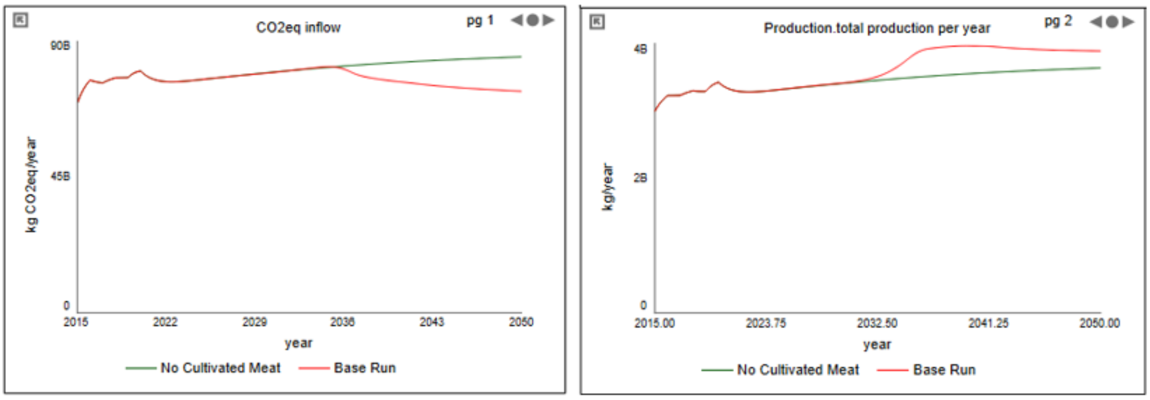


Figure 41: No CM - CO2eq & total production

To consider other effects that the introduction of cultivated meat has on the meat industry, consider the graphs in figure 42. In the base run, not only does the market share of traditional meat products decreases noticeably, the average meat price also drops in an effort to keep being able to compete with cultivated meat products. This double effect would dramatically influence the income of workers in the traditional meat industry.

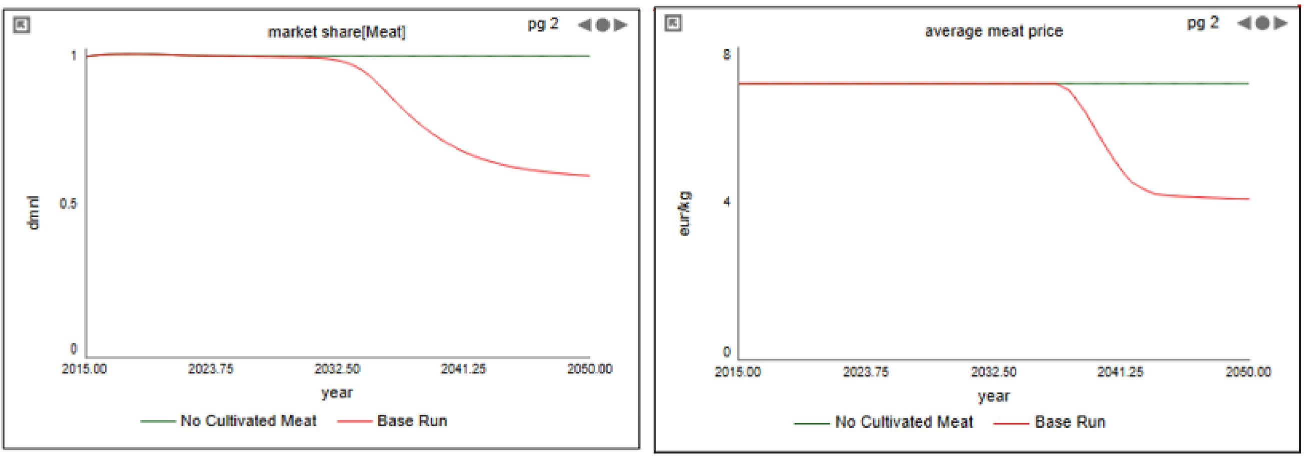


Figure 42: No CM - market share meat & price meat

This impact on the traditional meat industry is also visible in the stock livestock farmers portrayed in figure 43. As can be seen, a lot more livestock farmers will be employed in the scenario without cultivated meat. This makes sense considering the affected loop B4, but also when considering the real-world scenario.

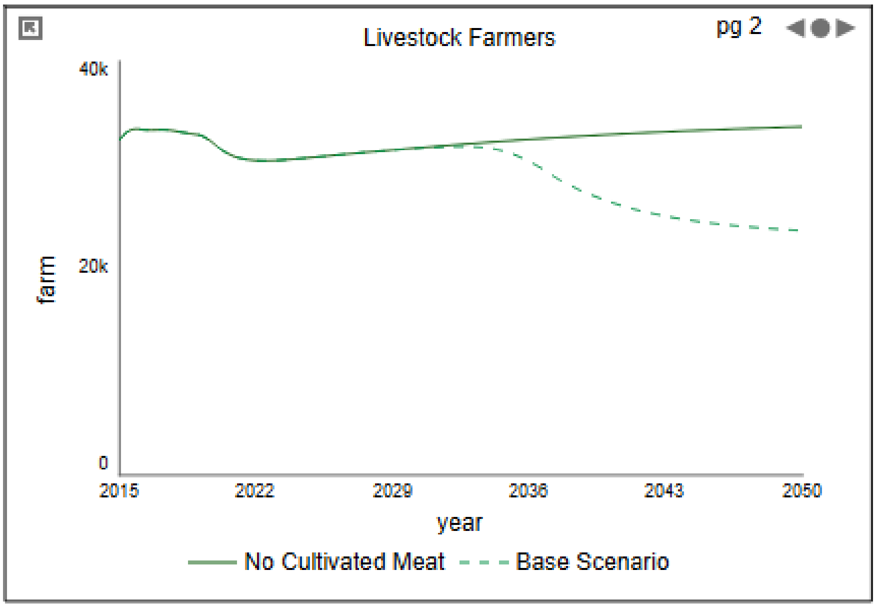


Figure 43: No CM - livestock farmers

Export Scenarios

Finally, several export scenarios are considered. The base run with 60% export is compared to a scenario where there is no export, a scenario with 50% export and a scenario where there is 80% export. The calculation of the domestic market is based on the consumption of meat and meat alternatives of the Dutch population, which numerically stays the same over each scenario. The relative value of this will change though depending on what percentage is exported. Figure 44 portrays the market share of cultivated meat products for each export scenario.

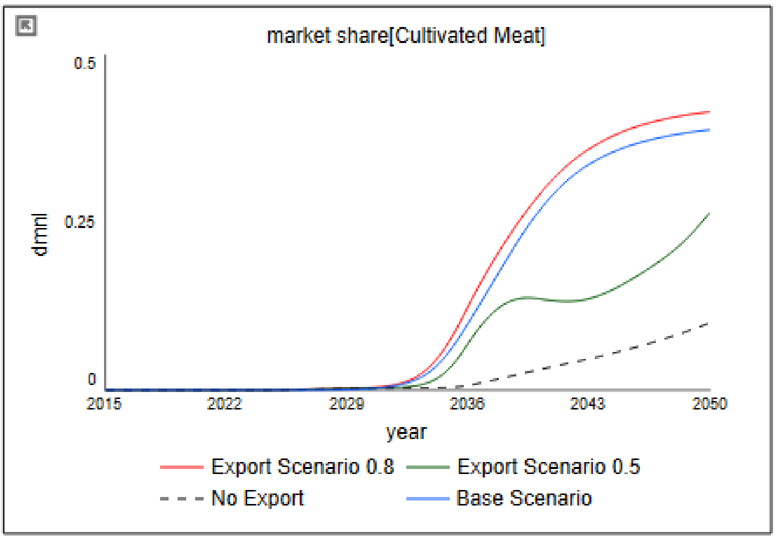


Figure 44: market share CM - export scenarios

Initially, this variety of behaviour produced might be surprising. Proportionately export would impact all meat and meat alternative products with the same percentage. However, the differences in the behaviour of the market share of cultivated meat is caused by the balancing loop B4. More specifically, it is caused by the model structure that incorporates the competitive pricing of traditional meat products. What was argued before regarding the competitive pricing of meat products in the base and optimistic scenario, was that its reaction to the system was too slow for it to catch up with the dropping price projections of cultivated meat products. Therefore, the changing of the prices did not have a significant effect on influencing the growing market share of cultivated meat. However, as can be seen in figure 45, the changes in price occur at a different point in time.

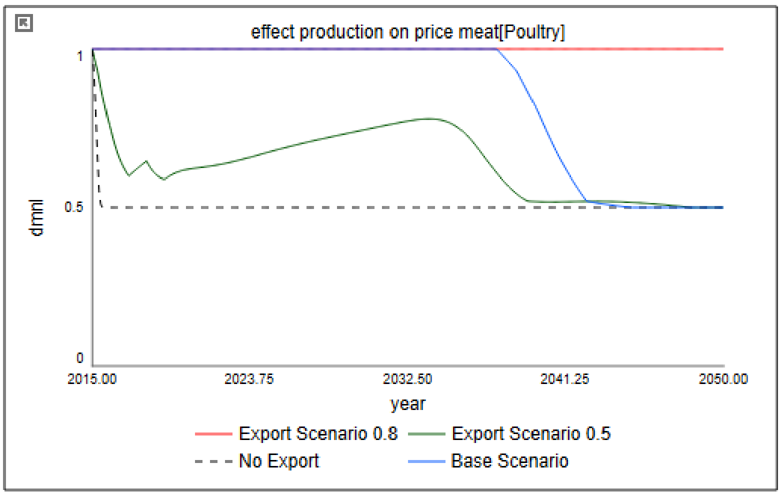


Figure 45: competitive meat pricing

Starting with the scenario that does not include export. Meat production is based on the number of livestock farmers and this stock is initialized to accommodate production for 60% export. If suddenly the export would drop to zero percent, this stock would be affected and production drops drastically. The price of meat reacts to this change in demand since it is connected to meat production. This explains the significant drop in price, and since the prices of cultivated meat have not been able to decrease yet, the adoption fraction of cultivated meat is affected ensuring that the market share in the zero-export scenario does not increase to the same extent as in the base scenario.

This same principle also affects the scenario with 50% export. The drop in production compared to the base run is not as significant in this scenario as it decreases from 60% to 50%. After somewhat stabilizing production to this new export value, production increases again to accommodate for a growing population, thus increasing the price of meat again. As this happens, the relative price of cultivated meat decreases and as a result will gain more adopters. Cultivated meat gains a bigger portion of the production, decreasing the production of traditional meat products, this is what eventually causes the price of meat to drop again as perceived in figure 45.

Chapter Conclusion

To get insights into the different effects of the market introduction of cultivated meat, several scenarios were compared to each other in this chapter. The next chapter will look into what conclusions can actually be drawn from the insights presented in this section.

Discussion

Policy Implications

Now that the model output has been analysed, reflections need to be made whether or not the suggested policies are actually feasible regarding the implementation and the obstacles that might arise.

As shown in the previous chapter, the most optimistic scenario regarding the market growth of cultivated meat includes two policy options, a meat tax and a cattle restriction policy. Even though these policies could have a beneficial effect on the cultivated meat market and the environment, through decreased CO2eq emissions, there are obstacles that need to be considered when implementing these policies in order for them to be successful. How each policy is introduced to the public is crucial to its effect. The before mentioned farmer's protests in the Netherlands are an indication of this. These protests were in response to the announcement of the Dutch government that they intent to reduce cattle by 30% before 2030 (Levitt, 2021) in order to reduce greenhouse gas emissions. Obtaining and maintaining farming permits will be more difficult and this puts the livelihood of many farmers at risk. In response to this announcement the farmers have been protesting for months, for example by occupying highways, starting fires or dumping garbage, often creating unsafe situations. Hundreds of protesters have been arrested since the start of the protests on June 22 (Nieuws NOS, 2022). There is also a lot of support for the farmers from the Dutch population (NOS Nieuws, 2022b). These protests highlight that there is an abundance of policy resistance. Since the introduction of cultivated meat will also contribute to major changes in the traditional agriculture and livestock industry, concerns need to be considered and prepared for to minimize obstacles when implementing these policies.

Government communication with the farmers and public will be essential so that they feel listened to and supported. Farmers in the Netherlands indicate that they perceive the current situation to be unfair because they feel that they are solely impacted by this cattle restriction policy while they are not the only ones contributing to the emission problem (NOS Nieuws, 2022a). It could be argued therefore, that a policy such as the meat tax would be considered to be fairer in the eyes of the farmers as this would impact the Dutch population as a whole, or possibly a combination of both policies. However, as mentioned before, at the moment there have been several political parties in the Netherlands that have criticized the proposed meat tax policy (NOS, 2022). Other options, such as subsidising the training of new employees for the cultivated meat industry could also be considered by the Dutch government, although large delays would be likely for such a policy.

Cultural obstacles will also determine the success of the introduction of cultivated meat. Data that was used in the model regarding consumer acceptance indicates that 66% of consumers would be willing to try cultivated meat (Morach et al., 2021). This is a very promising number; however, this is not an indication that these consumers are willing to adjust their lifestyle to buy mostly cultivated meat products as their main source of protein. This is a legitimate concern, as meat is very prominent in the diet of the Dutch population. Additionally, there could be financial obstacles as well. For example, as mentioned before, the Netherlands is the biggest exporter of meat in Europe, earning a total of 8.8 billion euros from meat exports (CBS, 2021). As the traditional meat industry would decline, it is not certain that the cultivated meat industry could be as successful when it comes to the export of products. However, a meat tax could compensate for possible financial losses in export.

Research Questions

1. **What could be some unforeseen circumstances that could limit the growth of the market share of cultivated meat products in the Netherlands?**

There are a few elements explored in this research that could limit the growth of cultivated meat products. As mentioned in the previous chapter, the division of land can hold back the market growth of cultivated meat. Land needs to be managed properly and re-purposed to ensure that there is enough to mass produce crops needed for cultivated meat. Additionally, depending on the price developments of cultivated meat, a changing price of competing traditional meat products could also affect the market growth of cultivated meat. Other than that, the development of consumer acceptance will play a considerable role in the success of the growth of the cultivated meat market.

   a. **How does the introduction of cultivated meat impact the traditional meat industry in the Netherlands and what are their dynamic implications?**

As mentioned before, with the introduction of cultivated meat, this might provide the traditional meat market with competition. As the model portrays, a growing cultivated meat sector could alternate the demand for traditional meat and this could affect the prices of meat products. If the demand decreases for traditional meat products, the price for traditional meat products would likely drop in order to stay competitive. This will have an effect on the income for famers and other workers in the meat industry. In addition to that, if the cultivated meat market grows significantly, the livelihood of farmers could become at risk as there won't be a need for the same number of farmers compared to the current market. Especially livestock farmers could be at risk and could possibly lose their jobs. Of course, new jobs would be created in the cultivated meat sector, but as the production process differs from traditional meat production, workers would require different skill sets and these jobs would not be directly interchangeable. Farmers impacted by the introduction of cultivated meat are likely to apply for government support.

2. **What policy options for the Dutch government can be identified to optimize sustainable meat production?**

Cultivated meat is a policy option in itself that the government has recently started subsidizing (Schuengel, 2022). It is clear that the production of cultivated meat can become more sustainable as the technology progresses, compared to the production of traditional meat. However, as this policy becomes more successful and the market share of cultivated meat increases, the impact it would have on society, most notably the disrupting effect on the agricultural industry, would increase as well. It is therefore likely that the policy option could face some resistance. This would have to be explored in further research. Other policy options that were explored are a cattle restriction and a meat tax policy. These will be discussed below.

   a. **How do livestock restrictions influence the market share of cultivated meat products?**

As seen in the previous chapter, a cattle restriction policy would have a significant influence on the market share of cultivated meat. As there would be less traditional meat products due to a decrease in livestock, a majority of those products can be substituted with cultivated meat products. In order to reduce CO2eq emissions as much as possible, the cattle restriction would be impactful. As mentioned before, this policy has already provoked some policy resistance as there have been protests in the summer of 2022 in response to the announcement of cattle restrictions. Therefore, this policy option could prove to be effective, however, the model does not yet include certain policy obstacles such as the farmers protests. This could influence the market growth of cultivated meat products, as such more detailed research into this policy option should be conducted.

b. What would the effect of a meat tax be on the growth of the market share of cultivated meat in the Netherlands?

A meat tax would also affect the market share of cultivated meat. As seen in the previous chapter, it would ensure that people would adopt to cultivated meat sooner compared to the base run as it would make cultivated meat products a more attractive option if they are cheaper compared to traditional meat products. In the long run, the meat tax does not seem to contribute to a higher market share. This could be an important obstacle when soliciting government support as at the moment there is no majority in the Dutch government that is in favour of implementing this policy in the foreseeable future (NOS, 2022).

3. What are insights into the feasibility of market share projections of cultivated meat products in the Netherlands?

According to the model behaviour, the market share projections do seem to be feasible. However, there might still be restricting elements that were not fully explored in this model due to uncertainty in available data and previously mentioned obstacles. With regard to the former, production capacity for example, might not develop according to current projections and therefore limit the amount of cultivated meat products that can be produced and thus limit the market share growth as well. Concerns regarding other obstacles and their effect on the feasibility of the market share of cultivated meat have been discussed above.

a. What effect does the introduction of cultivated meat products have on the greenhouse gas emissions of the meat industry in the Netherlands?

The introduction of cultivated meat products seems to contribute to decreasing the greenhouse gas emissions of the meat industry. As the meat industry is a big contributor to the emissions of greenhouse gasses an alternative like cultivated meat would seem to be a good option in combatting this issue. The degree of its impact on the emissions can vary, depending on what combination of policy options will be implemented as shown by the different scenarios explored in the previous chapter. However, the scenarios where cultivated meat had the biggest market share, also proved to be the most environmentally friendly in regard to the emissions of greenhouse gasses.

Limitations & Further Research

This final section discusses the limitations of this research and possibilities to further build upon this research in the future.

There are still many uncertainties when it comes to the cultivated meat industry. One big uncertainty is the development of the production capacity. As mentioned above, production capacity is used as exogenous data in the current model, but it is not guaranteed that within that predicted time, cultivated meat will be available at low costs, mass scale and at high quality (O'Neill, 2020) since there is only limited data available. More data regarding for example, price projections or the average demand of cultivated meat per adopter, could also contribute to better quantify future models within this topic. Future research will provide more accurate data and could therefore allow for more accurate predictions regarding the effect of cultivated meat and the effect of any relating policies.

For future research, to increase the accuracy of the model output, certain elements, such as the import of meat and meat alternatives and the inclusion of the use of animal manure, could be included in the model boundary.

The goal of this research has not been to discover what the best policy is when it comes to the introduction of cultivated meat, but to see what happens when cultivated meat is introduced to the market. Further research can build upon this model and explore each policy in more detail including feasibility restrictions, policy resistance and policy costs to discover what policy option and/or combination would be the most preferable.

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Appendix 1 – Model Documentation

Top-Level Model:
adopters_of_cm(t) = adopters_of_cm(t - dt) + (adopting - competing_meat_price) * dt
INIT adopters_of_cm = initial_adopters_of_cm
UNITS: person
DOCUMENT: Stock of the population that are adopters of cultivated meat products.
market_share[Meat](t) = market_share[Meat](t - dt) + (change_in_market_share[Meat]) * dt
INIT market_share[Meat] = 0.975
UNITS: dmnl
DOCUMENT: This stock shows the market share for the meat sector, the plant-based meat sector and the cultivated meat sector. Initialized to data from 2020 (Bakker, 2021). If you add the market shares together, the value 1 will be produced.
market_share[Plant_Based_Meat](t) = market_share[Plant_Based_Meat](t - dt) + (change_in_market_share[Plant_Based_Meat]) * dt
INIT market_share[Plant_Based_Meat] = 0.025
UNITS: dmnl
DOCUMENT: This stock shows the market share for the meat sector, the plant-based meat sector and the cultivated meat sector. Initialized to data from 2020 (Bakker, 2021). If you add the market shares together, the value 1 will be produced.
market_share[Cultivated_Meat](t) = market_share[Cultivated_Meat](t - dt) + (change_in_market_share[Cultivated_Meat]) * dt
INIT market_share[Cultivated_Meat] = 0
UNITS: dmnl
DOCUMENT: This stock shows the market share for the meat sector, the plant-based meat sector and the cultivated meat sector. Initialized to data from 2020 (Bakker, 2021). If you add the market shares together, the value 1 will be produced.
unwilling_to_try_cm(t) = unwilling_to_try_cm(t - dt) + (predicted_population_growth - willingness) * dt
INIT unwilling_to_try_cm = initial_unwilling_to_try_cm
UNITS: person
DOCUMENT: Stock of the population that is not willing to try cultivated meat products.
willing_if_price_is_right(t) = willing_if_price_is_right(t - dt) + (willingness + competing_meat_price - adopting) * dt
INIT willing_if_price_is_right = initial_willing_if_price_is_right
UNITS: person
DOCUMENT: Stock of the population that is willing to try cultivated meat products when the price is right.
adopting = (willing_if_price_is_right*(natural_convincing*effect_of_price_cm_on_adopting))/time_to_adopt_cm
UNITS: person/years
DOCUMENT: To get the number of people that are adopting, the stock of people that are willing to buy cultivated meat products if the price is right is multiplied with a fraction that represents the people that naturally are convinced to become adopters. This fraction can change (through multiplication) according to the effect that the price of cultivated meat has on convincing the willing people to become adopters. All of this is divided by the time it takes consumers to adopt the cultivated meat products.

change_in_market_share[Meat] = ((SUM(Production.meat_production_NL)/total_production_Netherlands)-market_share)/at_market_share
UNITS: dmnl/year
DOCUMENT: To calculate the change in market share for each meat/meat alternative category, the production of that category is divided by the total production. The stock market share is subtracted from that to get the change in market share. All this combined is divided by the adjustment time of the market share.
change_in_market_share[Plant_Based_Meat] = ((Production."production_plant-based_products"/total_production_Netherlands)-market_share)/at_market_share
UNITS: dmnl/year
DOCUMENT: To calculate the change in market share for each meat/meat alternative category, the production of that category is divided by the total production. The stock market share is subtracted from that to get the change in market share. All this combined is divided by the adjustment time of the market share.
change_in_market_share[Cultivated_Meat] = ((Production.production_CM_products/total_production_Netherlands)-market_share)/at_market_share
UNITS: dmnl/year
DOCUMENT: To calculate the change in market share for each meat/meat alternative category, the production of that category is divided by the total production. The stock market share is subtracted from that to get the change in market share. All this combined is divided by the adjustment time of the market share.
competing_meat_price = (adopters_of_cm*(natural_changing_mind*effect_competing_meat_price))/time_to_adopt_cm
UNITS: person/year
DOCUMENT: It is possible for adopters to change their mind, for example due to changes in the price of traditional meat. To get the number of people that are switching back to buying meat products, the stock of people that are adopters is multiplied with a fraction that represents the people that would naturally change their mind about being an adopter. This fraction can change (through multiplication) according to the effect that the price of traditional meat has on convincing adopters to switch back to meat. All of this is divided by the time it takes consumers to adopt the products.
predicted_population_growth = (Production.population_predictions_NL_data-total_population)/time_to_adjust_population
UNITS: person/year
DOCUMENT: To account for a growing population, the difference between the population that is currently included in the three stocks and the population predictions is divided with the adjustment time.
willingness = MAX(0, population_becoming_willing)
UNITS: person/year
DOCUMENT: This inflow represents the total amount of people who become willing to buy cultivated meat if the price is right.
actual_private_investments = private_investments_data*effect_market_share_on_private_investments
UNITS: eur
DOCUMENT: It is assumed that when the market share grows, it will attract private investments. To calculate the value of these investments, the private investments from 2021 are multiplied with the effect the market share has on the private investments.
at_market_share = 1

UNITS: year
DOCUMENT: Adjustment time of the market share. Not a sensitive variable.
average_meat_price = SUM(price_meat_products)/3
UNITS: eur/kg
DOCUMENT: The average meat price between beef, pork and poultry products.
average_price_meat_products_data[Beef] = 4
UNITS: eur/kg
DOCUMENT: Average prices of traditional meat products based on different sources. Poultry prices based on CBS(2015) and Wageningen University & Research (2022). Pork prices based on a news article from Lesscher (2021) and beef prices on an article by Lamers & Lesscher (2021).
average_price_meat_products_data[Pork] = 7.9
UNITS: eur/kg
DOCUMENT: Average prices of traditional meat products based on different sources. Poultry prices based on CBS (2015) and Wageningen University & Research (2022). Pork prices based on a news article from Lesscher (2021) and beef prices on an article by Lamers & Lesscher (2021).
average_price_meat_products_data[Poultry] = 9.35
UNITS: eur/kg
DOCUMENT: Average prices of traditional meat products based on different sources. Poultry prices based on CBS (2015) and Wageningen University & Research (2022). Pork prices based on a news article from Lesscher (2021) and beef prices on an article by Lamers & Lesscher (2021).
average_product_demand_per_adopter = GRAPH(TIME)
Points(11): (2020.00, 20.1338570185), (2023.00, 20.3597241992), (2026.00, 20.9485174636), (2029.00, 22.3840584404), ...
UNITS: kg/person/year
DOCUMENT: This variable represents on average how much product the adopter would buy per year. The assumption is that over the years, adopters will exchange more of their protein needs with cultivated meat products instead of traditional meat products. As there is a limit to how much consumers would buy it is assumed this variable is S-shaped. Sensitive variable.
cm_consumption_NL = MIN(production_capacity_with_funding_adjustment, demand_cm)
UNITS: kg/year
DOCUMENT: It is assumed that demand is met as long as production capacity is not exceeded.
CM_market_share_gap = MAX(0, market_share_goal_cm_products-market_share[Cultivated_Meat])
UNITS: dmnl
DOCUMENT: This variable represents the gap between the actual market share of cultivated meat products and the goal value of the market share. To get this gap, the market share of cultivated meat is subtracted from the goal value. A MAX function is added to ensure this value cannot go negative.
cm_start_time = 2024
UNITS: years
DOCUMENT: There are currently no cultivated meat products for sale. However, tasting trials are happening in the Netherlands (de Heus, 2022). Therefore, it is assumed that in 2024, cultivated meat products will be available for the public.
contact_potential_adopters = contacts_willing_population*fraction_unwilling_population
UNITS: person/year
DOCUMENT: The number of adopters the non-adopters come in contact with.
contact_rate = 40
UNITS: person/person/year
DOCUMENT: The amount of people, a person is in contact with every year. Not a sensitive variable.

contacts_willing_population = (adopters_of_cm+willing_if_price_is_right)*contact_rate
UNITS: person/year
DOCUMENT: The contacts with the willing population is calculated by adding up the willing population, which includes the adopters stock and the stock of people who are willing to buy cultivated meat products if the price is right. These people are multiplied with the contact rate.
demand_cm = IF policy_status_cm = 1 THEN MAX(0, (average_product_demand_per_adopter)*adopters_of_cm) ELSE 0
UNITS: kg/year
DOCUMENT: When the policy status for cultivated meat is turned on, the demand for cultivated meat products is calculated by multiplying the number of adopters with the product demand per adopter.
desired_adjustment_rate = MAX(0, CM_market_share_gap/policy_adjustment_time)
UNITS: dmnl/year
DOCUMENT: The adjustment rate is determined by dividing the market share gap with the policy adjustment time.
effect_competing_meat_price = GRAPH(relative_price_cm)
Points(11): (0.000, 0.0133857018486), (0.200, 0.0359724199242), (0.400, 0.0948517463551), (0.600, 0.238405844044), ...
UNITS: dmnl
DOCUMENT: When the relative price of cultivated meat products go down, it means, cultivated meat products are cheaper compared to traditional meat products. So if this happens, the less likely adopters would be to switch back to traditional meat and vice versa. Assumed to have an S-shaped effect.
effect_gap_on_meat_tax = GRAPH(desired_adjustment_rate)
Points(11): (0.0000, 1.000), (0.0400, 1.11050759184), (0.0800, 1.23498001904), (0.1200, 1.37518201668), ...
UNITS: dmnl
DOCUMENT: The Dutch minister of agriculture, nature and food quality announced in March that an investigation will be started into the introduction of a meat tax (NOS, 2022). This variable shows the effect of that meat tax depending on the desired adjustment rate of the government. It is assumed that if there is a big gap between the goal of the market share of cultivated meat products and the actual market share, the government would take more extreme measures and introduce a higher meat tax compared to when this gap is smaller.
effect_market_share_on_private_investments = GRAPH(market_share[Cultivated_Meat])
Points(11): (0.000, 1.000), (0.100, 1.49728416329), (0.200, 2.05741008567), (0.300, 2.68831907508), ...
UNITS: dmnl
DOCUMENT: It is assumed that when the market share is increasing, more private investors would want to invest and that this effect would increase increasingly.
effect_of_gap_on_gov_funding = GRAPH(desired_adjustment_rate)
Points(11): (0.000, 1.000), (0.100, 1.18362107368), (0.200, 1.38655374426), (0.300, 1.61082903011), ...
UNITS: dmnl
DOCUMENT: It is assumed that when there is a big gap between the goal value of the market share of cultivated meat, and the actual value of cultivated meat, the government would be more likely to invest to try and close that gap and that this effect would increase increasingly depending on the desired adjustment rate.
effect_of_investments_on_price_cm = GRAPH(IF switch_investment_scenarios = 0 OR switch_investment_scenarios = 1 THEN relative_investments ELSE 1)

Points(11): (1.000, 0.994980361807), (1.200, 0.986510342528), (1.400, 0.964430595117), (1.600, 0.910597808483), ...
UNITS: dmnl
DOCUMENT: As the investments increase, the price will go down. This effect is assumed to be s-shaped as the relative investments increase, it can have a bigger effect on the price. However, there is a limit to how much prices can drop, due to elements like profit margins. Sensitive variable.
effect_of_investments_on_production_capacity = GRAPH(IF switch_investment_scenarios = 0 OR switch_investment_scenarios = 3 THEN relative_investments ELSE 1)
Points(11): (1.000, 1.000), (1.400, 1.55086322104), (1.800, 2.15966123277), (2.200, 2.83248709032), ...
UNITS: dmnl
DOCUMENT: It is assumed that the production capacity will not decrease, it can only increase with more investments. Not a sensitive variable.
effect_of_investments_on_public_education = GRAPH(IF switch_investment_scenarios = 0 OR switch_investment_scenarios = 2 THEN relative_investments ELSE 1)
Points(11): (1.000, 1.00669285092), (1.100, 1.01798620996), (1.200, 1.04742587318), (1.300, 1.11920292202), ...
UNITS: dmnl
DOCUMENT: Pakseresht et al. (2022), share results of their study that participants were almost twice as likely to adopt to cultivated meat products after more knowledge about cultivated meat was shared with them. This is represented in the graph that is S-shaped because it is assumed that there is a limit to the effect a public education campaign can have. At some point more investment in public education campaigns will not increase the amount of adopters.
effect_of_price_cm_on_adopting = GRAPH(relative_price_cm)
Points(13): (0.000, 1.98661429815), (0.166666666667, 1.96946569224), (0.333333333333, 1.93110960867), (0.500, 1.84828363996), ...
UNITS: dmnl
DOCUMENT: When the price of cultivated meat products go down, the people who will become adopters increases. Assumed to have an S-shaped effect.
effect_price_meat[Farms] = IF switch_competitive_pricing_meat = 1 THEN effect_production_on_price_meat ELSE 1
UNITS: dmnl
DOCUMENT: If this switch is on (1) the changing meat prices based on market developments and competition will be taken into consideration. If it is turned off (0) it is assumed market competition does not influence the prices of the traditional meat products.
effect_production_on_price_meat[Farms] = GRAPH(relative_meat_production)
Points(6): (0.7500, 0.500), (0.8000, 0.520), (0.8500, 0.660), (0.9000, 0.810), ...
UNITS: dmnl
DOCUMENT: It is assumed that as the market share of cultivated meat increases, and its production increases, as a competitive reaction, the prices of traditional meat products will go down in order to become more attractive for the consumer to try to counteract the growth of cultivated meat products. Moderately sensitive variable.
fraction_unwilling_population = unwilling_to_try_cm/Production.population_predictions_NL_data
UNITS: dmnl
DOCUMENT: To get the fraction of the unwilling population the stock is divided by the total population.
government_investments = 60e6
UNITS: eur

DOCUMENT: The Dutch government has announced in April 2022 to invest 60 million into the cultivated meat industry (Schuengel, 2022).
initial_adopters_of_cm = INIT(Production.population_predictions_NL_data)*initial_fraction_adopters_cm
UNITS: person
DOCUMENT: To determine the actual amount of people that would be adopting to cultivated meat products, the fraction of adopters is multiplied with the population amount of the Netherlands of 2020.
initial_fraction_adopters_cm = 0.11
UNITS: dmnl
DOCUMENT: Based on consumer research, 11% of consumers indicated they were very interested to try cultivated meat products (Morach et al., 2021). Not a sensitive variable.
initial_fraction_unwilling_cm = MAX(0, MIN(1, 1-(initial_fraction_adopters_cm+initial_fraction_willing_cm)))
UNITS: dmnl
DOCUMENT: To calculate the fraction of the population that is not willing to try cultivated meat products, the other fraction values (from adopters and willing to try) are both subtracted from the total value of 1.
initial_fraction_willing_cm = 0.66
UNITS: dmnl
DOCUMENT: Based on consumer research, 66% of consumers indicated they were willing to try cultivated meat products (Morach et al., 2021). Not a sensitive variable.
initial_investment = 122e6 + 60e6
UNITS: eur
DOCUMENT: The initial values of the private and government investments added up together.
initial_unwilling_to_try_cm = INIT(Production.population_predictions_NL_data)*initial_fraction_unwilling_cm
UNITS: person
DOCUMENT: To determine the actual amount of people that are unwilling to try cultivated meat products, the fraction of adopters is multiplied with the population amount of the Netherlands of 2020.
initial_willing_if_price_is_right = INIT(Production.population_predictions_NL_data)*initial_fraction_willing_cm
UNITS: person
DOCUMENT: To determine the actual amount of people that would be willing to try cultivated meat products if the price is right, the fraction of adopters is multiplied with the population amount of the Netherlands of 2020.
"kg/metric_tonne" = 1000
UNITS: kg/metric ton
DOCUMENT: The amount of kg in a metric tonne.
market_share_goal_cm_products = GRAPH(TIME)
Points(31): (2020.00, 0.3000), (2021.00, 0.308592445039), (2022.00, 0.317547486512), (2023.00, 0.326880425786), ...
UNITS: dmnl
DOCUMENT: Assumption that the goal of the cultivated meat market share will increase over time. Considering the significant effect the market share of cultivated meat would have on the traditional meat industry, it is assumed the Dutch government would like to make this transition gradually. However, as the government indicated they have strict goals for reducing emissions and becoming climate neutral by 2050 (VVD et al., 2021), the initial goal value is assumed to be relatively high at 0.3.

meat_tax = IF switch_meat_tax = 1 THEN effect_gap_on_meat_tax ELSE 1
UNITS: dmnl
DOCUMENT: The Dutch minister of agriculture, nature and food quality announced in March that an investigation will be started into the introduction of a meat tax (NOS, 2022). If this switch is 1 it will turn on that effect on the rest of the model.
natural_changing_mind = 0.04
UNITS: dmnl
DOCUMENT: It is of course possible for adopters to change their mind, for example due to changes in the price of traditional meat.This is the fraction that indicates the strength of that value. Calibrated to match market share projections. Sensitive variable.
natural_convincing = 0.1
UNITS: dmnl
DOCUMENT: There will also be people who will adopt to cultivated meat products regardless of the price. These people are included in this variable. Based on calibration and assumption. Not a sensitive variable.
normal_fraction_of_becoming_willing = 0.08
UNITS: dmnl
DOCUMENT: The normal fraction of consumers becoming willing to try cultivated meat products when the price is right. Based on calibration and assumption. Not a sensitive variable.
policy_adjustment_time = 2
UNITS: years
DOCUMENT: As the government has set some strict goals regarding reaching climate neutrality by 2050 (VVD et al., 2021), it is assumed that this variable is relatively small at 2 years. Not sensitive.
policy_status_cm = IF switch_cm = 1 AND (cm_start_time<TIME) THEN 1 ELSE 0
UNITS: dmnl
DOCUMENT: The policy status is on (1) when the switch is turned on and it is after the start time of when cultivated meat products would be available for the public.
Policy_status_competitive_pricing = IF switch_competitive_pricing_meat = 1 AND Production.switch_cattle_policy = 0 THEN 1 ELSE 0
UNITS: dmnl
DOCUMENT: This variable ensures that the competitive pricing is not activated when the cattle restriction policy is activated. The reason for this is that this cattle policy decreases the supply of traditional meat products. When supply is decreased, according to workings of the market, the price would increase. What this price competitiveness effect is meant to do is to cut the price of traditional meat when the DEMAND for traditional meat decreases (as the demand for cultivated meat increases). Because when demand drops, the price would drop too (Asmundson, 2020). As demand is not the factor for a drastic decrease of production, a decrease of the price should not happen under the circumstance of an active cattle restriction policy. For future iterations of this model, a more accurate representation should be introduced of the workings of the market and how price reacts to changes in supply and demand.
population_becoming_willing = (normal_fraction_of_becoming_willing*effect_of_investments_on_public_education)*contact_potential_adopters
UNITS: person/year
DOCUMENT: To calculate the people per year that would become willing to try cultivated meat products if the price is right, the normal fraction of becoming willing to buy cultivated meat products if the price is right, is multiplied with the effect that investments have on public education. This is the case because when the public knowledge increases through education, it

increases their willingness (Bryant & Barnett, 2018). To get the actual number of people that are becoming willing, the fraction is multiplied with the number of adopters the non-adopters come in contact with.
price_cm = price_projection_data*effect_of_investments_on_price_cm
UNITS: eur/kg
DOCUMENT: It is assumed that the investments in the industry could be used to directly focus on lowering the consumer prices of cultivated meat products. The effect the investments could have on the price, is multiplied with the price projection data.
price_meat_products[Farms] = average_price_meat_products_data*meat_tax*effect_price_meat
UNITS: eur/kg
DOCUMENT: The average meat prices are multiplied with different effects. One is the effect on the meat prices that is caused by market competition. The other is the effect of a meat tax, if this would be introduced by the Dutch government.
price_projection_data = GRAPH(TIME)
Points(5): (2020.00, 60.00), (2027.50, 16.00), (2035.00, 7.16), (2042.50, 6.41), ...
UNITS: eur/kg
DOCUMENT: Price projections based on research from Vergeer et al. (2021). This is a sensitive variable.
private_investments_data = 122e6
UNITS: eur
DOCUMENT: This amount is based on the private investments received by the two main and biggest cultivated meat companies in the Netherlands (Business Insider Nederland, 2020, 2021).
production_capacity_conversion = (production_capacity_projections*"kg/metric_tonne")
UNITS: kg/year
DOCUMENT: Conversion variable to transfer the production capacity projections from metric tonne to kg.
production_capacity_projections = GRAPH(TIME)
Points: (2022.00, 200), (2025.00, 2000), (2030.00, 8000), (2050.00, 2000000)
UNITS: metric ton/year
DOCUMENT: Based on data from the Good Food Institute (2021).
production_capacity_with_funding_adjustment = production_capacity_conversion*effect_of_investments_on_production_capacity
UNITS: kg/year
DOCUMENT: The production capacity projections are multiplied with the effect that investments could have on the production capacity.
relative_investments = total_funding/initial_investment
UNITS: dmnl
DOCUMENT: The relative investments are calculated by dividing the funding (at any point within the time-frame) with the initial funding received in 2020.
relative_meat_production[Farms] = Production.meat_production_NL/INIT(Production.meat_production_NL)
UNITS: dmnl
DOCUMENT: The relative meat production is determined by dividing the meat production at any time with the initial meat production from 2020.
relative_price_cm = price_cm/average_meat_price
UNITS: dmnl

DOCUMENT: The relative price of cultivated meat products compared to traditional meat products.
switch_cm = 1
UNITS: dmnl
DOCUMENT: Switch to turn the use of cultivated meat on (1) or off (0).
switch_competitive_pricing_meat = 1
UNITS: dmnl
DOCUMENT: If this switch is on (1) the changing meat prices based on market developments and competition will be taken into consideration. If it is turned off (0) it is assumed market competition does not influence the prices of the traditional meat products.
switch_investment_scenarios = 0
UNITS: dmnl
DOCUMENT: This switch variable enables switching between different investment scenarios. If the switch is set at 0, it means that all investment effect functions are enabled and will get all get full effects according to each of their values. If the switch is set at 1, it is assumed that all investments are allocated to lowering the price of cultivated meat products. If it is set at 2, all investments will go towards public education campaigns and if it is set at 3, the investments will be allocated to increasing the production capacity.
switch_meat_tax = 0
UNITS: dmnl
DOCUMENT: The Dutch minister of agriculture, nature and food quality announced in March that an investigation will be started into the introduction of a meat tax (NOS, 2022). If this switch is 1 it will turn on that effect on the rest of the model.
time_to_adjust_population = 1
UNITS: year
DOCUMENT: Not a sensitive variable.
time_to_adopt_cm = 1/12
UNITS: years
DOCUMENT: It is assumed that it takes one month for consumers to adjust their buying habits. This is a sensitive value.
total_funding = MAX(0, ((government_investments*effect_of_gap_on_gov_funding) + actual_private_investments))
UNITS: eur
DOCUMENT: The total funding combines the private investments and the government investments and takes the effect of the market share on the government investments in consideration.
total_population = adopters_of_cm + unwilling_to_try_cm + willing_if_price_is_right
UNITS: person
DOCUMENT: Sum of the population that is currently included in the three stocks.
total_production_Netherlands = SUM(Production.meat_production_NL)+Production."production_plant-based_products" +Production.production_CM_products
UNITS: kg/year
DOCUMENT: Sum of all production from the meat and meat alternatives categories.
Environment:
CO2eq_meat_industry_NL(t) = CO2eq_meat_industry_NL(t - dt) + (CO2eq_inflow - dispersion) * dt
INIT CO2eq_meat_industry_NL = CO2_meat_industry_DATA
UNITS: kg CO2eq

DOCUMENT: Stock that shows the amount of CO2eq produced by the meat industry. Based on various sources (Milieu Centraal, 2022; RIVM, 2021).
degraded_land(t) = degraded_land(t - dt) + (land_degradation[Beef] + land_degradation[Cultivated_Meat_conventional] + land_degradation[Pork] + land_degradation[Poultry] + land_degradation[Cultivated_Meat_sustainable] + land_degradation[Plantbased_products] - land_recovery) * dt
INIT degraded_land = 25000
UNITS: hectare
DOCUMENT: Stock showing degraded agricultural land. Assumed initialization variable. Not sensitive.
"land-use"[Beef](t) = "land-use"[Beef](t - dt) + ("change_in_land-use"[Beef] + "re-purposing_land_for_cm"[Beef] - land_degradation[Beef] - "land_re-purpose"[Beef]) * dt
INIT "land-use"[Beef] = 1.16e6
UNITS: hectare
DOCUMENT: Stock showing the division of land that is currently being used to produce crops needed for the meat and meat alternatives products. The data that was used to initialize this stock was regarding agricultural land in the Netherlands (CBS, 2020; van Rossum, 2021) as portrayed as reference variables in the above sector. The specific values were found through the calibration process. Only the initialization of cultivated meat land is sensitive, the other categories are not sensitive.
"land-use"[Cultivated_Meat_conventional](t) = "land-use"[Cultivated_Meat_conventional](t - dt) + ("change_in_land-use"[Cultivated_Meat_conventional] + "re-purposing_land_for_cm"[Cultivated_Meat_conventional] - land_degradation[Cultivated_Meat_conventional] - "land_re-purpose"[Cultivated_Meat_conventional]) * dt
INIT "land-use"[Cultivated_Meat_conventional] = initial_cm_land*(1-fraction_of_sustainable_energy_for_cm_production)
UNITS: hectare
DOCUMENT: Stock showing the division of land that is currently being used to produce crops needed for the meat and meat alternatives products. The data that was used to initialize this stock was regarding agricultural land in the Netherlands (van Rossum, 2021; CBS, 2020) as portrayed as reference variables in the above sector. The specific values were found through the calibration process. Only the initialization of cultivated meat land is sensitive, the other categories are not sensitive.
"land-use"[Pork](t) = "land-use"[Pork](t - dt) + ("change_in_land-use"[Pork] + "re-purposing_land_for_cm"[Pork] - land_degradation[Pork] - "land_re-purpose"[Pork]) * dt
INIT "land-use"[Pork] = 374000
UNITS: hectare
DOCUMENT: Stock showing the division of land that is currently being used to produce crops needed for the meat and meat alternatives products. The data that was used to initialize this stock was regarding agricultural land in the Netherlands (van Rossum, 2021; CBS, 2020) as portrayed as reference variables in the above sector. The specific values were found through the calibration process. Only the initialization of cultivated meat land is sensitive, the other categories are not sensitive.
"land-use"[Poultry](t) = "land-use"[Poultry](t - dt) + ("change_in_land-use"[Poultry] + "re-purposing_land_for_cm"[Poultry] - land_degradation[Poultry] - "land_re-purpose"[Poultry]) * dt
INIT "land-use"[Poultry] = 137000
UNITS: hectare

DOCUMENT: Stock showing the division of land that is currently being used to produce crops needed for the meat and meat alternatives products. The data that was used to initialize this stock was regarding agricultural land in the Netherlands (van Rossum, 2021; CBS, 2020) as portrayed as reference variables in the above sector. The specific values were found through the calibration process. Only the initialization of cultivated meat land is sensitive, the other categories are not sensitive.
"land-use"[Cultivated_Meat_sustainable](t) = "land-use"[Cultivated_Meat_sustainable](t - dt) + ("change_in_land-use"[Cultivated_Meat_sustainable] + "re-purposing_land_for_cm"[Cultivated_Meat_sustainable] - land_degradation[Cultivated_Meat_sustainable] - "land_re-purpose"[Cultivated_Meat_sustainable]) * dt
INIT "land-use"[Cultivated_Meat_sustainable] = initial_cm_land*fraction_of_sustainable_energy_for_cm_production
UNITS: hectare
DOCUMENT: Stock showing the division of land that is currently being used to produce crops needed for the meat and meat alternatives products. The data that was used to initialize this stock was regarding agricultural land in the Netherlands (van Rossum, 2021; CBS, 2020) as portrayed as reference variables in the above sector. The specific values were found through the calibration process. Only the initialization of cultivated meat land is sensitive, the other categories are not sensitive.
"land-use"[Plantbased_products](t) = "land-use"[Plantbased_products](t - dt) + ("change_in_land-use"[Plantbased_products] + "re-purposing_land_for_cm"[Plantbased_products] - land_degradation[Plantbased_products] - "land_re-purpose"[Plantbased_products]) * dt
INIT "land-use"[Plantbased_products] = 13000
UNITS: hectare
DOCUMENT: Stock showing the division of land that is currently being used to produce crops needed for the meat and meat alternatives products. The data that was used to initialize this stock was regarding agricultural land in the Netherlands (van Rossum, 2021; CBS, 2020) as portrayed as reference variables in the above sector. The specific values were found through the calibration process. Only the initialization of cultivated meat land is sensitive, the other categories are not sensitive.
"re-usable_land"(t) = "re-usable_land"(t - dt) + (land_recovery - "change_in_land-use"[Beef] - "change_in_land-use"[Cultivated_Meat_conventional] - "change_in_land-use"[Pork] - "change_in_land-use"[Poultry] - "change_in_land-use"[Cultivated_Meat_sustainable] - "change_in_land-use"[Plantbased_products]) * dt
INIT "re-usable_land" = 80000
UNITS: hectares
DOCUMENT: Stock of available land that is currently not in use. Initialized with the leftover land according to the maximum hectare available for agricultural land.
"change_in_land-use"[Meat_Products] = MIN ("re-usable_land"/"land-use_at", MAX(0, land_use_per_product-"land-use"/"land-use_at"))
UNITS: Hectares/Years
DOCUMENT: The MIN function in this formula ensures that the stock re-usable land cannot deplete by more than is left in the stock. If there is enough in the stock, the land use will change according to how much more or less land is needed to meet the production of each product.
CO2eq_inflow = MAX(0, (carbon_footprint_CM+carbon_footprints_meat_&_pb_products))
UNITS: kg CO2eq/year

DOCUMENT: The CO2 emission of the yearly meat, plant-based and cultivated meat production combined.
dispersion = CO2eq_meat_industry_NL/dispersion_time
UNITS: kg CO2eq/year
DOCUMENT: This outflow shows the dispersion of CO2 leaving the atmosphere. To get this value, the stock is divided by the dispersion time of CO2 molecules.
land_degradation[Meat_Products] = "land-use"*land_loss_rate
UNITS: Hectares/Years
DOCUMENT: The land degradation is calculated by multiplying the land-use with the fraction of land loss.
"land_re-purpose"[Beef] = IF "switch_re-purposing_land" = 1 THEN "land-use"[Beef]*"fraction_to_re-purpose" ELSE 0
UNITS: Hectares/Years
DOCUMENT: If the switch for land re-purposing is enabled, the stock of the land-used for beef products is multiplied with the fraction to re-purpose. This policy could be enabled to ensure a bigger production of cultivated meat products. Beef is currently using a significantly higher amount of land, and is also the largest emitter of CO2eq. Therefore, when the switch is on, it is chosen to re-purpose the land used to produce beef products to make room for cultivated meat products.
"land_re-purpose"[Cultivated_Meat_conventional] = 0
UNITS: Hectares/Years
DOCUMENT: If the switch for land re-purposing is enabled, the stock of the land-used for beef products is multiplied with the fraction to re-purpose. This policy could be enabled to ensure a bigger production of cultivated meat products. Beef is currently using a significantly higher amount of land, and is also the largest emitter of CO2eq. Therefore, when the switch is on, it is chosen to re-purpose the land used to produce beef products to make room for cultivated meat products.
"land_re-purpose"[Pork] = 0
UNITS: Hectares/Years
DOCUMENT: If the switch for land re-purposing is enabled, the stock of the land-used for beef products is multiplied with the fraction to re-purpose. This policy could be enabled to ensure a bigger production of cultivated meat products. Beef is currently using a significantly higher amount of land, and is also the largest emitter of CO2eq. Therefore, when the switch is on, it is chosen to re-purpose the land used to produce beef products to make room for cultivated meat products.
"land_re-purpose"[Poultry] = 0
UNITS: Hectares/Years
DOCUMENT: If the switch for land re-purposing is enabled, the stock of the land-used for beef products is multiplied with the fraction to re-purpose. This policy could be enabled to ensure a bigger production of cultivated meat products. Beef is currently using a significantly higher amount of land, and is also the largest emitter of CO2eq. Therefore, when the switch is on, it is chosen to re-purpose the land used to produce beef products to make room for cultivated meat products.
"land_re-purpose"[Cultivated_Meat_sustainable] = 0
UNITS: Hectares/Years
DOCUMENT: If the switch for land re-purposing is enabled, the stock of the land-used for beef products is multiplied with the fraction to re-purpose. This policy could be enabled to ensure a bigger production of cultivated meat products. Beef is currently using a significantly higher amount of land, and is also the largest emitter of CO2eq. Therefore, when the switch is on, it is chosen to re-purpose the land used to produce beef products to make room for cultivated meat products.

"land_re-purpose"[Plantbased_products] = 0
UNITS: Hectares/Years
DOCUMENT: If the switch for land re-purposing is enabled, the stock of the land-used for beef products is multiplied with the fraction to re-purpose. This policy could be enabled to ensure a bigger production of cultivated meat products. Beef is currently using a significantly higher amount of land, and is also the largest emitter of CO2eq. Therefore, when the switch is on, it is chosen to re-purpose the land used to produce beef products to make room for cultivated meat products.
land_recovery = degraded_land/"land-use_at"
UNITS: Hectares/Years
DOCUMENT: The stock degraded land divided by the adjustment time.
"re-purposing_land_for_cm"[Beef] = 0
UNITS: Hectares/Years
DOCUMENT: If the switch for land re-purposing is enabled, this inflow ensures that the land to re-purpose is added to the cultivated meat land-use. This policy could be enabled to ensure a bigger production of cultivated meat products. Beef is currently using a significantly higher amount of land, and is also the largest emitter of CO2eq. Therefore, when the switch is on, it is chosen to re-purpose the land used to produce beef products to make room for cultivated meat products.
"re-purposing_land_for_cm"[Cultivated_Meat_conventional] = MIN ((MAX(0, land_use_per_product[Cultivated_Meat_conventional]-"change_in_land-use"[Cultivated_Meat_conventional])), ("land_re-purpose"[Beef]*(1-fraction_of_sustainable_energy_for_cm_production)))
UNITS: Hectares/Years
DOCUMENT: If the switch for land re-purposing is enabled, this inflow ensures that the land to re-purpose is added to the cultivated meat land-use. This policy could be enabled to ensure a bigger production of cultivated meat products. Beef is currently using a significantly higher amount of land, and is also the largest emitter of CO2eq. Therefore, when the switch is on, it is chosen to re-purpose the land used to produce beef products to make room for cultivated meat products. A MIN function is used to not have too much land for CM products when it is not required.
"re-purposing_land_for_cm"[Pork] = 0
UNITS: Hectares/Years
DOCUMENT: If the switch for land re-purposing is enabled, this inflow ensures that the land to re-purpose is added to the cultivated meat land-use. This policy could be enabled to ensure a bigger production of cultivated meat products. Beef is currently using a significantly higher amount of land, and is also the largest emitter of CO2eq. Therefore, when the switch is on, it is chosen to re-purpose the land used to produce beef products to make room for cultivated meat products.
"re-purposing_land_for_cm"[Poultry] = 0
UNITS: Hectares/Years
DOCUMENT: If the switch for land re-purposing is enabled, this inflow ensures that the land to re-purpose is added to the cultivated meat land-use. This policy could be enabled to ensure a bigger production of cultivated meat products. Beef is currently using a significantly higher amount of land, and is also the largest emitter of CO2eq. Therefore, when the switch is on, it is chosen to re-purpose the land used to produce beef products to make room for cultivated meat products.
"re-purposing_land_for_cm"[Cultivated_Meat_sustainable] = MIN ((MAX(0, land_use_per_product[Cultivated_Meat_sustainable]-"change_in_land-use"[Cultivated_Meat_sustainable])), ("land_re-purpose"[Beef]*fraction_of_sustainable_energy_for_cm_production))
UNITS: Hectares/Years
DOCUMENT: If the switch for land re-purposing is enabled, this inflow ensures that the land to re-purpose is added to the cultivated meat land-use. This policy could be enabled to ensure a bigger production of cultivated meat products. Beef is currently using a significantly higher amount

of land, and is also the largest emitter of CO2eq. Therefore, when the switch is on, it is chosen to re-purpose the land used to produce beef products to make room for cultivated meat products.
"re-purposing_land_for_cm"[Plantbased_products] = 0
UNITS: Hectares/Years
DOCUMENT: If the switch for land re-purposing is enabled, this inflow ensures that the land to re-purpose is added to the cultivated meat land-use. This policy could be enabled to ensure a bigger production of cultivated meat products. Beef is currently using a significantly higher amount of land, and is also the largest emitter of CO2eq. Therefore, when the switch is on, it is chosen to re-purpose the land used to produce beef products to make room for cultivated meat products.
carbon_footprint_CM = Production.production_CM_products*carbon_footprint_per_product[Cultivated_Meat_conventional]*(1-fraction_of_sustainable_energy_for_cm_production) + fraction_of_sustainable_energy_for_cm_production* Production.production_CM_products*carbon_footprint_per_product[Cultivated_Meat_sustainable]
UNITS: kg CO2eq/year
DOCUMENT: The data used for portions of this model from Sinke & Odegaard (2021), made the distinction between two production processes of cultivated meat. A more sustainable process and a conventional production process. Therefore a fraction determines how much of the cultivated meat process is produced in the most sustainable way possible vs the conventional way. This is taken into consideration when calculating the CO2eq emissions here. The total production of cultivated meat is divided as per that fraction of sustainable production, and are each multiplied with the corresponding CO2eq produced per kg of product and added together.
carbon_footprint_per_product[Beef] = 70
UNITS: kg CO2eq/kg
DOCUMENT: This variable shows the kg of CO2eq that is produced with the production of each kg of product. Each type of meat/meat alternative product has a different carbon footprint. Based on data (Sinke & Odegaard, 2021) and calibration. Naturally, this is a sensitive variable.
carbon_footprint_per_product[Cultivated_Meat_conventional] = 11
UNITS: kg CO2eq/kg
DOCUMENT: This variable shows the kg of CO2eq that is produced with the production of each kg of product. Each type of meat/meat alternative product has a different carbon footprint. Sinke & Odegaard (2021) produce these numbers in their report. Naturally, this is a sensitive variable.
carbon_footprint_per_product[Pork] = 14
UNITS: kg CO2eq/kg
DOCUMENT: This variable shows the kg of CO2eq that is produced with the production of each kg of product. Each type of meat/meat alternative product has a different carbon footprint. Sinke & Odegaard (2021) produce these numbers in their report. Naturally, this is a sensitive variable.
carbon_footprint_per_product[Poultry] = 9
UNITS: kg CO2eq/kg
DOCUMENT: This variable shows the kg of CO2eq that is produced with the production of each kg of product. Each type of meat/meat alternative product has a different carbon footprint. Sinke & Odegaard (2021) produce these numbers in their report. Naturally, this is a sensitive variable.
carbon_footprint_per_product[Cultivated_Meat_sustainable] = 3
UNITS: kg CO2eq/kg
DOCUMENT: This variable shows the kg of CO2eq that is produced with the production of each kg of product. Each type of meat/meat alternative product has a different carbon footprint. Sinke & Odegaard (2021) produce these numbers in their report. Naturally, this is a sensitive variable.
carbon_footprint_per_product[Plantbased_products] = 1.5
UNITS: kg CO2eq/kg

DOCUMENT: This variable shows the kg of CO2eq that is produced with the production of each kg of product. Each type of meat/meat alternative product has a different carbon footprint. Sinke & Odegaard (2021) produce these numbers in their report. Naturally, this is a sensitive variable.
carbon_footprints_meat_&_pb_products = Production.meat_production_NL[Beef]*carbon_footprint_per_product[Beef] + Production.meat_production_NL[Pork]*carbon_footprint_per_product[Pork] + Production.meat_production_NL[Poultry]*carbon_footprint_per_product[Poultry] + Production."production_plant-based_products"*carbon_footprint_per_product[Plantbased_products]
UNITS: kg CO2eq/year
DOCUMENT: The production of each type of meat and meat alternative is multiplied with the corresponding CO2eq produced per kg of product and added together.
CO2_meat_industry_DATA = MAX(0, NL_CO2_emission_data*fraction_total_co2_meat_industry*Production.relative_population_NL)
UNITS: kg CO2eq
DOCUMENT: This variable shows is used for data referencing CO2eq emissions. To calculate the emissions the meat sector produces, the total emissions of the Netherlands is multiplied with the fraction of emissions that are produced by the meat industry.
dispersion_time = 3
UNITS: year
DOCUMENT: The time a CO2 molecule remains in the atmosphere on average is 3 years (KNMI, 2017).
fraction_agricultural_land_used_for_meat_production = 0.8
UNITS: dmnl
DOCUMENT: Average fraction of total agricultural land that is being used for meat production (Ritchie, 2017).
fraction_of_sustainable_energy_for_cm_production = 0.3
UNITS: dmnl
DOCUMENT: The data used for portions of this model from Sinke & Odegaard (2021), made the distinction between two production processes of cultivated meat. A more sustainable process and a conventional production process. Therefore this fraction determines how much of the cultivated meat process is produced in the most sustainable way possible vs the conventional way. Assumed value that can be adjusted for scenario analysis. Not sensitive.
"fraction_to_re-purpose" = 0.05
UNITS: dmnl/year
DOCUMENT: Fraction of land to re-purpose. Assumed variable. Not sensitive.
fraction_total_co2_meat_industry = 0.4
UNITS: dmnl
DOCUMENT: 40% of the Dutch CO2eq production can be allocated to the meat industry (Milieu Centraal, 2022). This variable is used for data referencing only.
initial_cm_land = 50
UNITS: hectare
DOCUMENT: Initialized at a low value to cover the still low production of cultivated meat in the testing phase. Assumed variable that is sensitive when land re-purposing is not enabled. Not sensitive when land re-purposing is enabled.
land_loss_rate[Beef] = MAX(0, MIN(0.01, 1-"fraction_to_re-purpose"))
UNITS: dmnl/year

DOCUMENT: Assumed to be 0.01 for most categories of land-use. Sensitive variable, especially when land re-purposing is not enabled.
For beef land, it is assumed that the fraction to re-purpose land influences the land-loss rate. When land gets re-purposed it is assumed that it stops the degradation of that portion of land. This would only have a significant effect if the fraction to re-purpose would be very high to overcome that land-loss rate.
land_loss_rate[Cultivated_Meat_conventional] = 0.01
UNITS: dmnl/year
DOCUMENT: Assumed to be 0.01 for most categories of land-use. Sensitive variable, especially when land re-purposing is not enabled.
For beef land, it is assumed that the fraction to re-purpose land influences the land-loss rate. When land gets re-purposed it is assumed that it stops the degradation of that portion of land. This would only have a significant effect if the fraction to re-purpose would be very high to overcome that land-loss rate.
land_loss_rate[Pork] = 0.01
UNITS: dmnl/year
DOCUMENT: Assumed to be 0.01 for most categories of land-use. Sensitive variable, especially when land re-purposing is not enabled.
For beef land, it is assumed that the fraction to re-purpose land influences the land-loss rate. When land gets re-purposed it is assumed that it stops the degradation of that portion of land. This would only have a significant effect if the fraction to re-purpose would be very high to overcome that land-loss rate.
land_loss_rate[Poultry] = 0.01
UNITS: dmnl/year
DOCUMENT: Assumed to be 0.01 for most categories of land-use. Sensitive variable, especially when land re-purposing is not enabled.
For beef land, it is assumed that the fraction to re-purpose land influences the land-loss rate. When land gets re-purposed it is assumed that it stops the degradation of that portion of land. This would only have a significant effect if the fraction to re-purpose would be very high to overcome that land-loss rate.
land_loss_rate[Cultivated_Meat_sustainable] = 0.01
UNITS: dmnl/year
DOCUMENT: Assumed to be 0.01 for most categories of land-use. Sensitive variable, especially when land re-purposing is not enabled.
For beef land, it is assumed that the fraction to re-purpose land influences the land-loss rate. When land gets re-purposed it is assumed that it stops the degradation of that portion of land. This would only have a significant effect if the fraction to re-purpose would be very high to overcome that land-loss rate.
land_loss_rate[Plantbased_products] = 0.01
UNITS: dmnl/year
DOCUMENT: Assumed to be 0.01 for most categories of land-use. Sensitive variable, especially when land re-purposing is not enabled.
For beef land, it is assumed that the fraction to re-purpose land influences the land-loss rate. When land gets re-purposed it is assumed that it stops the degradation of that portion of land. This would only have a significant effect if the fraction to re-purpose would be very high to overcome that land-loss rate.
land_use_per_kg_product[Beef] = 31.6
UNITS: m2a/kg
DOCUMENT: The land that is used to produce 1 kg of meat/meat alternative product (Sinke & Odegaard, 2021).
land_use_per_kg_product[Cultivated_Meat_conventional] = 1.8

UNITS: m2a/kg
DOCUMENT: The land that is used to produce 1 kg of meat/meat alternative product (Sinke & Odegaard, 2021).
land_use_per_kg_product[Pork] = 6
UNITS: m2a/kg
DOCUMENT: The land that is used to produce 1 kg of meat/meat alternative product (Sinke & Odegaard, 2021).
land_use_per_kg_product[Poultry] = 4.6
UNITS: m2a/kg
DOCUMENT: The land that is used to produce 1 kg of meat/meat alternative product (Sinke & Odegaard, 2021).
land_use_per_kg_product[Cultivated_Meat_sustainable] = 1.7
UNITS: m2a/kg
DOCUMENT: The land that is used to produce 1 kg of meat/meat alternative product (Sinke & Odegaard, 2021).
land_use_per_kg_product[Plantbased_products] = 1.8
UNITS: m2a/kg
DOCUMENT: The land that is used to produce 1 kg of meat/meat alternative product (Sinke & Odegaard, 2021).
land_use_per_product[Beef] = ((Production.meat_production_NL[Beef]*land_use_per_kg_product[Beef]))/m2a_per_ha
UNITS: Hectares/Years
DOCUMENT: To calculate the land use per product, the production of each meat/meat alternative product is multiplied with the amount of land one kg of product would require. This was divided by the amount of m2a in a hectare for unit consistency.
In addition to that, for the cultivated meat products, a distinction was made between sustainable and conventional cultivated meat production. A fraction of sustainable cultivated meat production was used to take that in consideration.
land_use_per_product[Cultivated_Meat_conventional] = (((Production.production_CM_products*land_use_per_kg_product[Cultivated_Meat_conventional]))*(1-fraction_of_sustainable_energy_for_cm_production))/m2a_per_ha
UNITS: Hectares/Years
DOCUMENT: To calculate the land use per product, the production of each meat/meat alternative product is multiplied with the amount of land one kg of product would require. This was divided by the amount of m2a in a hectare for unit consistency.
In addition to that, for the cultivated meat products, a distinction was made between sustainable and conventional cultivated meat production. A fraction of sustainable cultivated meat production was used to take that in consideration.
land_use_per_product[Pork] = ((Production.meat_production_NL[Pork]*land_use_per_kg_product[Pork]))/m2a_per_ha
UNITS: Hectares/Years
DOCUMENT: To calculate the land use per product, the production of each meat/meat alternative product is multiplied with the amount of land one kg of product would require. This was divided by the amount of m2a in a hectare for unit consistency.
In addition to that, for the cultivated meat products, a distinction was made between sustainable and conventional cultivated meat production. A fraction of sustainable cultivated meat production was used to take that in consideration.
land_use_per_product[Poultry] = ((Production.meat_production_NL[Poultry]*land_use_per_kg_product[Poultry]))/m2a_per_ha
UNITS: Hectares/Years

DOCUMENT: To calculate the land use per product, the production of each meat/meat alternative product is multiplied with the amount of land one kg of product would require. This was divided by the amount of m2a in a hectare for unit consistency.
In addition to that, for the cultivated meat products, a distinction was made between sustainable and conventional cultivated meat production. A fraction of sustainable cultivated meat production was used to take that in consideration.
land_use_per_product[Cultivated_Meat_sustainable] = (((Production.production_CM_products*land_use_per_kg_product[Cultivated_Meat_conventional]))*(fraction_of_sustainable_energy_for_cm_production))/m2a_per_ha
UNITS: Hectares/Years
DOCUMENT: To calculate the land use per product, the production of each meat/meat alternative product is multiplied with the amount of land one kg of product would require. This was divided by the amount of m2a in a hectare for unit consistency.
In addition to that, for the cultivated meat products, a distinction was made between sustainable and conventional cultivated meat production. A fraction of sustainable cultivated meat production was used to take that in consideration.
land_use_per_product[Plantbased_products] = ((Production."production_plant-based_products"*land_use_per_kg_product[Plantbased_products]))/m2a_per_ha
UNITS: Hectares/Years
DOCUMENT: To calculate the land use per product, the production of each meat/meat alternative product is multiplied with the amount of land one kg of product would require. This was divided by the amount of m2a in a hectare for unit consistency.
In addition to that, for the cultivated meat products, a distinction was made between sustainable and conventional cultivated meat production. A fraction of sustainable cultivated meat production was used to take that in consideration.
"land-use_at" = 1
UNITS: year
DOCUMENT: Time for land to adjust. Assumed variable. When land re-purposing is enabled, this variable is not sensitive. When land re-purposing is not enabled, it is a sensitive variable.
m2a_per_ha = 10000
UNITS: m2a/hectare
DOCUMENT: Conversion variable showing how many m2a there are per hectare.
max_ha_for_agriculture_NL_data = 2236317
UNITS: hectare
DOCUMENT: Max land available for agriculture in the Netherlands. Based on data from the central bureau of statistics of the Netherlands (CBS, 2020).
max_ha_for_meat_production_NL = fraction_agricultural_land_used_for_meat_production*max_ha_for_agriculture_NL_data
UNITS: hectare
DOCUMENT: Max land available for meat production in the Netherlands. This is also just a reference variable that was used to initialize the stocks. The total of agricultural land is multiplied with the fraction of agricultural land that is used for meat production.
NL_CO2_emission_data = GRAPH(TIME)
Points(8): (1990.00, 220500000000), (1995.00, 230300000000), (2000.00, 218100000000), (2005.00, 2.13e+11), ...
UNITS: kg CO2eq
DOCUMENT: The total CO2eq emissions from the Netherlands (RIVM, 2021). This variable is for data referencing only.
"switch_re-purposing_land" = 1
UNITS: dmnl

DOCUMENT: If this switch is on (1) it will enable land re-allocation to go to cultivated meat products instead of land that is used for the process of producing beef products (including feed crops). This policy could be enabled to ensure a bigger production of cultivated meat products. Beef is currently using a significantly higher amount of land, and is also the largest emitter of CO2eq. Therefore, when the switch is on, it is chosen to re-purpose the land used to produce beef products to make room for cultivated meat products.
total_land_use = SUM("land-use"[*]) + "re-usable_land" + degraded_land
UNITS: hectare
DOCUMENT: The total agricultural land acquired by adding all the stocks together. Just a reference variable to ensure the maximum of agricultural land is not exceeded.
Production:
dairy_cows(t) = dairy_cows(t - dt) + (adjustment_of_cows - normal_cow_death_after_lifespan) * dt
INIT dairy_cows = initial_dairy_cows_NL
UNITS: animal
DOCUMENT: The amount of dairy cows in the Netherlands. Initialized to data from 2020 (Wageningen University & Research, 2022d).
feed_farmers[Animal_Feed](t) = feed_farmers[Animal_Feed](t - dt) + (change_in_feed_farmers[Animal_Feed]) * dt
INIT feed_farmers[Animal_Feed] = 18669
UNITS: farm
DOCUMENT: The amount of feed farmers in the Netherlands. Initialized according to data (Wageningen University & Research, 2022c). Not sensitive.
feed_farmers[Crop_PlantBased](t) = feed_farmers[Crop_PlantBased](t - dt) + (change_in_feed_farmers[Crop_PlantBased]) * dt
INIT feed_farmers[Crop_PlantBased] = 100
UNITS: farm
DOCUMENT: The amount of feed farmers in the Netherlands. Initialized according to data (Wageningen University & Research, 2022c). Not sensitive.
feed_farmers[Crop_CM](t) = feed_farmers[Crop_CM](t - dt) + (change_in_feed_farmers[Crop_CM]) * dt
INIT feed_farmers[Crop_CM] = 10
UNITS: farm
DOCUMENT: The amount of feed farmers in the Netherlands. Initialized according to data (Wageningen University & Research, 2022c). Not sensitive.
livestock_farms[Beef](t) = livestock_farms[Beef](t - dt) + (change_in_livestock_farmers[Beef]) * dt
INIT livestock_farms[Beef] = 17000
UNITS: farm
DOCUMENT: Stock representing the livestock farms that are in the Netherlands. Initialized with data from 2020 (Wageningen University & Research, 2022d).
livestock_farms[Pork](t) = livestock_farms[Pork](t - dt) + (change_in_livestock_farmers[Pork]) * dt
INIT livestock_farms[Pork] = 11000
UNITS: farm
DOCUMENT: Stock representing the livestock farms that are in the Netherlands. Initialized with data from 2020 (Wageningen University & Research, 2022d).

livestock_farms[Poultry](t) = livestock_farms[Poultry](t - dt) + (change_in_livestock_farmers[Poultry]) * dt
INIT livestock_farms[Poultry] = 4400
UNITS: farm
DOCUMENT: Stock representing the livestock farms that are in the Netherlands. Initialized with data from 2020 (Wageningen University & Research, 2022d).
adjustment_of_cows = ((cows_needed_dairy_consumption_including_export- dairy_cows/at_dairy_cows))+normal_cow_death_after_lifespan
UNITS: animal/Years
DOCUMENT: The inflow to dairy cows is based on the variable calculating the cows needed to cover dairy consumption. The current amount of cows in the stock is subtracted from the amount of needed cows so that the inflow is only the change of cows that are needed. The death rate is also added to this inflow to compensate for the cows that die.
change_in_feed_farmers[Animal_Feed] = (feed_farmers_needed[Animal_Feed]- feed_farmers[Animal_Feed])/adjustment_time_farms
UNITS: farm/year
DOCUMENT: This inflow shows the change in feed farmers. Calculated by subtracting the stock of feed farmers from the needed feed farmers for each meat/meat alternative category and dividing this by the time farmers need to adjust.
change_in_feed_farmers[Crop_PlantBased] = (feed_farmers_needed[Crop_PlantBased]- feed_farmers[Crop_PlantBased])/adjustment_time_farms
UNITS: farm/year
DOCUMENT: This inflow shows the change in feed farmers. Calculated by subtracting the stock of feed farmers from the needed feed farmers for each meat/meat alternative category and dividing this by the time farmers need to adjust.
change_in_feed_farmers[Crop_CM] = (feed_farmers_needed[Crop_CM]- feed_farmers[Crop_CM])/adjustment_time_farms
UNITS: farm/year
DOCUMENT: This inflow shows the change in feed farmers. Calculated by subtracting the stock of feed farmers from the needed feed farmers for each meat/meat alternative category and dividing this by the time farmers need to adjust.
change_in_livestock_farmers[Beef] = MAX((((livestock_farmers_needed- livestock_farms)/adjustment_time_livestock_farmers)*gap_animal_feed_farmers), (((dairy_farmers- livestock_farms)/adjustment_time_livestock_farmers)*gap_animal_feed_farmers))
UNITS: farm/year
DOCUMENT: This inflow shows the change in livestock farmers. To get this value, the stock livestock farms are subtracted from the livestock farms that are needed and this is divided by the time farmers would need to adjust this. This is multiplied with the gap of animal feed farmers, as animal feed is a limiting factor for livestock farmers if there isn't enough feed to give the animals. This gap value, will not go above 1, so it can only limit the farmers. For the beef farmers that carry cows, there is another addition to the equation. A MAX function was added to include dairy cows. Over time, the demand for beef could decline, however, if there is still a high demand for dairy, the amount of cows in the Netherlands will not decline. This is what the MAX function takes into account.

change_in_livestock_farmers[Pork] = ((livestock_farmers_needed-livestock_farms)/adjustment_time_livestock_farmers)*gap_animal_feed_farmers
UNITS: farm/year
DOCUMENT: This inflow shows the change in livestock farmers. To get this value, the stock livestock farms are subtracted from the livestock farms that are needed and this is divided by the time farmers would need to adjust this. This is multiplied with the gap of animal feed farmers, as animal feed is a limiting factor for livestock farmers if there isn't enough feed to give the animals. This gap value, will not go above 1, so it can only limit the farmers. For the beef farmers that carry cows, there is another addition to the equation. A MAX function was added to include dairy cows. Over time, the demand for beef could decline, however, if there is still a high demand for dairy, the amount of cows in the Netherlands will not decline. This is what the MAX function takes into account.
change_in_livestock_farmers[Poultry] = ((livestock_farmers_needed-livestock_farms)/adjustment_time_livestock_farmers)*gap_animal_feed_farmers
UNITS: farm/year
DOCUMENT: This inflow shows the change in livestock farmers. To get this value, the stock livestock farms are subtracted from the livestock farms that are needed and this is divided by the time farmers would need to adjust this. This is multiplied with the gap of animal feed farmers, as animal feed is a limiting factor for livestock farmers if there isn't enough feed to give the animals. This gap value, will not go above 1, so it can only limit the farmers. For the beef farmers that carry cows, there is another addition to the equation. A MAX function was added to include dairy cows. Over time, the demand for beef could decline, however, if there is still a high demand for dairy, the amount of cows in the Netherlands will not decline. This is what the MAX function takes into account.
normal_cow_death_after_lifespan = dairy_cows/lifespan_years
UNITS: animal/Years
DOCUMENT: The death rate of cows is found by dividing the amount of cows with its lifespan in years.
actual_meat_production[Farms] = (livestock_farms*average_animals_per_farm_data_NL*(fraction_carcass_weight_per_animal*average_weight_per_animal))
UNITS: kg/year
DOCUMENT: To calculate the actual meat production produced in the Netherlands, the livestock farmers is multiplied with the average animals per farm for each type of animal.To calculate how much meat production is produced from these animals, this number is multiplied with the weight per animal and the fraction of carcass weight.
adjustment_time_farms = 1
UNITS: year
DOCUMENT: Time needed to adjust the amount of feed farmers that are necessary to cover the feed requirements needed for meat production and meat alternatives (export included). This is based on assumption and calibration. Sensitive variable.
adjustment_time_livestock_farmers = 1
UNITS: year
DOCUMENT: Time needed to adjust the amount of livestock farmers that are necessary to cover meat consumption and export. This is based on assumption and calibration. Sensitive variable.
animals_needed_to_cover_meat_consumption_NL[Farms] = meat_consumption_NL/(average_weight_per_animal*fraction_carcass_weight_per_animal)
UNITS: animal/year
DOCUMENT: To calculate the animals that are needed to cover the Dutch meat consumption, the meat consumption is divided by the average weight per animal multiplied with the fraction of carcass weight per animal for each type of animal.

at_dairy_cows = 1
UNITS: year
DOCUMENT: Time needed to adjust the amount of cows that are necessary to cover dairy consumption. Not a sensitive value.
average_animals_per_farm_data_NL[Beef] = GRAPH(TIME)
Points(21): (2000.00, 51.00), (2001.00, 55.00), (2002.00, 56.00), (2003.00, 59.00), ...
UNITS: animal/farm/year
DOCUMENT: The average number of animals per farm. Sensitive variable. Based on data (Wageningen University & Research, 2022d)
average_animals_per_farm_data_NL[Pork] = GRAPH(TIME)
Points(21): (2000.00, 504), (2001.00, 541), (2002.00, 529), (2003.00, 562), ...
UNITS: animal/farm/year
DOCUMENT: The average number of animals per farm. Sensitive variable. Based on data (Wageningen University & Research, 2022d)
average_animals_per_farm_data_NL[Poultry] = GRAPH(TIME)
Points(21): (2000.00, 62250), (2001.00, 65078), (2002.00, 66747), (2003.00, 74006), ...
UNITS: animal/farm/year
DOCUMENT: The average number of animals per farm. Sensitive variable. Based on data (Wageningen University & Research, 2022d)
average_feed_production_per_farmer = average_hectare_NL_farms*average_production_per_ha
UNITS: kg/farm/year
DOCUMENT: To calculate the average feed production per famer, the average production per hectare is multiplied with the average hectare per farm.
average_fraction_consumer_food_waste = 1.42
UNITS: dmnl
DOCUMENT: Percentage of food thrown away per consumer (NL Times, 2019).
average_hectare_NL_farms = 60
UNITS: hectare/farm
DOCUMENT: The average amount of hectare of Dutch farms as documented in 2022 (Wageningen University & Research, 2022b). This variable is not sensitive.
"average_meat_consumption_pp_NL_2010-2020"[Beef] = GRAPH(TIME)
Points(16): (2005.00, 15.900), (2006.00, 16.100), (2007.00, 16.100), (2008.00, 16.100), ...
UNITS: kg/person/year
DOCUMENT: Average meat consumption per person per year based on data used from Wageningen Economic Research (Dagevos et al., 2021).
"average_meat_consumption_pp_NL_2010-2020"[Pork] = GRAPH(TIME)
Points(16): (2005.00, 37.20), (2006.00, 37.40), (2007.00, 37.60), (2008.00, 37.80), ...
UNITS: kg/person/year
DOCUMENT: Average meat consumption per person per year based on data used from Wageningen Economic Research (Dagevos et al., 2021).
"average_meat_consumption_pp_NL_2010-2020"[Poultry] = GRAPH(TIME)
Points(16): (2005.00, 20.700), (2006.00, 20.800), (2007.00, 21.500), (2008.00, 21.600), ...
UNITS: kg/person/year
DOCUMENT: Average meat consumption per person per year based on data used from Wageningen Economic Research (Dagevos et al., 2021).
average_plant_based_products_consumption_pp_NL = GRAPH(TIME)
Points(16): (2005.00, 1.500), (2006.00, 1.500), (2007.00, 1.600), (2008.00, 1.700), ...
UNITS: kg/person/year
DOCUMENT: The average consumption of plant based meat products per person per year based on data from 2020 (Bakker, 2021).

average_production_per_ha = 8600
UNITS: kg/hectare/year
DOCUMENT: Average amount of crop production of various types of crops, such as wheat, barley, oats and corn (CBS, 2022). Not a sensitive variable.
average_weight_per_animal[Beef] = 650
UNITS: kg/animal
DOCUMENT: Based on data from various sources (Carp-van Dijke et al., 2016; Driessen & van Thielen, 2012; Schotman, 2017).
average_weight_per_animal[Pork] = 115
UNITS: kg/animal
DOCUMENT: Based on data from various sources (Schotman, 2017; Driessen et al. 2012; Carp-van Dijke et al., 2016).
average_weight_per_animal[Poultry] = 2.4
UNITS: kg/animal
DOCUMENT: Based on data from various sources (Schotman, 2017; Driessen et al. 2012; Carp-van Dijke et al., 2016).
calves_for_meat_consumption = calves_per_year*fraction_calves_sold_meat_consumption
UNITS: animal/year
DOCUMENT: To calculate the amount of calves that are being sold for meat consumption, the total amount of calves is multiplied with the fraction of calves that is being sold for meat consumption.
calves_per_cow = 3.7
UNITS: animal/animal
DOCUMENT: The average amount of calves being born per cow is 3.7 in its entire lifetime (CRV, 2022).
calves_per_cow_per_year = calves_per_cow/lifespan_years
UNITS: animal/animal/year
DOCUMENT: The amount of calves born per cow (in its lifetime) is divided by the cow's lifespan in years to get an average value of how many calves are born per cow per year.
calves_per_year = dairy_cows*calves_per_cow_per_year
UNITS: animal/year
DOCUMENT: To get the calves born per year, the amount of calves born per year per cow is multiplied with the amount of dairy cows.
cattle_restriction_policy = GRAPH(TIME)
Points(31): (2020.00, 1.000), (2021.00, 1.000), (2022.00, 0.990), (2023.00, 0.971), ...
UNITS: dmnl
DOCUMENT: The Dutch government announced a €25 billion plan to cut the livestock with one-third in the upcoming years (Levitt, 2021). The shape of this table function is an assumption, but as the government announced such significant cuts, a further extension of that trend is assumed to continue until 2050.
cows_needed_dairy_consumption_including_export = MAX(0, (dairy_cows_NL_data*(1-market_share_milk_alternatives_projections)))
UNITS: animal/year
DOCUMENT: To get the total amount of cows needed to cover the dairy consumption, the growing market share of milk alternatives is taken into consideration. The amount of dairy cows in the Netherlands is multiplied with the fraction of the market that is dairy milk (calculated by

subtracting the market share of milk alternatives from the total market share value of 1). It is assumed here that the entire market is either a milk alternative or dairy milk.
dairy_cows_NL_data = 1.6e6
UNITS: animal/year
DOCUMENT: The total amount of dairy cows in the Netherlands in 2020 (Wageningen University & Research, 2022d).
dairy_farmers = MAX(0, cows_needed_dairy_consumption_including_export/average_animals_per_farm_data_NL[Beef])
UNITS: farm
DOCUMENT: To get the amount of dairy farmers, the amount of dairy cows is divided by the average amount of cows each per livestock farmer (as measured in 2021).
days_per_year = 365.25
UNITS: days/year
DOCUMENT: Total days in the year.
export_scenario = 0.6
UNITS: dmnl
DOCUMENT: This variable represent the percentage of total meat production from the Netherlands that is exported. According to the Dutch Statistics Bureau (CBS, 2021a), of the total Dutch earnings of meat sales, 60% comes from exported meat products and 40% is generated through domestic sales. Therefore in the base scenario, this value is set at 0.6.
export_switch = 1
UNITS: dmnl
DOCUMENT: A switch variable for different export scenarios. Export could be turned off if this variable is set at 0, if set at 1, it will only consider the set export scenario, if set at 2, the change in relative calves will also be considered.
According to research (Wageningen University & Research, 2022a), 92% of veal meat (from calves) is being exported. Under the initial circumstances, this will already be incorporated in the export fraction. However, it is assumed here that if there is a difference in relative veal meat, it would most notably influence export. Therefore it is incorporated in this part of the model.
feed_farmers_needed[Animal_Feed] = MAX(0, MIN ("max_farmers_(land_restriction)"[Animal_Feed], (predicted_feed_required[Animal_Feed]/average_feed_production_per_farmer)))
UNITS: farm
DOCUMENT: This variable shows the feed farmers that are needed to cover the feed for all protein categories. The MIN function is an important element in this equation because it incorporates the land restriction that could limit the meat/meat alternatives production. So one element of the MIN equation shows the max farmers that are possible with the land that is available, and the other shows the feed farmers that are actually required to cover consumption and export (this number of farmers is found by dividing the kg of feed required with the average kg of feed production per farmer).
feed_farmers_needed[Crop_PlantBased] = MAX(0, MIN ("max_farmers_(land_restriction)"[Crop_PlantBased], (predicted_feed_required[Crop_PlantBased]/average_feed_production_per_farmer)))
UNITS: farm
DOCUMENT: This variable shows the feed farmers that are needed to cover the feed for all protein categories. The MIN function is an important element in this equation because it incorporates the land restriction that could limit the meat/meat alternatives production. So one element of the MIN equation shows the max farmers that are possible with the land that is available, and the other shows the feed farmers that are actually required to cover consumption

and export (this number of farmers is found by dividing the kg of feed required with the average kg of feed production per farmer).
feed_farmers_needed[Crop_CM] = MAX(0, MIN ("max_farmers_(land_restriction)"[Crop_CM], predicted_feed_required[Crop_CM]/average_feed_production_per_farmer))
UNITS: farm
DOCUMENT: This variable shows the feed farmers that are needed to cover the feed for all protein categories. The MIN function is an important element in this equation because it incorporates the land restriction that could limit the meat/meat alternatives production. So one element of the MIN equation shows the max farmers that are possible with the land that is available, and the other shows the feed farmers that are actually required to cover consumption and export (this number of farmers is found by dividing the kg of feed required with the average kg of feed production per farmer).
Feed_input_per_product[Beef] = 5.7
UNITS: kg/kg
DOCUMENT: This variable represents how much kg of crop (feed) that is necessary to produce 1 kg of meat/meat alternative product. Data based on research done by Sinke & Odegaard (2021).
Note regarding the feed for cultivated meat products. In reality, to produce cultivated meat products, more elements would be needed, such as the crops (biomass) would need to be converted to glucose so it can be processed (Sinke & Odegaard, 2021) and - depending on how the research progresses - animal cells would be needed too. However, in this model it is assumed that as long as the production capacity is not exceeded, all that is needed are feed crops to provide nutrients as a growth medium for cultivated meat.
Feed_input_per_product[Cultivated_Meat_conventional] = 0.8
UNITS: kg/kg
DOCUMENT: This variable represents how much kg of crop (feed) that is necessary to produce 1 kg of meat/meat alternative product. Data based on research done by Sinke & Odegaard (2021).
Note regarding the feed for cultivated meat products. In reality, to produce cultivated meat products, more elements would be needed, such as the crops (biomass) would need to be converted to glucose so it can be processed (Sinke & Odegaard, 2021) and - depending on how the research progresses - animal cells would be needed too. However, in this model it is assumed that as long as the production capacity is not exceeded, all that is needed are feed crops to provide nutrients as a growth medium for cultivated meat.
Feed_input_per_product[Pork] = 4.6
UNITS: kg/kg
DOCUMENT: This variable represents how much kg of crop (feed) that is necessary to produce 1 kg of meat/meat alternative product. Data based on research done by Sinke & Odegaard (2021).
Note regarding the feed for cultivated meat products. In reality, to produce cultivated meat products, more elements would be needed, such as the crops (biomass) would need to be converted to glucose so it can be processed (Sinke & Odegaard, 2021) and - depending on how the research progresses - animal cells would be needed too. However, in this model it is assumed that as long as the production capacity is not exceeded, all that is needed are feed crops to provide nutrients as a growth medium for cultivated meat.
Feed_input_per_product[Poultry] = 2.8
UNITS: kg/kg

DOCUMENT: This variable represents how much kg of crop (feed) that is necessary to produce 1 kg of meat/meat alternative product. Data based on research done by Sinke & Odegaard (2021).
Note regarding the feed for cultivated meat products. In reality, to produce cultivated meat products, more elements would be needed, such as the crops (biomass) would need to be converted to glucose so it can be processed (Sinke & Odegaard, 2021) and - depending on how the research progresses - animal cells would be needed too. However, in this model it is assumed that as long as the production capacity is not exceeded, all that is needed are feed crops to provide nutrients as a growth medium for cultivated meat.
Feed_input_per_product[Cultivated_Meat_sustainable] = 0.8
UNITS: kg/kg
DOCUMENT: This variable represents how much kg of crop (feed) that is necessary to produce 1 kg of meat/meat alternative product. Data based on research done by Sinke & Odegaard (2021).
Note regarding the feed for cultivated meat products. In reality, to produce cultivated meat products, more elements would be needed, such as the crops (biomass) would need to be converted to glucose so it can be processed (Sinke & Odegaard, 2021) and - depending on how the research progresses - animal cells would be needed too. However, in this model it is assumed that as long as the production capacity is not exceeded, all that is needed are feed crops to provide nutrients as a growth medium for cultivated meat.
Feed_input_per_product[Plantbased_products] = 0.4
UNITS: kg/kg
DOCUMENT: This variable represents how much kg of crop (feed) that is necessary to produce 1 kg of meat/meat alternative product. Data based on research done by Sinke & Odegaard (2021).
Note regarding the feed for cultivated meat products. In reality, to produce cultivated meat products, more elements would be needed, such as the crops (biomass) would need to be converted to glucose so it can be processed (Sinke & Odegaard, 2021) and - depending on how the research progresses - animal cells would be needed too. However, in this model it is assumed that as long as the production capacity is not exceeded, all that is needed are feed crops to provide nutrients as a growth medium for cultivated meat.
fraction_calves_sold_meat_consumption = 0.7
UNITS: dmnl
DOCUMENT: Fraction of calves that are being sold for meat consumption (Bregman, 2022).
fraction_carcass_weight_per_animal[Beef] = 0.60
UNITS: dmnl
DOCUMENT: As the data to determine the meat consumption was based on carcass weight, this fraction of carcass weight is needed to calculate how many animals would be needed to cover that consumption. Carcass weight is the weight of the slaughtered animal after the inedible portions of the animal have been removed. Based on data (KU Leuven, 2000).
fraction_carcass_weight_per_animal[Pork] = 0.775
UNITS: dmnl
DOCUMENT: As the data to determine the meat consumption was based on carcass weight, this fraction of carcass weight is needed to calculate how many animals would be needed to cover that consumption. Carcass weight is the weight of the slaughtered animal after the inedible portions of the animal have been removed. Based on data from KU Leuven (2000).

fraction_carcass_weight_per_animal[Poultry] = 0.75
UNITS: dmnl
DOCUMENT: As the data to determine the meat consumption was based on carcass weight, this fraction of carcass weight is needed to calculate how many animals would be needed to cover that consumption. Carcass weight is the weight of the slaughtered animal after the inedible portions of the animal have been removed. Based on data from KU Leuven (2000).
fraction_export = IF export_switch = 0 THEN 0 ELSE IF export_switch = 1 THEN export_scenario ELSE export_scenario*relative_calves_for_consumption
UNITS: dmnl
DOCUMENT: A switch variable determines the value of this export fraction. Export could be turned off if the switch is set at 0, if set at 1, it will only consider the set export scenario value, if set at 2, the change in relative calves will also be considered.
According to Wageningen University & Research (2022a) 92% of veal meat (from calves) is being exported. Under the initial circumstances, this will already be incorporated in the export fraction. However, it is assumed here that if there is a difference in relative veal meat, it would most notably influence export. Therefore it is incorporated in this part of the model.
fraction_feed_farmers = SUM(feed_farmers)/total_farmers
UNITS: dmnl
DOCUMENT: To determine the fraction of farmers that are feed farmers, the amount of feed farmers is divided by the total farmers. Feed farmers produce the crops that are necessary to produce the meat or alternative meat products.
fraction_livestock_farmers = SUM(livestock_farms)/total_farmers
UNITS: dmnl
DOCUMENT: To determine the fraction of farmers that are livestock farmers, the amount of livestock farmers is divided by the total farmers.
fraction_national_use = 1-fraction_export
UNITS: dmnl
DOCUMENT: The fraction of meat products that are sold nationally is calculated by subtracting the fraction of export from the total production value of 1.
gap_animal_feed_farmers = MIN((feed_farmers[Animal_Feed]/feed_farmers_needed[Animal_Feed]), 1)
UNITS: dmnl
DOCUMENT: This variable indicates if there is a gap between the needed animal feed farmers and the actual feed farmers. A MIN function is used so that this gap will not go above 1, which is when the animal feed requirement is met. When this variable does go below 1, it means that the stock of feed farmers is lower than the amount of feed farmers that are needed to supply the animal feed that is required. This will have a limiting effect on the livestock farmers.
initial_dairy_cows_NL = 1.6e06
UNITS: animal
DOCUMENT: The total amount of dairy cows in the Netherlands in 2020 (Wageningen University & Research, 2022d)
land_cm = Environment."land-use"[Cultivated_Meat_conventional] + Environment."land-use"[Cultivated_Meat_sustainable]
UNITS: hectare
DOCUMENT: All land that is used to grow crops for cultivated meat production summed up.
land_meat = Environment."land-use"[Beef] + Environment."land-use"[Pork] + Environment."land-use"[Poultry]
UNITS: hectare

DOCUMENT: All land that is used for meat production summed up. This also includes the land that is used to grow crops used for animal feed.
land_pb = Environment."land-use"[Plantbased_products]
UNITS: hectare
DOCUMENT: All land that is used to grow crops for plant based products summed up.
lifespan_years = lifespans_in_days/days_per_year
UNITS: year
DOCUMENT: To calculate the lifespan of a cow in years, the lifespan that was documented in days is divided by the amount of days per year.
lifespans_in_days = 2180
UNITS: days
DOCUMENT: The average lifespan in days per cow as documented in 2021 (CRV, 2022).
livestock_farmers_needed[Farms] = IF switch_cattle_policy = 1 THEN MAX(0, (predicted_animals_needed_for_meat_consumption/average_animals_per_farm_data_NL*cattle_restriction_policy)) ELSE MAX(0, (predicted_animals_needed_for_meat_consumption/average_animals_per_farm_data_NL))
UNITS: farm
DOCUMENT: The basic equation to get the number of livestock farmers that are needed, the predicted needed animals are divided by the average animals per farm. In addition to that, a cattle restriction policy option has been included in this equation. The Dutch government has announced they want to reduce cattle for all animal types by 30% in the upcoming years (Levitt, 2021). If this policy switch is turned on, the effect of that policy is multiplied that lowers the amount of farmers.
market_share_milk_alternatives_projections = GRAPH(TIME)
Points(31): (2020.00, 0.015), (2021.00, 0.016676724156), (2022.00, 0.0184102810677), (2023.00, 0.0202025970876), ...
UNITS: dmnl
DOCUMENT: Based on market projections of milk alternatives from both the NOS (2020)and Fortune (2021).
"max_farmers_(land_restriction)"[Animal_Feed] = ((Environment."land-use"[Beef]+Environment."land-use"[Pork]+Environment."land-use"[Poultry])/average_hectare_NL_farms)
UNITS: farm
DOCUMENT: To calculate the max amount of farmers possible for each product category (taking land restrictions in consideration), the max amount of land per category is divided by the average hectare of land per farm.
"max_farmers_(land_restriction)"[Crop_PlantBased] = Environment."land-use"[Plantbased_products]/average_hectare_NL_farms
UNITS: farm
DOCUMENT: To calculate the max amount of farmers possible for each product category (taking land restrictions in consideration), the max amount of land per category is divided by the average hectare of land per farm.
"max_farmers_(land_restriction)"[Crop_CM] = ((Environment."land-use"[Cultivated_Meat_conventional]+Environment."land-use"[Cultivated_Meat_sustainable])/average_hectare_NL_farms)
UNITS: farm
DOCUMENT: To calculate the max amount of farmers possible for each product category (taking land restrictions in consideration), the max amount of land per category is divided by the average hectare of land per farm.

meat_consumption_NL[Farms] = .market_share[Meat]*"average_meat_consumption_pp_NL_2010-2020"*population_predictions_NL_data

UNITS: kg/year

DOCUMENT: Meat consumption per year in the Netherlands. The average meat consumption per capita from 2020 is multiplied with the population. In addition to that, the market share for both cultivated and plant-based meat products are taken into consideration. If they increase, the meat consumption would decrease. Therefore the total meat consumption is multiplied with its market share.

meat_production_NL[Farms] = MAX(0, actual_meat_production)

UNITS: kg/year

DOCUMENT: The actual meat production with a MAX function to ensure it cannot go negative.

plantbased_consumption_NL = population_predictions_NL_data*average_plant_based_products_consumption_pp_NL

UNITS: kg/year

DOCUMENT: To determine the total consumption of plant-based products in the Netherlands per year, the plant-based consumption per capita is multiplied with the total population projections of the Netherlands

policy_status_cattle_restriction= IF .policy_status_cm = 1 AND switch_cattle_policy = 1 THEN 1 ELSE 0

UNITS: dmnl

DOCUMENT: It is assumed that cattle restrictions can only be turned on when the cultivated meat policy status is on. Otherwise the model would not provide reliable insights. If the cattle restrictions would be activated, there will be a lot less traditional meat products produced. In the scenario where cultivated meat is introduced to the market, to compensate for that lack of traditional meat products, more cultivated meat products would be produced. In the scenario where cultivated meat is not introduced to the market, the lack of products would have to be substituted by either plant-based products or imported products. The current model structure is not sufficient enough to incorporate that scenario and would therefore provide a falsely optimistic emission output.

population_predictions_NL_data = GRAPH(TIME)

Points(31): (2020.00, 17408000), (2021.00, 17475000), (2022.00, 17594000), (2023.00, 17736000), ...

UNITS: person

DOCUMENT: These projections of the population are based on the data from the central bureau of statistics of the Netherlands (CBS, 2021b).

predicted_animals_needed_for_meat_consumption[Farms] = IF .policy_status_cm = 1 THEN (animals_needed_to_cover_meat_consumption_NL + (animals_needed_to_cover_meat_consumption_NL*(fraction_export/fraction_national_use))) ELSE IF production_gap > 1 THEN (animals_needed_to_cover_meat_consumption_NL + (animals_needed_to_cover_meat_consumption_NL*(fraction_export/fraction_national_use))) ELSE (animals_needed_to_cover_meat_consumption_NL + (animals_needed_to_cover_meat_consumption_NL*(fraction_export/fraction_national_use))) + ((1-production_gap)*(animals_needed_to_cover_meat_consumption_NL + (animals_needed_to_cover_meat_consumption_NL*(fraction_export/fraction_national_use))))

UNITS: animal/year

DOCUMENT: The basis of this formulation are the animals that are needed to cover meat consumption from the Netherlands that are added to the animals that are needed to also cover export. This is done by adding a multiplication of the animals needed for Dutch consumption with the fraction of export divided by the fraction of national use. This division would produce the value

that is needed to include export. For example, if that national demand is only 40% of the total production, a multiplication of 1.5 would be needed to cover that other 60% of export (0.6/0.4=1.5).
In addition to that, there is an IF THEN ELSE function added. When the policy of introducing cultivated meat products is turned off, and there is a gap between the production requirement and actual production, this gap will be need to be filled and extra animals would be needed. When cultivated meat is introduced in the market, more cultivated meat products would be produced to cover the gap, but when they are not included, it will be covered with traditional meat products. This is done by the IF THEN ELSE function.

predicted_feed_required[Animal_Feed] = meat_consumption_NL[Beef]*Feed_input_per_product[Beef] + meat_consumption_NL[Pork]*Feed_input_per_product[Pork] + meat_consumption_NL[Poultry]*Feed_input_per_product[Poultry] + (fraction_export/fraction_national_use)*(meat_consumption_NL[Beef]*Feed_input_per_product[Beef] + meat_consumption_NL[Pork]*Feed_input_per_product[Pork] + meat_consumption_NL[Poultry]*Feed_input_per_product[Poultry])

UNITS: kg/year

DOCUMENT: Variable predicting how much crop feed is necessary to cover the protein need.

The basic equation is multiplying the consumption from each product category with the feed that is required per product. What is added to this is the feed that is required to cover export as well. Which is the same formula, but multiplied with the export fraction divided with the national fraction.
In addition to this, for cultivated meat there is also another element added. If the production gap - the gap between the protein requirement and the actual protein production - is below 1 (meaning there is more requirement than production) this gap will be compensated with cultivated meat products and the feed needed to cover this extra production is added to the cultivated meat formula.

predicted_feed_required[Crop_PlantBased] = (plantbased_consumption_NL*Feed_input_per_product[Plantbased_products]) + ((fraction_export/fraction_national_use)*(plantbased_consumption_NL*Feed_input_per_product[Plantbased_products]))

UNITS: kg/year

DOCUMENT: Variable predicting how much crop feed is necessary to cover the protein need.

The basic equation is multiplying the consumption from each product category with the feed that is required per product. What is added to this is the feed that is required to cover export as well. Which is the same formula, but multiplied with the export fraction divided with the national fraction.
In addition to this, for cultivated meat there is also another element added. If the production gap - the gap between the protein requirement and the actual protein production - is below 1 (meaning there is more requirement than production) this gap will be compensated with cultivated meat products and the feed needed to cover this extra production is added to the cultivated meat formula.

predicted_feed_required[Crop_CM] = IF production_gap >1 THEN (.cm_consumption_NL*Feed_input_per_product[Cultivated_Meat_conventional]) + ((fraction_export/fraction_national_use)*(.cm_consumption_NL*Feed_input_per_product[Cultivated_Meat_conventional])) ELSE ((.cm_consumption_NL*Feed_input_per_product[Cultivated_Meat_conventional]) + ((fraction_export/fraction_national_use)*(.cm_consumption_NL*Feed_input_per_product[Cultiva

ted_Meat_conventional]))) + ((1-production_gap)*.cm_consumption_NL*Feed_input_per_product[Cultivated_Meat_conventional])
UNITS: kg/year
DOCUMENT: Variable predicting how much crop feed is necessary to cover the protein need.
The basic equation is multiplying the consumption from each product category with the feed that is required per product. What is added to this is the feed that is required to cover export as well. Which is the same formula, but multiplied with the export fraction divided with the national fraction. In addition to this, for cultivated meat there is also another element added. If the production gap - the gap between the protein requirement and the actual protein production - is below 1 (meaning there is more requirement than production) this gap will be compensated with cultivated meat products and the feed needed to cover this extra production is added to the cultivated meat formula.
production_CM_products = MAX(0, feed_farmers[Crop_CM]*average_feed_production_per_farmer)
UNITS: kg/year
DOCUMENT: To calculate the amount of cultivated meat production, the amount of farmers growing feed crops for the cultivated meat production is multiplied with the average kg of feed production. In reality, to produce cultivated meat products, more elements would be needed, such as the crops (biomass) would need to be converted to glucose so it can be processed (Sinke & Odegaard, 2021) and - depending on how the research progresses - animal cells would be needed too. However, in this model it is assumed that as long as the production capacity is not exceeded, all that is needed are feed crops to provide nutrients as a growth medium for cultivated meat.
production_gap = total_production_per_year/total_protein_demand
UNITS: dmnl
DOCUMENT: To calculate the protein production gap, the total production is divided by the protein demand. Export is included in this variable.
"production_plant-based_products" = MAX(0, feed_farmers[Crop_PlantBased]*average_feed_production_per_farmer)
UNITS: kg/year
DOCUMENT: To calculate the amount of plant based meat production, the amount of farmers growing feed crops for the plant based meat production is multiplied with the average kg of feed production.
protein_demand_per_capita = 0.103
UNITS: kg/person/day
DOCUMENT: The average needed protein per person per day (Henchion et al., 2017).
relative_calves_for_consumption = calves_for_meat_consumption/INIT(calves_for_meat_consumption)
UNITS: dmnl
DOCUMENT: The variable shows the growth or decline of the amount of calves that are being sold for meat consumption over time. To get this value, the amount of calves for meat consumption is divided by its initial value from 2020.
relative_population_NL = population_predictions_NL_data/INIT(population_predictions_NL_data)
UNITS: dmnl
DOCUMENT: The relative population divides the population projections with the initial population in 2020. The value that is produced represents the growth or decline of the population

at a certain time compared to its initial value. For example, if this value would be 2, the population would have doubled since 2020.
sum_animals = SUM(predicted_animals_needed_for_meat_consumption)
UNITS: animal/year
DOCUMENT: All livestock needed to cover meat consumption (including export) added together.
switch_cattle_policy = 0
UNITS: dmnl
DOCUMENT: Switch value to turn the cattle restriction policy on (1) or off (0).
total_farmers = SUM(feed_farmers[*]) + SUM(livestock_farms[*])
UNITS: farm
DOCUMENT: The sum of both feed farmers and livestock farmers. Feed farmers produce the crops that are necessary to produce the meat or alternative meat products.
total_livestock_farms = SUM(livestock_farms[*])
UNITS: farm
DOCUMENT: Sum of the arrayed stock of livestock farms
total_production_per_year = (SUM(meat_production_NL)+"production_plant-based_products"+production_CM_products)
UNITS: kg/year
DOCUMENT: To get the total protein production, the amount of produced meat products, cultivated meat products and plant-based meat products are added together.
total_protein_demand = (population_predictions_NL_data*protein_demand_per_capita*days_per_year)*average_fraction_consumer_food_waste + (fraction_export/fraction_national_use)*(population_predictions_NL_data*protein_demand_per_capita*days_per_year)*average_fraction_consumer_food_waste
UNITS: kg/year
DOCUMENT: The total protein demand per year is calculated by multiplying the protein demand per person per day with the amount of people in the Netherlands and the amount of days per year. What is also incorporated in the demand is the fraction of food waste. About 42% of food that is purchased by consumers is thrown away. As that is such a significant amount, it is included in this variable as this food would have to be produced as well. On top of this, export is included in this variable as well. The same formula as mentioned above is repeated and multiplied with the fraction of export divided by the fraction of national use. This division would produce the value that is needed to include export. For example, if that national demand is only 40% of the total production, a multiplication of 1.5 would be needed to cover that other 60% of export (0.6/0.4=1.5).

Appendix 2 – Sensitivity Analysis

VARIABLE	RANGE	SENSITIVE	REMARKS
at market share	0-2	no	
government investments	25e6-100e6	yes	Sensitive variable, as expected.
average price meat products	0-12	yes	As expected, all array categories were significantly sensitive.
contact rate	10-70	no	
initial fraction adopters cm	0.001-0.2	no	
initial fraction willing cm	0.01-0.7	no	
natural convincing	0.01-0.25	yes	Variable sensitive. Based on assumption and calibration.
normal fraction of becoming willing	0.01-0.25	no	
natural changing mind	0.01-0.25	yes	Sensitive variable, based on assumption and calibration.
policy adjustment time	0-20	no	
private investment data	20e6-200e6	yes	Sensitive variable, as expected.
time to adjust population	0.5-5	no	
time to adopt cm	0-2	yes	Variable significantly sensitive. Based on assumption and calibration.
carbon footprint per product	0-150	yes	All array categories are significantly sensitive. Values based on data.
dispersion time	0-10	yes	Significantly sensitive. Based on data.
fraction sustainable energy for cm production	0-0.8	no	
fraction to repurpose	0-0.8	no	
initial cm land	0-100k	yes	Not sensitive when land re-purposing is enabled.
land loss rate	0-0.5	yes	Not very sensitive when land re-purposing is enabled.
land use per kg product BEEF	10-50	no	
land use per kg product CM CONVENTIAL	0-5	yes	Not sensitive when land re-purposing is enabled.
land use per kg product PORK	2-12	no	
land use per kg product POULTRY	2-12	no	
land use per kg product CM SUSTAINABLE	0-5	no	
land use per kg product PLANT-BASED	0-5	no	
land use at	0-8	yes	Not sensitive when land re-purposing is enabled.
max ha for agriculture NL data	1000000-5000000	no	

fraction agricultural land used for meat production	0-1	no	
adjustment time farms	0-8	yes	Sensitive variable. Based on assumption and calibration.
adjustment time livestock farmers	0-8	yes	Variable moderatly sensitive. Based on assumption and calibration.
at dairy cows	0-8	no	
average fraction consumer food waste	1-2	no	
average hectare NL farms	10-100	no	
average production per ha	2000-12000	no	
average weight per animal BEEF	300-900	yes	Sensitive variable, based on data.
average weight per animal PORK	80-140	no	
average weight per animal POULTRY	1-6	no	
calves per cow	0-10	no	
dairy cows NL data	750000-2500000	yes	Based on data.
export scenarios	0-1	yes	Sensitive, as expected.
feed input per product BEEF	0-10	no	
feed input per product CULTIVATED MEAT	0-2	yes	Sensitive as expected, based on data.
feed input per product PORK	0-8	no	
feed input per product POULTRY	0-5	no	
feed input per product PLANT BASED	0-2	no	
fraction calves sold meat consumption	0-1	no	
fraction carcass weight per animal BEEF	0-1	yes	Sensitive variable. Would not fluctuate very significantly in reality. Based on data.
fraction carcass weight per animal PORK	0-1	no	
fraction carcass weight per animal POULTRY	0-1	no	
initial dairy cows	750000-2500000	no	
market share milk alternatives	0-1	yes	Moderatly sensitive. Based on data projections and assumptions.
market share	0-1	no	
CO2eq meat industry NL	50e9-150e9	no	
degraded land	10000-100000	no	
land-use BEEF	500000-2000000	no	

land-use PORK	200000-1000000	no	
land-use POULTRY	50000-300000	no	
land-use PLANT BASED	500-10000	no	
re-usable land	100000-600000	no	
feed farmers ANIMAL FEED	2000-20000	no	
feed farmers PLANT BASED	0-1000	no	
feed farmers CULTIVATED MEAT	0-1000	yes	Sensitive as expected, based on data.
livestock farms BEEF	2000-20000	yes	Different initialization values for this stock would effect the initial trajectory of the behaviour. Based on data.
livestock farms PORK	1000-10000	no	
livestock farms POULTRY	250-2500	no	
average animals per farm data BEEF	50-200	yes	Sensitive variable. Based on data, but the variable could differ over the years.
average animals per farm data PORK	1000-3000	yes	Sensitive variable. Based on data, but the variable could differ over the years.
average animals per farm data POULTRY	50000-200000	yes	Sensitive variable. Based on data, but the variable could differ over the years.
average plant-based products consumption pp NL	0-15	no	
Average meat consumption pp NL 2010-2020 BEEF	5-30	yes	Sensitive as expected. Based on data.
Average meat consumption pp NL 2010-2020 PORK	10-50	yes	Sensitive as expected. Based on data.
Average meat consumption pp NL 2010-2020 POULTRY	5-40	yes	Sensitive as expected. Based on data.

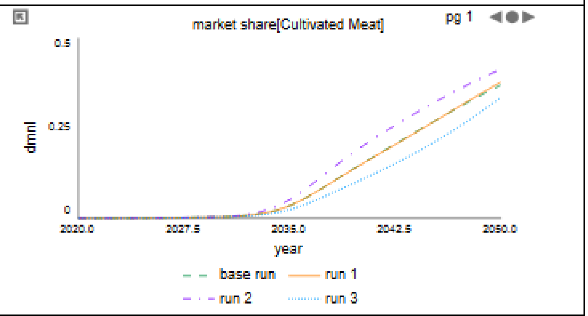
VARIABLE

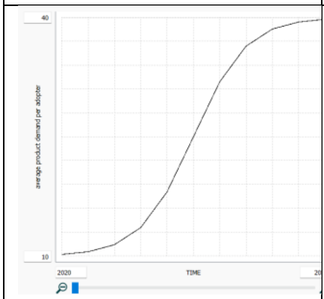
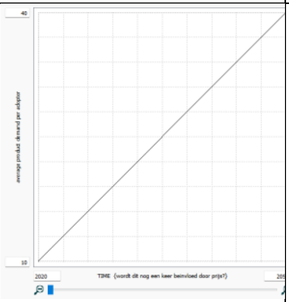
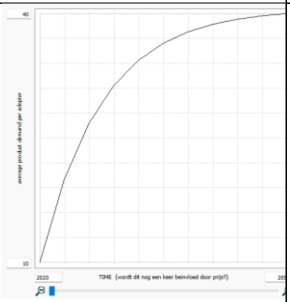
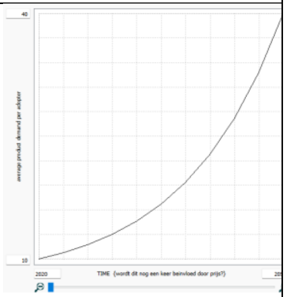
average product demand per adopter

REMARKS

Sensitive variable. Based on assumption and calibration.

SENSITIVE



BASE RUN	RUN 1	RUN 2	RUN 3
			

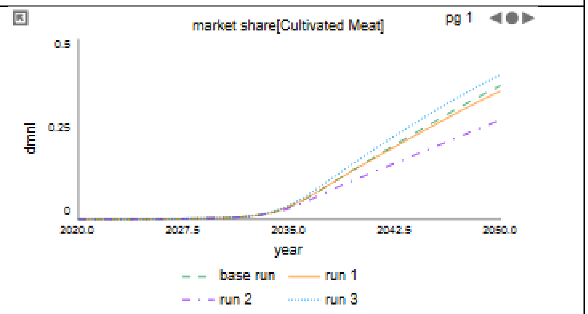
VARIABLE

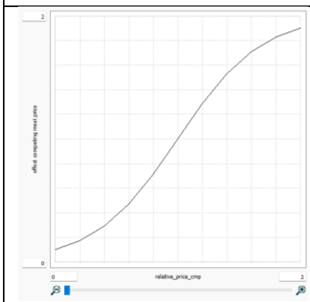
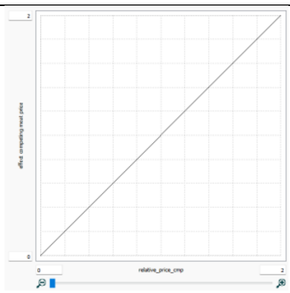
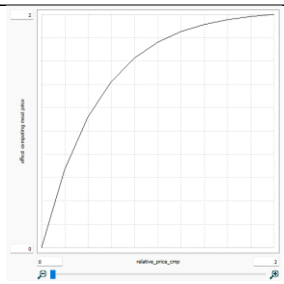
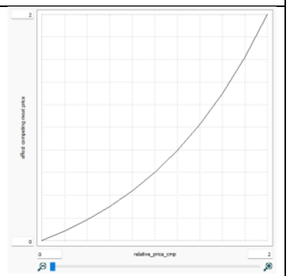
effect competing meat price

REMARKS

Sensitive variable. Based on assumptions and calibration.

SENSITIVE



BASE RUN	RUN 1	RUN 2	RUN 3
			

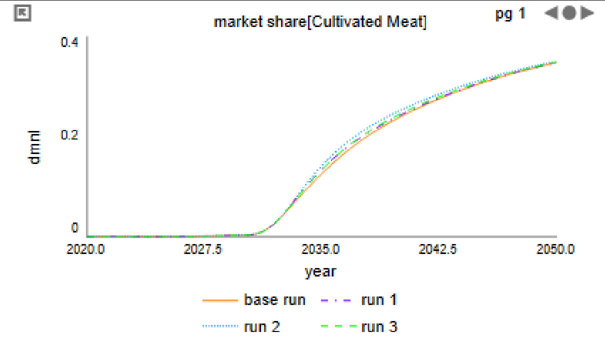
VARIABLE

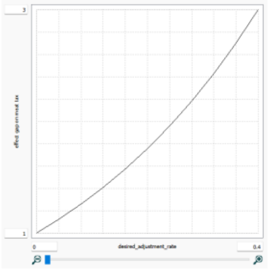
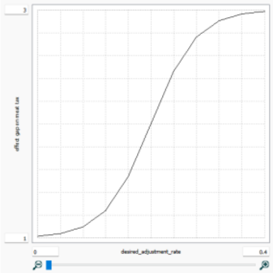
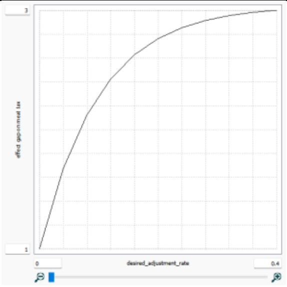
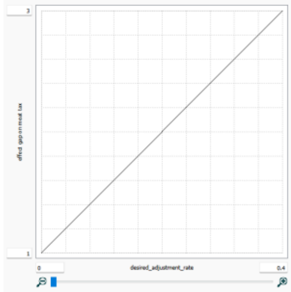
effect gap on meat tax

REMARKS

Not sensitive.

SENSITIVE



BASE RUN	RUN 1	RUN 2	RUN 3
			

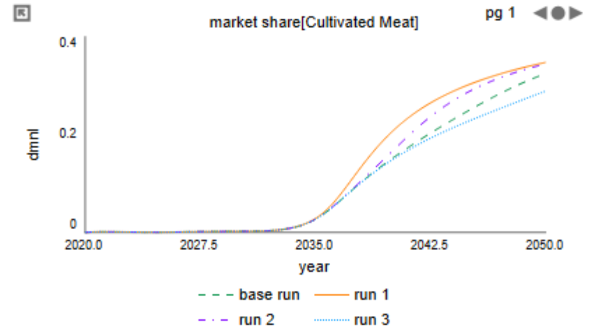
VARIABLE

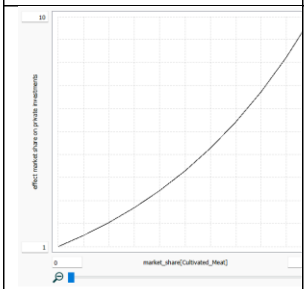
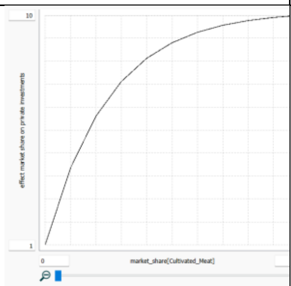
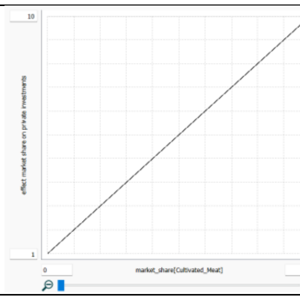
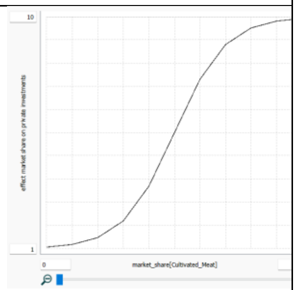
effect market share on private investments

REMARKS

Sensitive variable. Based on assumptions.

SENSITIVE



BASE RUN	RUN 1	RUN 2	RUN 3
			

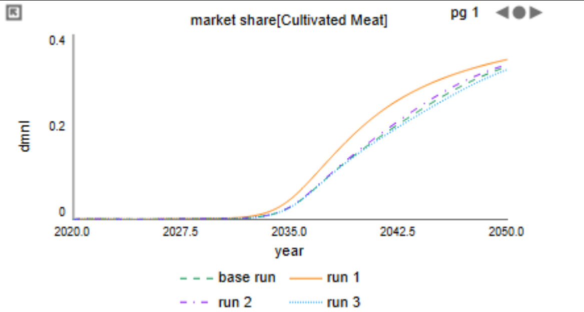
VARIABLE

effect of gap on gov funding

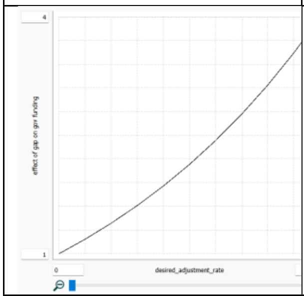
REMARKS

Sensitive variable. Based on assumptions.

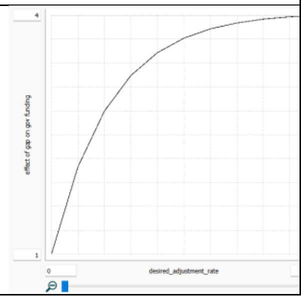
SENSITIVE



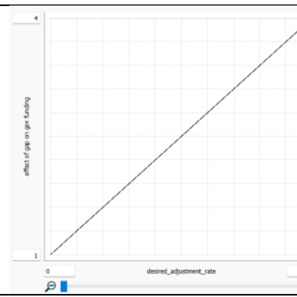
BASE RUN



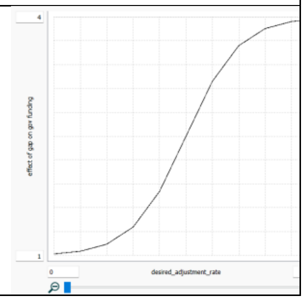
RUN 1



RUN 2



RUN 3



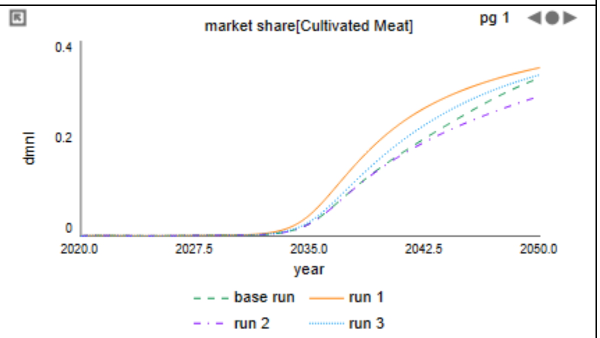
VARIABLE

effect of investments on price cm

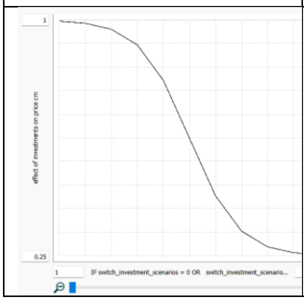
REMARKS

Sensitive variable. Based on assumptions and calibration.

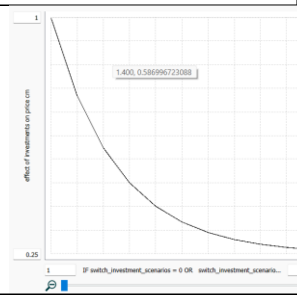
SENSITIVE



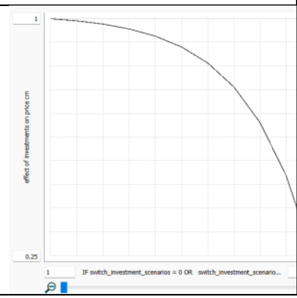
BASE RUN



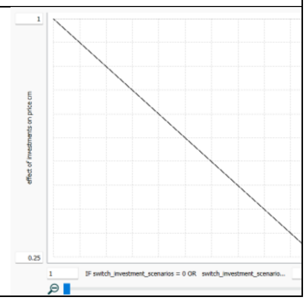
RUN 1



RUN 2



RUN 3



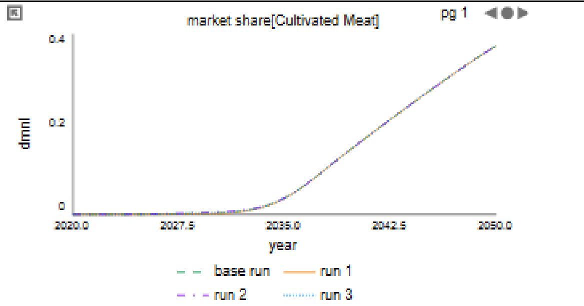
VARIABLE

effect of investments on production capacity

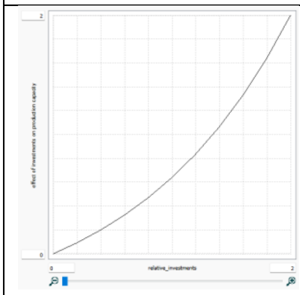
REMARKS

Not a sensitive variable.

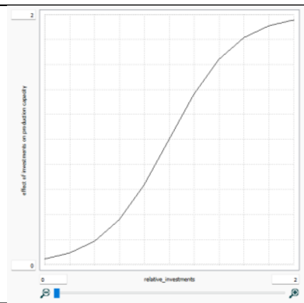
SENSITIVE



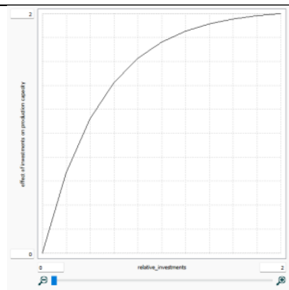
BASE RUN



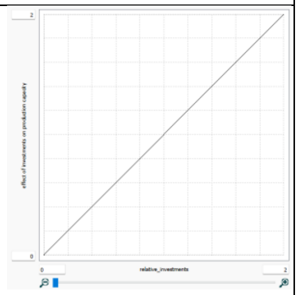
RUN 1



RUN 2



RUN 3



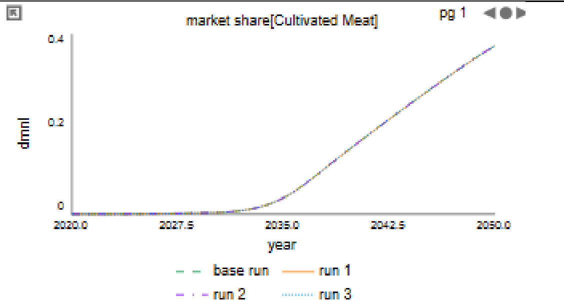
VARIABLE

effect of investments on public education

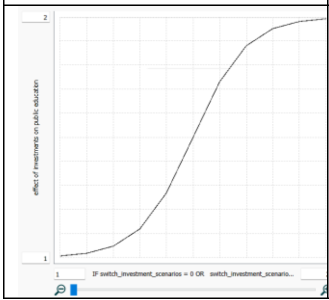
REMARKS

Not a sensitive variable

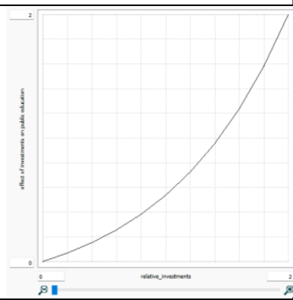
SENSITIVE



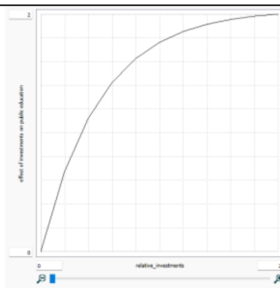
BASE RUN



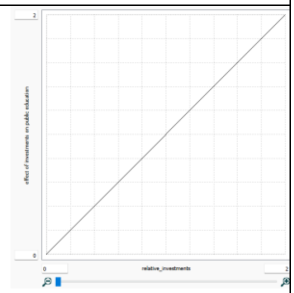
RUN 1



RUN 2



RUN 3



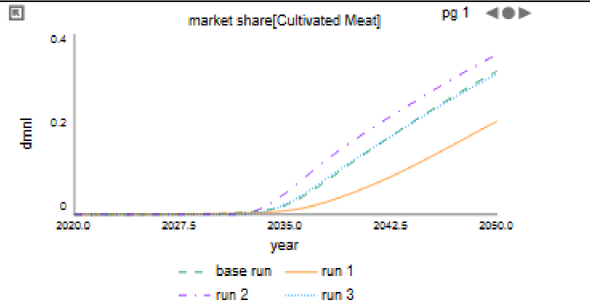
VARIABLE

effect of price cm on adopting

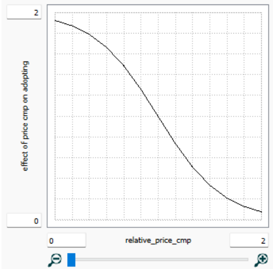
REMARKS

Sensitive variable. Based on assumptions and calibration.

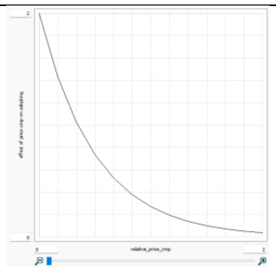
SENSITIVE



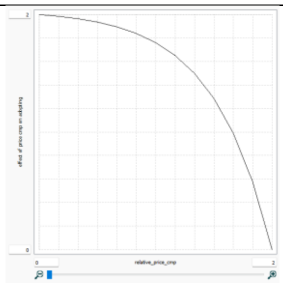
BASE RUN



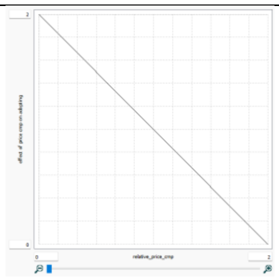
RUN 1



RUN 2



RUN 3



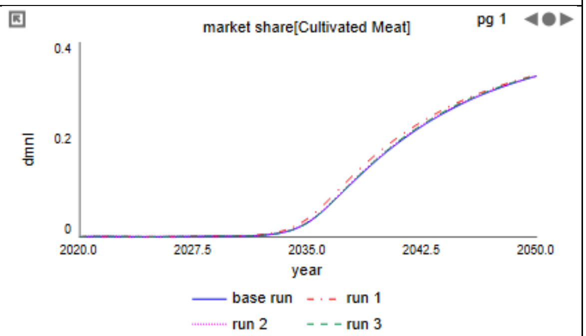
VARIABLE

market share goal cm products

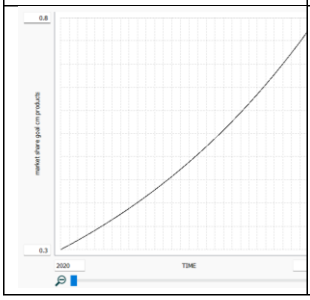
REMARKS

Not sensitive.

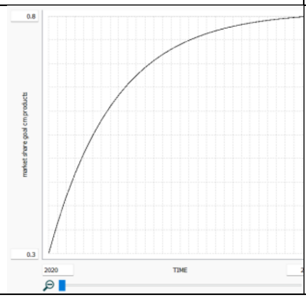
SENSITIVE



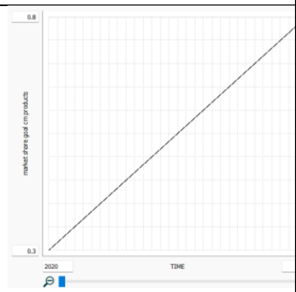
BASE RUN



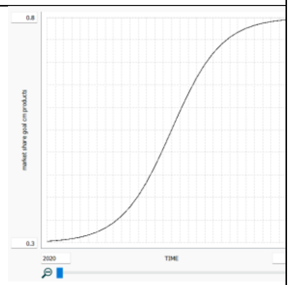
RUN 1

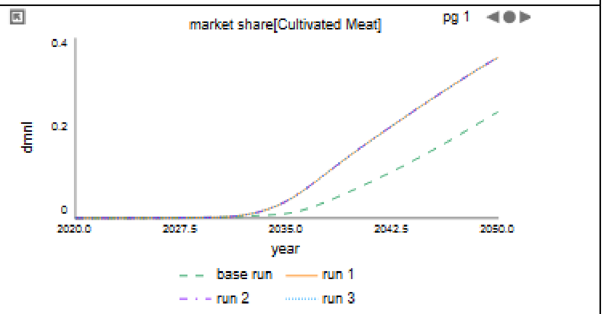


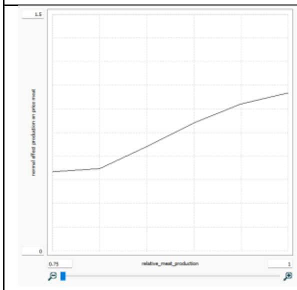
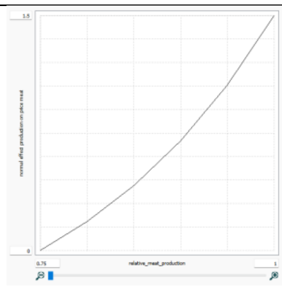
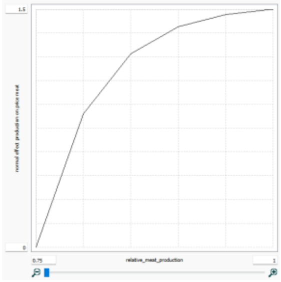
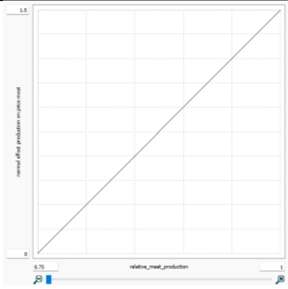
RUN 2

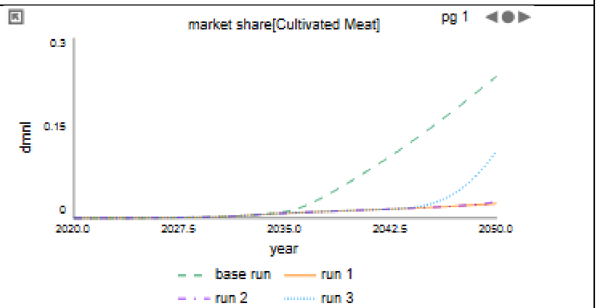


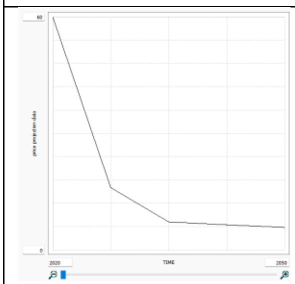
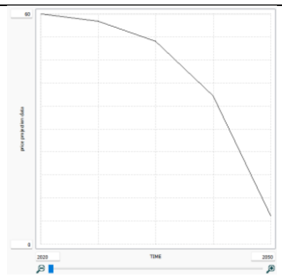
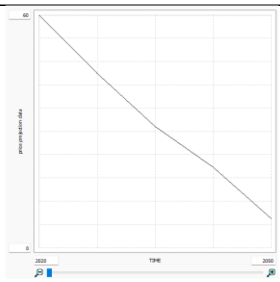
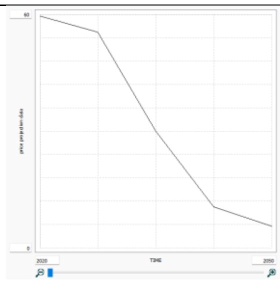
RUN 3

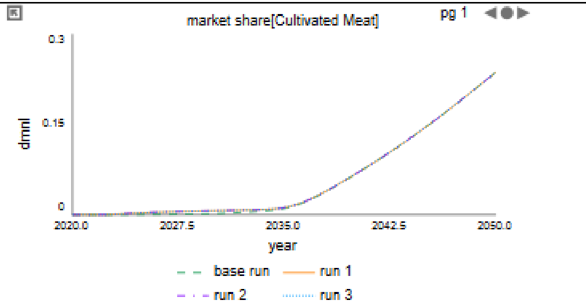


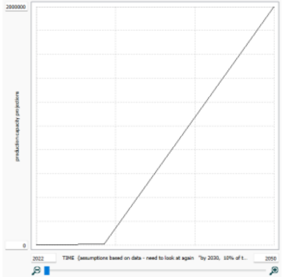
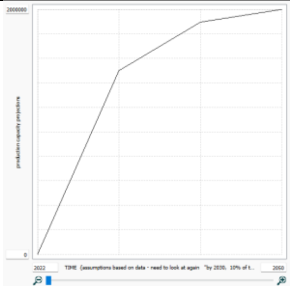
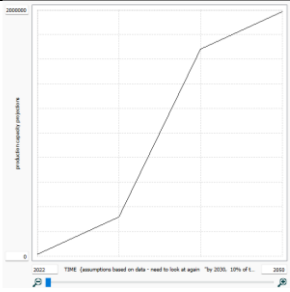
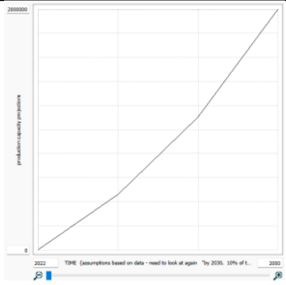
VARIABLE	SENSITIVE
effect production on price meat **REMARKS** Moderately sensitive variable. Based on assumptions.	

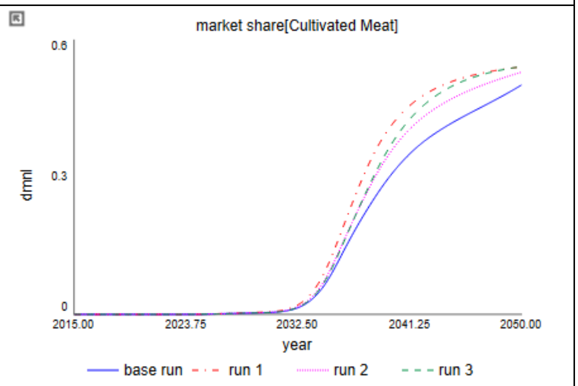
BASE RUN	RUN 1	RUN 2	RUN 3
			

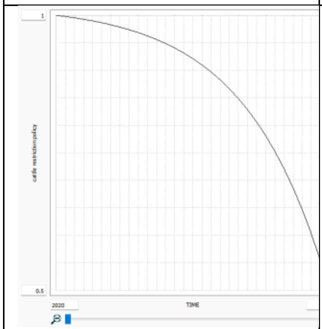
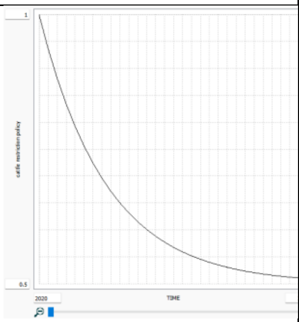
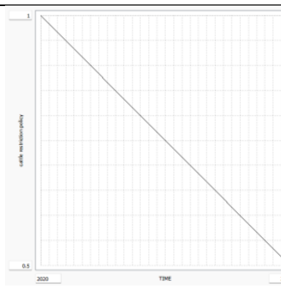
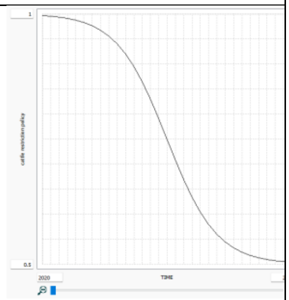
VARIABLE	SENSITIVE
price projection data **REMARKS** Sensitive variable. Based on data.	

BASE RUN	RUN 1	RUN 2	RUN 3
			

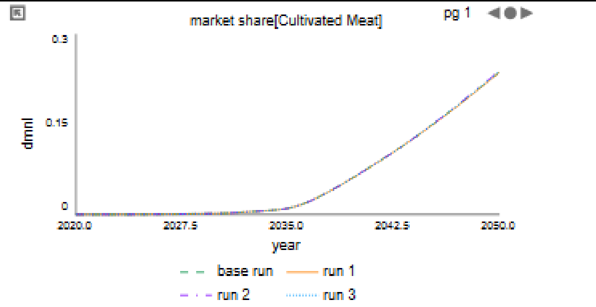
VARIABLE	SENSITIVE
production capacity projections	
REMARKS Not a sensitive variable	

BASE RUN	RUN 1	RUN 2	RUN 3
			

VARIABLE	SENSITIVE
cattle restriction policy	
REMARKS Sensitive variable.	

BASE RUN	RUN 1	RUN 2	RUN 3
			

VARIABLE	SENSITIVE
market share milk alternatives projections	

REMARKS Not a sensitive variable	

BASE RUN	**RUN 1**	**RUN 2**	**RUN 3**