Managing the agri-food supply chain

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Transporting wheat from farmers to producers

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Management Summary

After sketching the agri-food industry we took a closer look at the supply chain of wheat. From the fields of the farmers to the production locations of the traders the transportation is currently organised in a much decentralised manner. Each link in the supply chain bases their decisions on a single leg only. By looking at the supply chain as a whole, savings could be realised.

The following research question is formulated:

Given a set of farmers and traders, how can a model be formulated to analyse and improve the performance of a harvest transport network between them?

In order to come up with a model a toy problem is constructed to visualise the problem at hand and to narrow down the scale. With this toy problem a numerical model is drawn up to map out the consequences of broadening the view of the different actors. Step by step this model is expanded to include more variables and to take extra factors into account. In this manner a model representative of the reality is constructed. The small scale of this toy problem allows for a concise view of the changes in the optimal solution when the extra variables are modelled. In this way the results of the model are analysed.

Next, the actual situation of the supply chain is analysed. Based on real life data the model, which was constructed based on the toy problem, is put into practice. This validates the model by comparing the results of the toy problem, with the results on the real data. Furthermore, this could also give an indication to the actual costs of the current supply chain design compared to the scenarios in the model. Some limitations and assumptions are identified, which makes it precarious to accept the results of the model as being to the fullest true to reality, but it does provide a solid foundation to an indication of large potential savings.

Contents

1. Introduction

1.1. Framework

In light of completing my master Industrial Engineering and Management at the University of Twente, I performed research into the setup of the transportation network that consists within the wheat harvest industry. This research is focused on wheat harvest in the northern parts of The Netherlands, and the journey which the produce makes from the individual farmers to the production facilities for further processing.

Currently, the transportation of the wheat is done in an ad-hoc fashion, triggered by the farmers themselves. Since they base their decision of when and how to transport their harvest only on information of the first leg (which they can oversee), the performance of the entire network is probably not optimal.

1.2. Background

The days where people would procure their wheat, milk or vegetables directly from a neighbouring farmer are long gone. Nowadays we shop in supermarkets which sell products from all over the world and seasonal availability of certain products is stretched longer every year. The companies responsible for supplying us with these products operate in the agri-food industry. This industry covers all steps from developing the seeds, through growing and harvesting the crops, to producing products and everything in between. A lot of different actors are involved and the supply chain through which all these materials and products flow to and fro is complex. Some supply chain characteristics belonging to the agri-food industry, and which sets it apart from a generic supply chain, are:

- <u>Reciprocal relationships</u>
  Some parties do business with each other in different parts of the supply chain. For example, after acquiring fertilizers from a blender, a farmer may sell its wheat production back in order for the blender to use it as an ingredient in making cattle-fodder, which can be sold back to the same farmer. This can all happen multi-site which increases the complexity of the supply chain.
- <u>Volume fluctuation</u>
  The agricultural sector has a high fluctuation between peak and low demand and supply. As most harvests depend on seasons and the actual weather the flow of goods differs greatly over time. Often, blenders and retailers alternate periods of overtime with periods of vacancy. Farmers on the other hand have a steady demand of fertilizers and soils, but order their seeds late in advance, as they decide late on specific species. This creates peak demand which is hard to forecast.
- <u>Quality fluctuation</u>

Not only volume fluctuates greatly, also the quality of the harvested goods is difficult to predict. External (weather) factors have a big impact on the end product. Humidity and moisture levels, for example, can change overnight, making not only the volume, but also the quality volatile.

- Production

  Agricultural products do perish, but their lifespan differs. It ranges from one month to little over a year. Stocking up on certain products is therefore difficult and producers are reserved when it comes to producing-to-stock in anticipation of coming demand.

- Transportation

  The raw materials for agricultural products are generally moved and stored in bulk. Near the end of the supply chain products may be packaged in bigbags or sacks. The more valuable products like seeds may be packaged in even smaller sized containers. The transport of these products occurs by all modes of transport: by ship, train, truck or plane. The transportation vessels for bulk transport are often compartmentalised. Not only can different types of products be shipped simultaneously, but it also simplifies some deliveries. The volume of delivered products is known beforehand, as it depends on the capacity of the compartments.

- Routing

  The delivery of goods between farmers and retailers/blenders occurs predominantly by trucks. Multiple deliveries can be combined in one trip (with or without compartmentalisation) and sometimes the order of deliveries is an issue, e.g. with dump trucks. No delivery windows are used, but times for (un)loading are taken into account. Within a multi-site transportation problem, reloading during or after a trip is also done regularly.

- Pricing

  Price conditions vary, depending on delivery conditions (freight paid, delivery period, volume, time) or product ranges.

- Hazardous materials

  Some crop protection products contain hazardous materials. These are subject to laws and regulations. The production, transportation and storage of these products are restricted and requires licences issued by governmental agencies.

1.3. Case descriptions

To illustrate the dynamics of the agri-food supply chain, two case descriptions from the point of view of two key actors are outlined below. These two actors fulfil key roles within the typical supply chain of wheat. The cases describe the situations these actors find themselves in and the decisions they have to make.

1.3.1. Farmer Pete's produce planning

Farmer Pete is a medium sized farmer; he has around 50 hectares of land which he uses to grow wheat. Every year during the summertime he has to decide which seed to plant, how much to plant and when to plant. The amount of wheat that he is able to harvest in the spring and the revenue that this harvest produces depend on his decisions.

First of all he has to decide which seed to plant. Each year new families of seeds are developed and success ones from previous years reproduced; every species of seeds have their own characteristics. Based on some test harvests the yield can be predicted. When Pete has chosen the specific seed he wants to plant the coming year he can choose whether or not he would like to have the seed treated. Treating the seeds can improve their growth or resistance to certain diseases. However, treated seeds are more expensive and less preservable than untreated seeds. Pete opts for the seeds which he has planted for the last couple of years. They always grew well and brought him a healthy harvest every year, so why would that be different this year?

When the seeds are planted there really is not much that Pete can do but to hope for good weather and a steady growth of his crops. The one thing he can influence a bit is the protection to diseases. He sprays his growing wheat with crop protection to strengthen the crop and deter any diseases that might be circling his fields.

With spring time coming nearer and nearer Pete starts to wonder a bit about the coming harvest and the revenues that his wheat will bring. He knows that he only has a small time window in which the wheat reaches full maturity before it starts to wither again. He has to make the most of this small window, which usually only lasts for a week or two, if he wants to procure an optimal price for his crops.

When the period for harvesting approaches he has to find a party to which to sell his wheat. He contacts a couple of traders to inform them that he soon has 50 hectares of wheat to sell to them and inquires what price they are willing to give to him. Pete knows that the price of wheat fluctuates based on its moisture level. The drier the wheat is, the more valuable it is to the trader. When the moisture level is high, the trader gets less wheat per procured ton. And if the moisture level is above a certain threshold, it has to be dried before it can even be processed further. These thresholds and prices per moisture level differ per trader, but prices may differ up to 3% per percentage increase in moisture level, and the costs of any necessary drying activities might be subtracted from this price as well.

Pete checks his crops and mumbles to himself: "A couple of fine, sunny days will reduce the moisture level of my wheat from 20 to 15%". Without knowing the exact levels, his farmer's instincts are spot on. However, when he checks the weather forecast he sees that his hoped for sunny days will not come for at least the next week or so. Should he harvest now and settle for inferior crops, or wait for better weather and risk withering his wheat? He opts to wait…

Two weeks later he finally catches a spell of nice weather and rushes to harvest his pretty dry wheat. He has informed his trader that he is coming with truckloads of wheat and asks them to be ready for his delivery. A couple of years ago he has invested in his own truck so he does not have to rely on the trader sending trucks to pick up his harvest. When he has rushed the wheat off his land and into his truck he speeds to the nearest drop-off point of his trader. Upon arrival his truck is weighed and a sample of his load is taken to establish the exact moisture level. When his truck is unloaded it is weighed again and the weight difference, multiplied with the price corresponding with the moisture level is immediately credited to him. After he is done speeding back and forth to harvest and deliver his crops, and his fields are empty again he finally has the time to ponder over the past season. It took him quite some time to deal out an optimal price for his crops, and even so he believes that his neighbour, also a wheat farmer, receives a better price for his harvest.

His neighbour forms a pool with other farmers. They pool their (predicted) harvests together and offer this large amount to the traders in batches. However, selling this large quantity takes some time. Over the course of a couple of months the wheat is stored in a warehouse while batches are being sold. While this might ensure higher prices for the wheat, the individual farmers which are part of this pool are dependent on the results of this entire pool. They are paid a share of the total pool's result, in relation to the share they put in with their individual harvests.

1.3.2. Trader Tim tries to attain steady supply

Trader Tim is employed by a large trader specialized in buying harvests and handling the large quantities of produce that come with it. Tim is responsible for making sure that the wheat harvests of the coming season are processed correctly and profitably. To this end, Tim tries to buy the harvests for the lowest price possible, but also in such a state that little processing is required. He is aware that storage and handling of dry wheat is a lot easier and cheaper than wet wheat. However, as the company he works for is actually a cooperation, he has to service every farmer associated with it.

But those are worries for later. For now he has to make sure that the logistics' chain is fully operational. The coming peak of wheat supply is only a couple months ahead and he is not ready yet to process the expected quantities. He has to up the capacity of the chain by making reservations with transport companies for trucks and temporary employment agencies for workers. But every year he has difficulty in predicting when the wheat supply will reach its peak, and when this peak will take place. Of course, by issuing prices to farmers for their crops he has some influence in the expected supply, but he has to be careful. The processing equipment has a fixed capacity and exceeding this limit will lead to high costs: he either has to procure quick increase in capacity, or have to watch the produce wither away while waiting on the processing capacity to open up.

Most of his efforts are based on a plan of action, adapted from the plan of last year. And every year Tim is surprised by the amount of resources it takes to get ready for the couple of weeks of harvest. It dawns to him that all this preparation is a quite costly endeavour and tries to spread the supply of wheat a little, or at least try to predict it as good as he can. Price incentives, flexible delivery schedules or pickup windows and minimal registration; Tim does what he can to provide himself with any extra leeway he can. However, he knows that the wheat supply is difficult to influence, since the same mechanics have been around for decades and farmers are not easily persuaded into change.

As the time of the harvest comes closer and closer, Tim receives more and more pledges of farmers who will sell their wheat to him. Based on this information he starts to get a clearer picture of the volumes that he will have to process and he adjusts his pricing strategy for further negotiations accordingly. However, the exact timing of when the wheat will come in is still unsure. All Tim can do is prepare and hope that his chain is able to handle the upcoming supply. In the meantime he services his machinery, instructs his staff members and trains the temporary workers from the employment agencies.

The spring starts off wet and the wheat harvest lags behind in respect to the previous years. Tim and his trading company are ready for the flow of wheat but it is simply not picking up yet. Everyday a lot of resources are wasted on idle trucks and dozens of temporary workers with nothing to do. If the harvest is put off for a couple more weeks he will not be able to make a big profit this year. Then, when the weather has cleared for a couple of days he gets the first call to come and pick up the first truckload of wheat.

Within a week his company is in full swing, phones are ringing, trucks come and go and tons and tons of wheat are processed in his plants. His day to day activities have turned from planning and anticipating a peak flow of goods and preparing his company's chain for an optimal handling of this produce, to managing the (transporting) capacity to its full extent. As the days pass the absolute peak of supply comes in sight, and Tim loses more and more control of his operations. He has to allocate quite a bit of attention and resources to harvests which are not quite lucrative. But he cannot turn down any farmer which arrives with his harvest at one of his processing plants. Not even if the harvest is small, wet and/or transported in such a way that unloading and weighing it is a laborious job. Managing the flow of wheat which has been preregistered was challenging in itself, but combined with managing different batches, registering which produce is from which farmer and no time to solve any issues which may arise, it is hard to maintain an overall picture.

It is only after the ultimate peak that a solid stock-taking can take place. Tim finally gets a full insight in the stock levels at the different sites and the quality of the produce stored within. He gets his grip back on his business of selling the wheat as he slackens his procurement of external capacity. There lies less than a month between the first and last trucks with unprocessed wheat arriving at his plants, but it will take many more before all of the wheat is sold off to other parties.

1.4. Trader's dilemmas

In the previously described cases the mechanisms of the wheat market is described. When looking at the trader, a number of dilemmas can be identified. These can be decisions he has to make, risks he needs to asses or issues he has to think over.

1.4.1. Climate change

The world's climate is changing. The produce grown by farmers depends on the climate for growing and maturing. As the climate changes the environment in which this is done, the eventual end result starts to differ over time if no action is taken. Already there is evidence that the summers in Western Europe are wetter and the winters milder, compared to a couple decades ago. The harvest period is pushed backwards and the produce procured by the traders show a significant increase in moisture levels.

The consequences of climate change are unpredictable but the change itself is very real and unless addressed might pose problems in the very long term.

1.4.2. Uncertainty of long term supply

Traders rely on farmers to provide them with the supply of produce they require. When there are not enough farmers to satisfy their need, the price will go up resulting in problems for the traders. The structural amount of produce available (outside "regular" sings in harvest results) might change in the long term. Farmers can change their crops into others that are more profitable. The markets of the different types of crops are global ones and price fluctuations are transparent. By squeezing the farmers, traders may well persuade them into growing different crops, thus endangering the long term supply. Climate change could also influence the choice of farmers.

1.4.3. Collaboration of suppliers

Having to negotiate with each farmer can be quite a laborious task for the trader. However, since the power balance between an individual farmer and the trader tips in favour of the latter, it pays off. As more and more farmers start to cooperate with each other and form different sorts of partnerships, supply is being pooled. This increases the suppliers' power and pressures the trader in less favourable agreements. However, it also provides opportunities. For example: fewer resources are spent on supplier negotiations, the variance of the total expected harvest is smaller, and the larger quantities offer possibilities for an improved transportation schedule or storage solutions.

The pooling of suppliers also shifts the risk of losing (or acquiring!) your supply from small to large quantities at once. The individual farmers are no longer able to switch traders as they follow their group's agreement, so their smaller individual supply will remain at that specific trader. But when the group of farmers decides to switch, that could constitute a significant amount.

1.4.4. Uncertainty of short term supply

The harvest itself is unpredictable. The precise amount depends on the specific seeds being sown, the weather and some irrigation and crop protection from the farmer. During the season an estimation can be calculated based on these parameters, but the actual figures remain uncertain.

The trader can engage in price agreements between himself and farmers to secure certain supply. Prices can be based on various moistures levels, pick-up/delivery of produce and time of procurement or payment.

1.4.5. Long term capacity (processing)

Just like in most other industries the capacity of traders to process the harvests is quite inflexible in the short term. New factories or processing plants require high investments and take a long time to realise. When investing in new processing capacity, the trader has to not only make decisions about the time and scale, but also about the nature of the new capacity. He has to consider future trends and expectations, and take into account the strategic plans.

1.4.6. Supply chain design

The produce has to find its way from the farmers to the trader. The trader has to set up his supply chain in such a way that this can be done in the best way and for the lowest cost. First the trader has to decide what the best way is for him, where his priorities lay between servicing the farmers and containing his fixed and variable costs. He can opt for multiple collection points: sites where farmers can deliver their produce. From these sites (fixed costs) he can then transport (variable cost) larger quantities at once to his processing plants. The choice for the number, size and location of these collection points are subject to quite a few considerations, among others: proximity to suppliers, regional coverage, proximity to exit roads or water ways and various cost aspects. The trader can also use the location of the storage capacity to his advantage.

1.4.7. Medium term capacity (storage)

In anticipation of the coming harvest period the trader has to ready his chain to deal effectively with the expected supply of produce. While his processing capacity is limited for the season, his storage capacity is not. Produce can be preserved for a couple of months when stored correctly, so investing in storage capacity might be a cost effective way of enlarging the overall processing capacity as well. Silos or granaries can be quite quickly erected, or even hired from third parties. The location of these storage facilities depends on the supply chain design. Storage at processing plants is relatively cheap but could require higher transportation costs. On the other hand, extra storage on the other end of the chain, on the individual farms, is expensive but could result in lower transportation costs.

1.4.8. Short term capacity (transport and processing)

While the processing plants have a fixed capacity, the temporary employees operating these facilities have to be hired for a limited period of time. Hiring these employees too early will lead them to stand idle for a period of time, but if the trader hires them too late he is unable to instruct and train them properly, resulting in problems during operations.

The trader also has to contact external transporters to hire transport capacity during the harvesting period. Based on his supply chain design he estimates the required capacity and hires accordingly.

1.4.9. Daily transport planning

When the harvest is picking up and large quantities of produce have to be transported from farmers to storage facilities or processing plants, transportation planning turns into hectic firefighting. The trader would like to have a coherent overview of the different stock levels, idle capacity and transportation requests. For a better transport planning, he also needs insight in the planned or expected transportation requests.

1.5. Problem statement

The dilemmas encompass the entire, broad range of aspects that need to be considered when looking at the agri-food supply chain from a trader's point of view. This research will focus on just two of them: the uncertainty of short term supply and the supply chain design. There is no ready method to model the supply chain, and so the following research question is formulated:

Given a set of farmers and traders, how can a model be formulated to analyse and improve the performance of a harvest transport network between them?

1.6. Deliverables

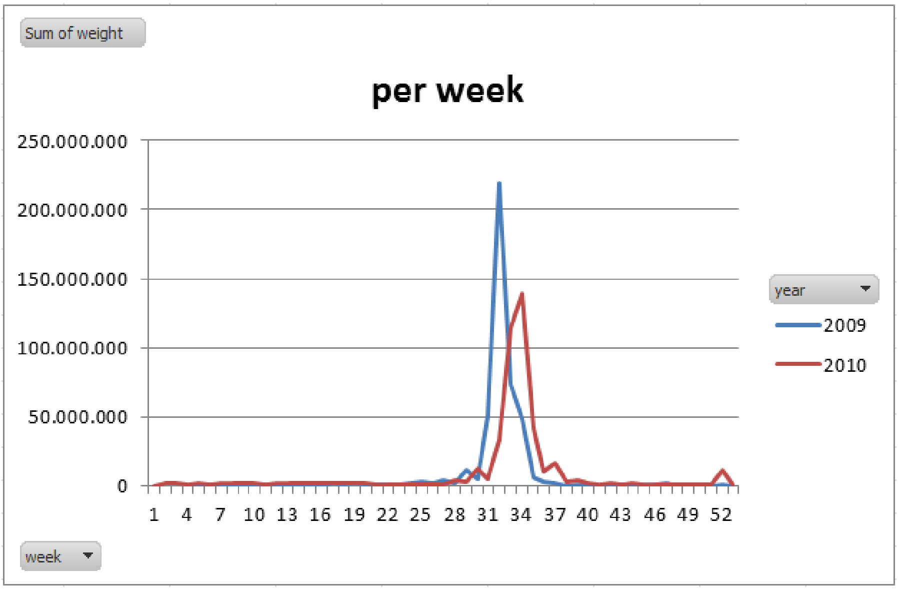
In order to answer the research question at hand, first of all we have to find a method with which we can analyse a harvest network. To this end we create a small scale version of the big picture; this toy problem can then be used to create a model which measures the performance of the network. The way in which the network performs can be analysed by changing or expanding the model's possibilities in a step-by-step fashion. In this way a concise understanding of its workings is obtained.

Once a model and its impact on the performance of the fictional data of the toy problem is clear, the model can be applied to real-life data. In this way the actual problem can be analysed, and ways to improve the network's performance, in respect to the current setup, can be identified.

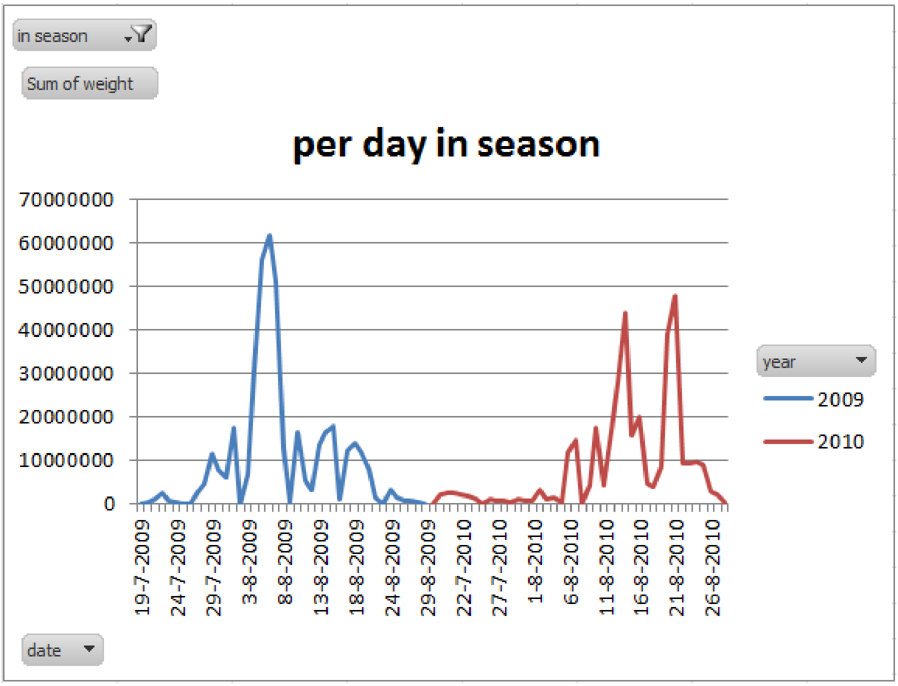
2. Uncertainty of short term supply

2.1. Introduction

Short term supply is hard to predict as the parameters on which it depends literally change with the weather. To illustrate this we can take a look at the supply figures of a large Dutch trader. The dataset comprises the actual real life amount of supplied wheat of the years 2009 and 2010. A quick glance at the distribution of the supply over the year shows indeed a strong seasonal pattern.



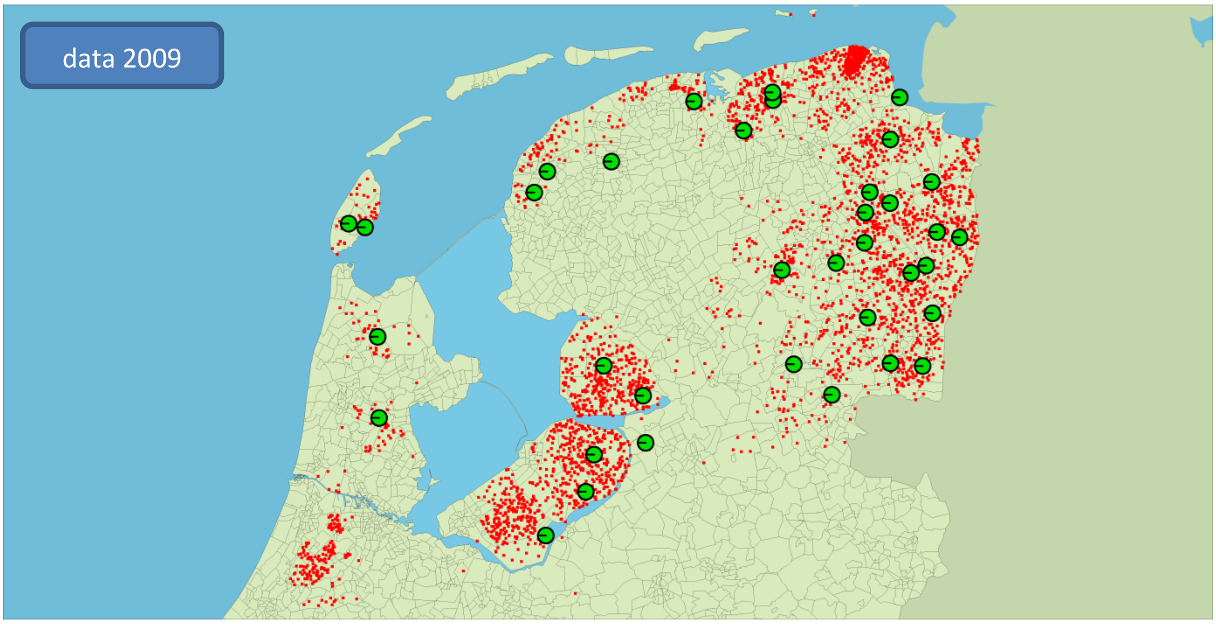
We identify the peak season to be between week 29 and 38. Within the peak season the total volume per day fluctuates quite a bit as well.

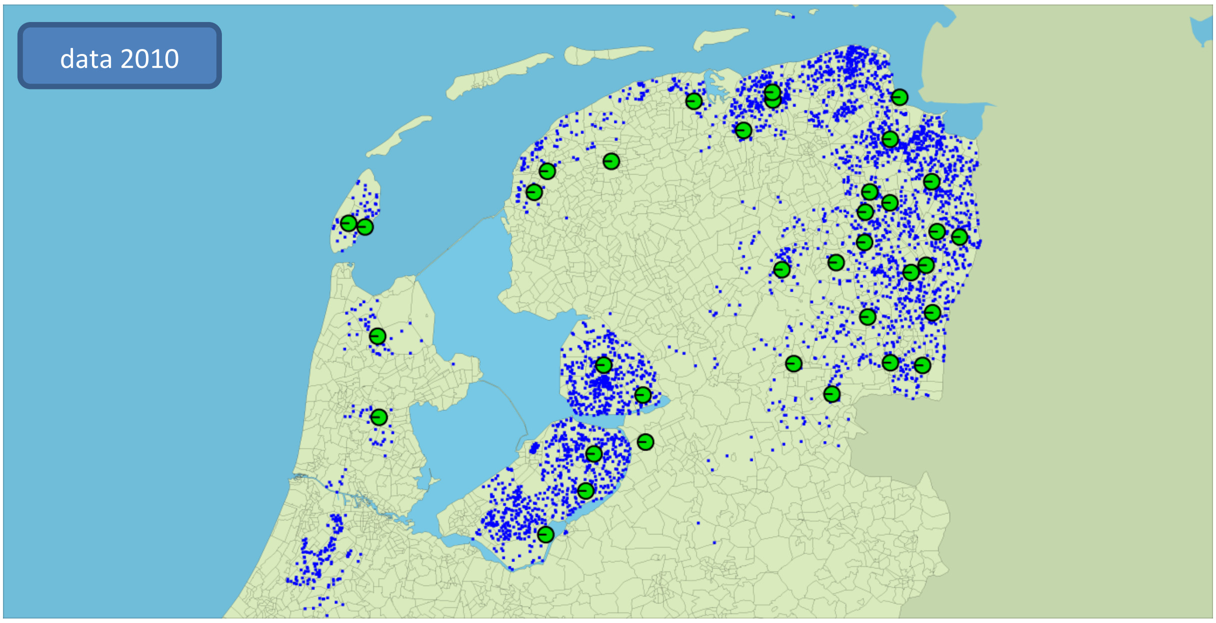


3. Supply chain design

3.1. Introduction

Using the same dataset as in the previous chapter, the geographical distribution of supply can be analysed. In the pictures below the supply of 2009 and 2010 is mapped (100 tonnes per dot), as well as the collection points to which the farmers deliver their produce (green circles). The production facilities lay near Kampen and Delfzijl.



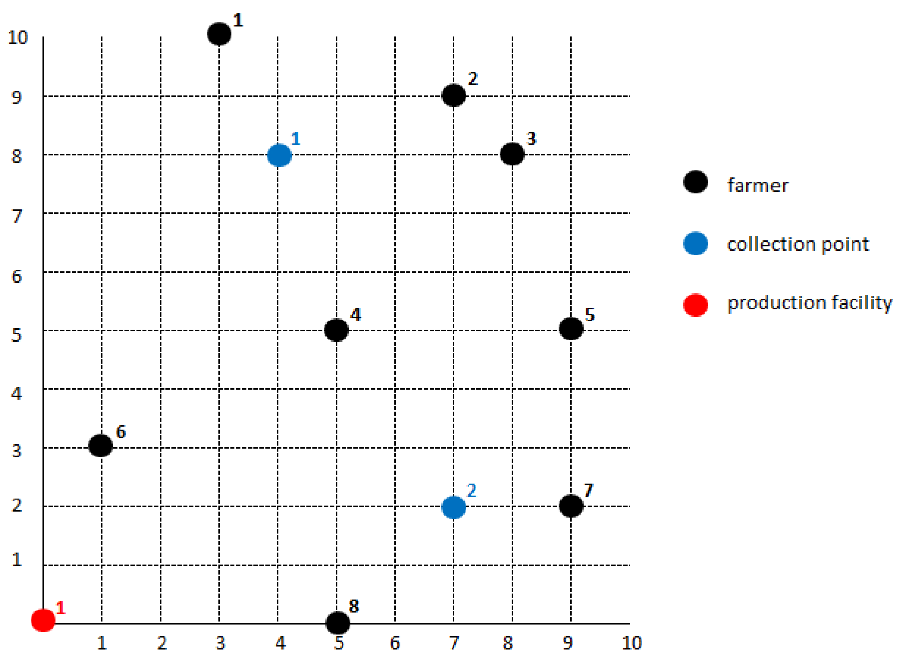


3.2. Toy problems

In order to gain insight in the model and analyse its inner workings, we will first take a look at a simplified problem. This simplified problem, with a number of assumptions, makes it easy to visualise and understand the mechanics of the model.

The problem consists of a hypothetical situation of a single production location, two collection points and a number of farmers whose wheat harvests have to find their way to the production location. We analyse the supply chain as a whole and try to minimise the logistical costs of transporting the wheat to the production location. In the following examples we build the model from the ground up. With every step we expand the model to come up with a more and more realistic resemblance of the real life situation or to gain insight in the mechanics of certain scenarios.

In the picture below the situation is sketched, the actors are placed on a grid for ease of distance calculation (using Manhattan distances).



In the following models we assume a secondary production location lying quite a distance away. Even though no farmer in this example will have its wheat transported to there, anticipating for multiple production locations improves the robustness of the model.

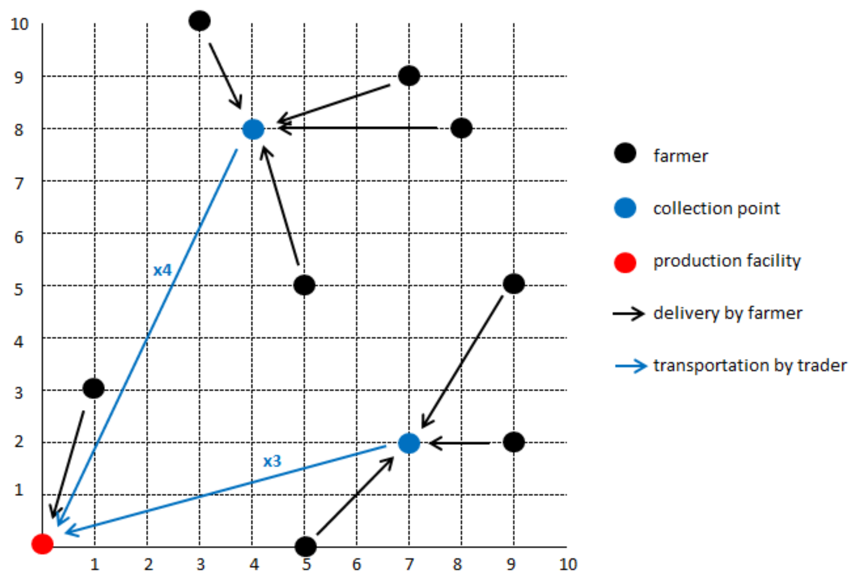
For solving the toy problems a simple LP solver is used to model the problems and find the optimal solutions. Appendix A shows the different models constructed for every step of the toy problem expansion.

3.2.1. Step 0 – current situation

To provide a base line to which the performance of the other models can be compared, the current situation is firstly examined.

Assumptions:

- Each farmer has exactly one full truckload of wheat
- All farmers deliver the wheat to the nearest collection point or production location
- The trader transports the wheat from the collection points to the production location
- The cost of transporting truck load over 1 distance by the farmer is 120, and by the trader is 60. Although the values are simplistic in this model, the proportions are realistic. Traders are able to transport larger volumes from the collection points at a smaller cost than the individual farmers with their inefficient transportation methods.



N.B. The arrows in the picture above and in the following pictures do not represent the distance as used in the calculating the transportation costs, since Manhattan distances are used. The arrows purely serve an indicative purpose.

The total costs equal: 8100

3.2.2. Step 1 – freedom of delivery

Now we can expand the model by looking into the effect of an overview. With the overview, the transportation costs for the individual farmers are no longer leading, but the transportation costs of all the legs from farmer to trader are taken into account. The costs of the entire chain are minimised, instead of just the first leg.

Assumptions:

- Each farmer has exactly one full truckload of wheat

- All farmers deliver the wheat to a collection point or production location
- The trader transports the wheat from the collection points to the production location

Decisions:

- To which location (collection points or production location) should each farmer deliver its wheat?

Model:

$$\min C_{total} = \sum_{i=1}^{N} \left(\sum_{l=1}^{M} \sum_{p=1}^{O} x_{ilp} * \left(C_{farm} * d(i,l) + C_{trad} * d(l,p) \right) + \sum_{p=1}^{O} y_{ip} * \left(C_{farm} * d(i,p) \right) \right)$$

For every farmer minimise the costs of transporting the wheat to:

- a collection point and from there on to the production location, or
- directly to the production location

s.t.

$\mathrm{x_{ilp}} = 0 \text{ or } 1$ for $\mathrm{i} = 1, \dots, \mathrm{N}$ and $\mathrm{l} = 1, \dots, \mathrm{M}$

$\mathrm{x_{ip}} = 0 \text{ or } 1$ for $\mathrm{i} = 1, \dots, \mathrm{N}$ and $\mathrm{p} = 1, \dots, \mathrm{O}$

$\sum_{l=1}^{M} \sum_{p=1}^{O} x_{ilp} + \sum_{p=1}^{O} y_{ip} = 1$ for $i = 1, \dots, N$ each farmer has to deliver their wheat to either a collection point or a production facility

with

$\mathrm{x_{ilp}} = 1$ if farmer i delivers to collection point l, from where it is transported to production location p, else 0

$\mathrm{y_{ip}} = 1$ if farmer i delivers to production location p, else 0

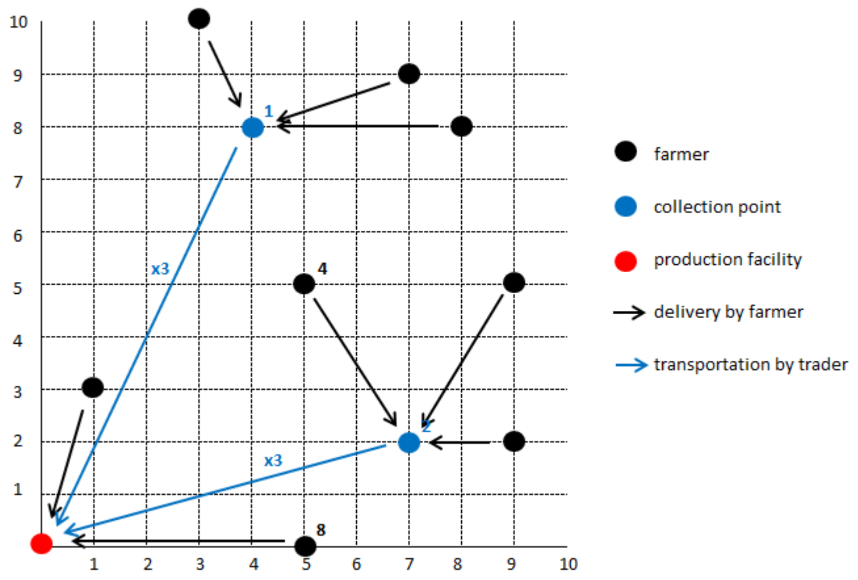
$\mathrm{C_{farm}} =$ costs of transporting truck load over 1 distance by the farmer = 120

$\mathrm{C_{trad}} =$ costs of transporting truck load over 1 distance by the trader = 60

$\mathrm{d(i,l)}$ = distance between farmer i and collection point l

$\mathrm{d(i,p)}$ = distance between farmer i and production point p

$\mathrm{d(l,p)}$ = distance between collection point l and production point p



The total costs equal: 7620

The freedom of deciding which farmer should deliver its wheat at which location has reduced the total costs by 480 in comparison to the situation where each farmer narrowly delivers the wheat to their nearest point. The situation for farmers 4 and 8 has changed; they both have to deliver their wheat a little bit further. Farmer 4 now delivers his wheat to collection point 2 instead of 1, and farmer 8 now delivers it directly to the production facility. These extra distances increase their individual transportation costs, the decrease in transportation costs further up the chain (less transport for the trader), improves the overall performance.

3.2.3. Step 2 – picking up

Now we introduce a new method of transporting the wheat from the farmers to the producer. Not only can the farmers deliver their wheat to a collection point or production facility, but the trader can also pick up the wheat from the farmers' location. The costs of picking up a truckload (and transporting it over 1 distance) lies between the previously identified transportation costs. The more professional transportation equipment of the trader yield a lower cost compared to the farmer's, but the smaller loads account for a higher cost compared to the bulk loads from the collection points.

Assumptions:

- Each farmer has exactly one full truckload of wheat
- The trader transports the wheat from the collection points to the production location
- The cost of transporting truck load over 1 distance by the by the trader for picking up is 100

Decisions:

- Should the farmer deliver the wheat to a location, or should the trader come and pick it up?
- To which location (collection points or production location) should each farmer deliver its wheat if it is not picked up by the trader?

Model:

$$\min C_{total} = \sum_{i=1}^{N} \left(\sum_{l=1}^{M} \sum_{p=1}^{O} x_{ilp} * \left(C_{farm} * d(i,l) + C_{trad} * d(l,p) \right) + \sum_{p=1}^{O} y_{ip} * \left(C_{farm} * d(i,p) \right) + \sum_{p=1}^{O} z_{ip} * \left(C_{pick} * d(i,p) \right) \right)$$

For every farmer minimise the costs of transporting the wheat:

- to a collection point and from there on to the production location, or
- directly to the production location, or
- by letting the trader pick it up

s.t.

$x_{ilp} = 0$ or 1 for $i = 1, \dots, N$ and $l = 1, \dots, M$

$y_{ip} = 0$ or 1 for $i = 1, \dots, N$ and $p = 1, \dots, O$

$z_{ip} = 0$ or 1 for $i = 1, \dots, N$ and $p = 1, \dots, O$

$\sum_{l=1}^{M} \sum_{p=1}^{O} x_{ilp} + \sum_{p=1}^{O} y_{ip} + \sum_{p=1}^{O} z_{ip} = 1$ for $i = 1, \dots, N$ each farmer has to deliver their wheat to either a collection point or a production facility, or get it picked up by the trader

with

$x_{ilp} = 1$ if farmer i delivers to collection point l, from where it is transported to production location p, else 0

$y_{ip} = 1$ if farmer i delivers to production location p, else 0

$z_{ip} = 1$ if trader picks up from farmer i to production location p, else 0

C_{farm} = costs of transporting truck load over 1 distance by the farmer = 120

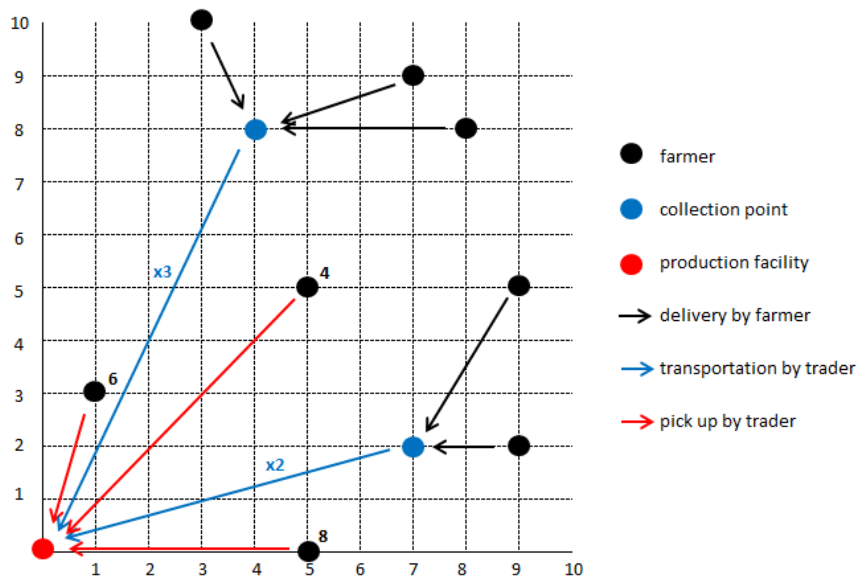
C_{trad} = costs of transporting truck load over 1 distance by the trader = 60

C_{pick} = costs of picking up truck load over 1 distance by the trader = 100

$d(i, l)$ = distance between farmer i and collection point l

$d(i, p)$ = distance between farmer i and production point p

$d(l, p)$ = distance between collection point l and production point p



The total costs equal: <u>7300</u>

As the cost of picking up is lower than the cost of delivery by the farmer, no farmer will deliver directly to the production location anymore. This is the case for farmers 6 and 8 in the picture above. Besides that, the wheat of farmer 4 is also picked up. The increased effort and coordination of the trader pays off in a better performance of the entire chain.

3.2.4. Step 3 – close collection point

Next we examine the mechanic of opening (or closing) a collection point. As the collection points themselves reduce the transportation costs, the model will always use the points. However, the points themselves also add costs to the entire chain. In this step we add costs to each point that is used, where wheat “flows through”. By adding a cost component to these points we let the model decide which collection point is viable and which point should not be used as the saving it provides for the transportation costs does not outweigh the fixed costs of keeping it open.

Assumptions:

- Each farmer has exactly one full truckload of wheat
- The trader transports the wheat from the collection points to the production location
- The costs of opening a collection point equals 600 (low estimate, but works for the indicative purpose of this step)

Decisions:

- Should the farmer deliver the wheat to a location, or should the trader come and pick it up?

- To which location (collection point or production location) should each farmer deliver its wheat if it is not picked up by the trader?

Model:

$$\min C_{total} = \sum_{i=1}^{N}\left(\sum_{l=1}^{M}\sum_{p=1}^{O} x_{ilp} * \left(C_{farm} * d(i,l) + C_{trad} * d(l,p)\right) + \sum_{p=1}^{O} y_{ip} * \left(C_{farm} * d(i,p)\right) + \sum_{p=1}^{O} z_{ip} * \left(C_{pick} * d(i,p)\right)\right) + \sum_{l=1}^{M} w_l * C_{col}$$

For every farmer minimise the costs of transporting the wheat:

- to a collection point and from there on to the production location, or
- directly to the production location, or
- by letting the trader pick it up
- and add the costs of keeping the used collection points open

s.t.

$x_{ilp} = 0 \text{ or } 1$ for $i = 1, \dots, N$ and $l = 1, \dots, M$

$y_{ip} = 0 \text{ or } 1$ for $i = 1, \dots, N$ and $p = 1, \dots, O$

$z_{ip} = 0 \text{ or } 1$ for $i = 1, \dots, N$ and $p = 1, \dots, O$

$w_l = 0 \text{ or } 1$ for $l = 1, \dots, M$

$\sum_{l=1}^{M}\sum_{p=1}^{O} x_{ilp} + \sum_{p=1}^{O} y_{ip} + \sum_{p=1}^{O} z_{ip} = 1$ for $i = 1, \dots, N$ each farmer has to deliver their wheat to either a collection point or a production facility, or get it picked up by the trader

$w_l \geq x_{ilp}$ for $i = 1, \dots, N$, $l = 1, \dots, M$ and $p = 1, \dots, O$

with

$x_{ilp} = 1$ if farmer i delivers to collection point l, from where it is transported to production location p, else 0

$y_{ip} = 1$ if farmer i delivers to production location p, else 0

$z_{ip} = 1$ if trader picks up from farmer i to production location p, else 0

$w_l = 1$ if the location point l is open (being used), else 0

C_{farm} = costs of transporting truck load over 1 distance by the farmer = 120

C_{trad} = costs of transporting truck load over 1 distance by the trader = 60

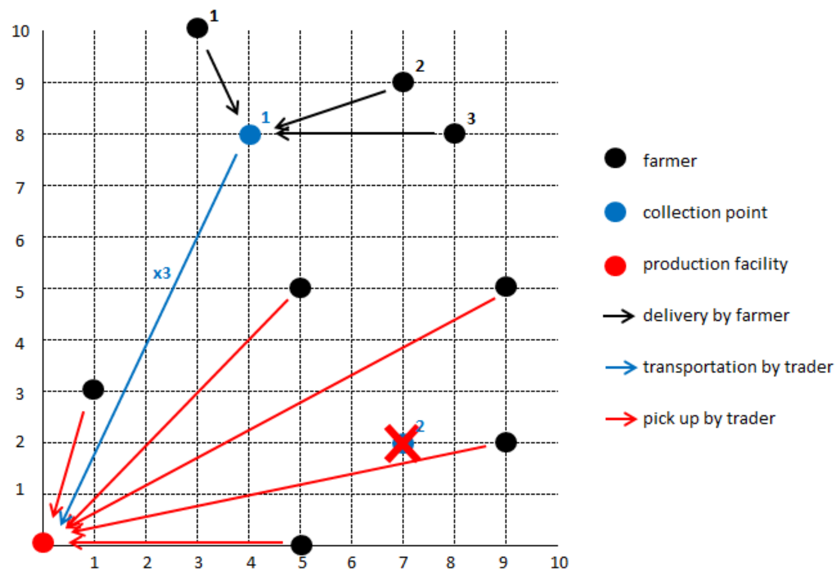
C_{pick} = costs of picking up truck load over 1 distance by the trader = 100

C_{col} = costs of opening a collection point = 600

$\mathrm{d(i,l)}$ = distance between farmer i and collection point l

$\mathrm{d(i,p)}$ = distance between farmer i and production point p

$\mathrm{d(l,p)}$ = distance between collection point l and production point p



The total costs equal: 8480

When incorporating the opening costs of 600 per collection point in the previous step, the total costs would have risen to 8500. By deciding to close collection point number 1, and having farmers 2 and 3 deliver their wheat to collection point 2 instead, the overall performance of the model improves.

However, closing or opening a collection point cannot be done overnight and is more often than not a strategic decision. Therefore, this addition to the model cannot be used while trying to find the optimal solution on a short term notice. It can be used to examine the effects of deciding to close a certain collection point for the next season for example. But only if the full costs (savings) of opening (closing) a collection point can be established with any degree of certainty (for example: how do you value the benefits of flexibility, proximity to farmers, capacity in the chain, etc.).

3.2.5. Step 4 – uneven wheat harvests

Previously we assumed that each farmer harvests the same amount of wheat (in # of truckloads). In this step we loosen this assumption and take a look into the effect that that has on the result of the model.

Assumptions:

- The farmers supply 0.5, 1 or 1.5 truckloads of wheat (total is still 8 full truckloads)

- Transportation costs are calculated by rounding up the transported quantity to the nearest integer, i.e. when a truck transports half a truckload, it still incurs the full cost as it would when transporting a full truckload.
- The trader transports the wheat from the collection points to the production location

Decisions:

- Should the farmer deliver the wheat to a location, or should the trader come and pick it up?
- To which location (collection point or production location) should each farmer deliver its wheat if it is not picked up by the trader?

Model:

$$\min C_{total} = \sum_{i=1}^{N} \left(\sum_{l=1}^{M} \sum_{p=1}^{O} x_{ilp} * \lceil A_i \rceil * \left(C_{farm} * d(i,l) \right) + \sum_{p=1}^{O} y_{ip} * \lceil A_i \rceil * \left(C_{farm} * d(i,p) \right) + \sum_{p=1}^{O} z_{ip} * \lceil A_i \rceil * \left(C_{pick} * d(i,p) \right) \right) + \sum_{l=1}^{M} \left(\sum_{l=1}^{N} \left\lceil \sum_{p=1}^{O} x_{ilp} * A_i \right\rceil * C_{trad} * d(l,p) \right)$$

For every farmer minimise the costs of transporting the wheat:

- to a collection point, or
- directly to the production location, or
- by letting the trader pick it up
- and add the costs of the trader transporting from the collection point to the production location

s.t.

$x_{ilp} = 0 \text{ or } 1$ for $i = 1, \dots, N$ and l = $1, \dots, M$

$y_{ip} = 0 \text{ or } 1$ for $i = 1, \dots, N$ and p = $1, \dots, O$

$z_{ip} = 0 \text{ or } 1$ for $i = 1, \dots, N$ and p = $1, \dots, O$

$\sum_{l=1}^{M} \sum_{p=1}^{O} x_{ilp} + \sum_{p=1}^{O} y_{ip} + \sum_{p=1}^{O} z_{ip} = 1$ for $i = 1, \dots, N$ each farmer has to deliver their wheat to either a collection point or a production facility, or get it picked up by the trader

with

$x_{ilp} = 1$ if farmer i delivers to collection point l, from where it is transported to production location p, else 0

$y_{ip} = 1$ if farmer i delivers to production location p, else 0

$z_{ip} = 1$ if trader picks up from farmer i to production location p, else 0

A_i = amount of full truckloads of wheat supplied by farmer i (0.5, 1 or 1.5)

C_{farm} = costs of transporting truck load over 1 distance by the farmer = 120

C_{trad} = costs of transporting truck load over 1 distance by the trader = 60

C_{pick} = costs of picking up truck load over 1 distance by the trader = 100

$\mathrm{d(i, l)}$ = distance between farmer i and collection point l

$\mathrm{d(i, p)}$ = distance between farmer i and production point p

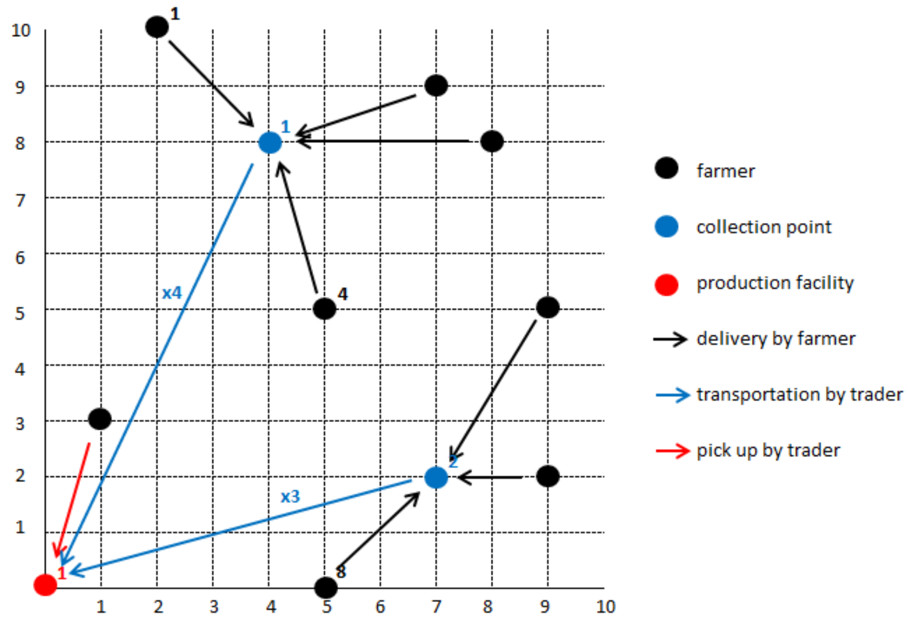
$\mathrm{d(l, p)}$ = distance between collection point l and production point p

Furthermore, we assume the following amounts of full truckloads of wheat for the farmers:

i	A
1	1.5
2	0.5
3	1.5
4	0.5
5	1
6	1
7	1.5
8	0.5

If we calculate the total costs of transporting these amounts of harvests using the resulting routes from the model of step 2, the total costs are: 9480.

But in that case some trucks only transport half a truckload. By using the model in this step, step 4, harvests are pooled to minimise spare truck transport.



The total costs equal: 9100

Farmer 4 originally had its harvest picked up by the trader. This would constitute one trip to farmer 4 (0.5 truckloads). However, now the harvests are pooled together at collection point 1. This results in the transports from collection point 1 to be fully utilised; in total 4 truckloads are transported from collection point 1 to the production location. Something similar happens with farmer 8. The trader still had half a truckload of spare transportation capacity from collection point 2, so his small harvest of 0.5 truckloads can be transported for free from that collection point.

This variation of the model can be further improved upon by allowing farmers to split up their harvests, and let it be transported through different channels. For example, let's say that we would have established in step 2 that it is cheaper for a truckload from farmer 1 to be picked up by the trader. Then we could allow a full truckload to be picked up, and the remainder (0.5 truckloads) to be pooled with the harvest from other farmers at collection point 1. So, by pooling the harvests, only the transport of residual truckloads will flow through different channels compared to step 2. However, this would offer little improvement in real life situations where harvests constitute many truckloads. On the other hand, in real life also the spare capacity may be much bigger. When the trader transports the collected harvest from a collection point to a production location by ship for example, a lot of truckloads can be transported for nearly zero costs if the ship has a lot of spare capacity.

Another expansion to this model is to allow farmers to pool their harvests together not only at collection points, but also at each other's location. This would effectively turn each farmer into a collection point, and the optimal solution to this model would reduce spare truck capacity even further.

3.2.6. Step 5 – collection point capacity

What would happen if the collection points had restrictions on the amount of wheat they could process? In this step we limit the amount of truckloads that can pass through a collection point.

Assumptions:

- The farmers supply 0.5, 1 or 1.5 truckloads of wheat
- Transportation costs are calculated by rounding up the transported quantity to the nearest integer, i.e. when a truck transports half a truckload, it still incurs the full cost as it would when transporting a full truckload.
- The trader transports the wheat from the collection points to the production location
- The collection points have a limited capacity (3 truckloads)

Decisions:

- Should the farmer deliver the wheat to a location, or should the trader come and pick it up?
- To which location (collection point or production location) should each farmer deliver its wheat if it is not picked up by the trader?

Model:

$$\min C_{total} = \sum_{i=1}^{N}\left(\sum_{l=1}^{M}\sum_{p=1}^{O} x_{ilp} * \lceil A_i \rceil * \left(C_{farm} * d(i,l)\right) + \sum_{p=1}^{O} y_{ip} * \lceil A_i \rceil * \left(C_{farm} * d(i,p)\right) + \sum_{p=1}^{O} z_{ip} * \lceil A_i \rceil * \left(C_{pick} * d(i,p)\right)\right) + \sum_{l=1}^{M}\left(\sum_{I=1}^{N}\left\lceil \sum_{p=1}^{O} x_{ilp} * A_i \right\rceil * C_{trad} * d(l,p)\right)$$

For every farmer minimise the costs of transporting the wheat:

- to a collection point, or
- directly to the production location, or
- by letting the trader pick it up
- and add the costs of the trader transporting from the collection point to the production location

s.t.

$x_{ilp} = 0 \text{ or } 1$ for $i = 1, \dots, N$ and $l = 1, \dots, M$

$y_{ip} = 0 \text{ or } 1$ for $i = 1, \dots, N$ and $p = 1, \dots, O$

$z_{ip} = 0 \text{ or } 1$ for $i = 1, \dots, N$ and $p = 1, \dots, O$

$\sum_{l=1}^{M}\sum_{p=1}^{O} x_{ilp} + \sum_{p=1}^{O} y_{ip} + \sum_{p=1}^{O} z_{ip} = 1$ for $i = 1, \dots, N$ each farmer has to deliver their wheat to

		either a collection point or a production facility, or get it picked up by the trader
$\sum_{i=1}^{N}\sum_{p=1}^{O} x_{ilp} * A_i \leq CAP_l$	for l$= 1, \ldots, M$	the harvests delivered to collection point l cannot exceed its capacity

with

$x_{ilp} = 1$ if farmer i delivers to collection point l, from where it is transported to production location p, else 0

$y_{ip} = 1$ if farmer i delivers to production location p, else 0

$z_{ip} = 1$ if trader picks up from farmer i to production location p, else 0

A_i = amount of full truckloads of wheat supplied by farmer i (0.5, 1 or 1.5)

C_{farm} = costs of transporting truck load over 1 distance by the farmer = 120

C_{trad} = costs of transporting truck load over 1 distance by the trader = 60

C_{pick} = costs of picking up truck load over 1 distance by the trader = 100

CAP_l = capacity of collection point l, $CAP_1 = CAP_2 = 3$

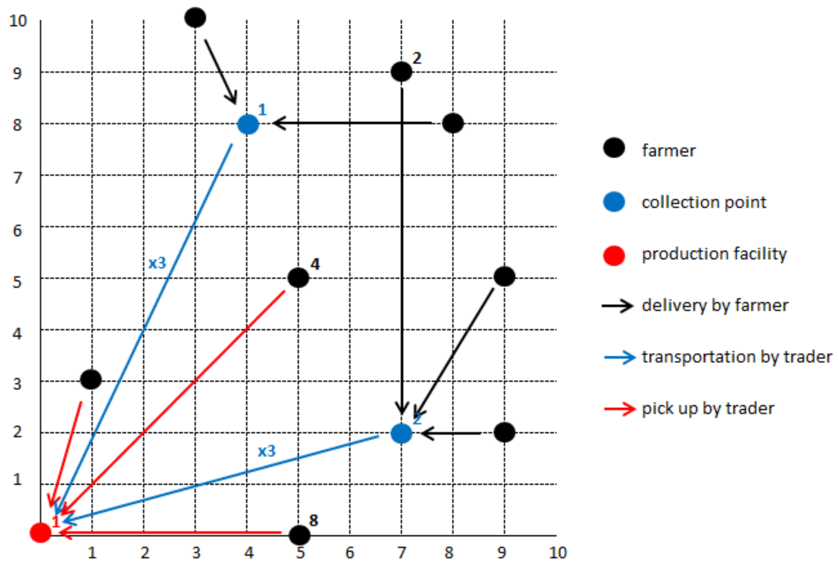
$d(i, l)$ = distance between farmer i and collection point l

$d(i, p)$ = distance between farmer i and production point p

$d(l, p)$ = distance between collection point l and production point p

Furthermore, we assume the following amounts of full truckloads of wheat for the farmers:

i	A
1	1.5
2	0.5
3	1.5
4	0.5
5	1
6	1
7	1.5
8	0.5



The total costs equal: <u>9280</u>

Both collection points operate at full capacity. The situation for farmers 2 and 4, who delivered their harvests to collection point 1 in the previous step, has changed. Farmer 4 has its harvest picked up, while farmer 2, who lies further away, has to deliver its harvest to collection point 2. This collection point was already at full capacity, forcing farmer 8 out of it and into picking up by the trader.

Again, this model could be improved upon by allowing farmers to split up their harvest and letting it be transported through different channels.

3.2.7. Step 6 – transportation capacity

Now we introduce the restriction that the trader only has a limited amount of truckloads it can transport. We can imagine that a limited amount of (hired) trucks pose restrictions on the amount of wheat that can be transported. If the model wants to exceed this limit, this will force farmers to start transporting their own wheat.

Assumptions:

- The farmers supply 0.5, 1 or 1.5 truckloads of wheat
- Transportation costs are calculated by rounding up the transported quantity to the nearest integer, i.e. when a truck transports half a truckload, it still incurs the full cost as it would when transporting a full truckload.
- The trader transports the wheat from the collection points to the production location
- The collection points have a limited capacity
- The trader has a limited capacity for both the transporting of wheat from the collection points and picking up (regardless of the distance of the transportation) (= 7 truckloads)

Decisions:

- Should the farmer deliver the wheat to a location, or should the trader come and pick it up?
- To which location (collection point or production location) should each farmer deliver its wheat if it is not picked up by the trader?

Model:

$$\min C_{total} = \sum_{i=1}^{N}\left(\sum_{l=1}^{M}\sum_{p=1}^{O} x_{ilp} * \lceil A_i \rceil * \left(C_{farm} * d(i,l)\right) + \sum_{p=1}^{O} y_{ip} * \lceil A_i \rceil * \left(C_{farm} * d(i,p)\right) + \sum_{p=1}^{O} z_{ip} * \lceil A_i \rceil * \left(C_{pick} * d(i,p)\right)\right) + \sum_{l=1}^{M}\left(\sum_{l=1}^{N}\left\lceil \sum_{p=1}^{O} x_{ilp} * A_i \right\rceil * C_{trad} * d(l,p)\right)$$

For every farmer minimise the costs of transporting the wheat:

- to a collection point, or
- directly to the production location, or
- by letting the trader pick it up
- and add the costs of the trader transporting from the collection point to the production location

s.t.

$x_{ilp} = 0 \text{ or } 1$ for $i = 1, \dots, N$ and $l = 1, \dots, M$

$y_{ip} = 0 \text{ or } 1$ for $i = 1, \dots, N$ and $p = 1, \dots, O$

$z_{ip} = 0 \text{ or } 1$ for $i = 1, \dots, N$ and $p = 1, \dots, O$

$\sum_{l=1}^{M}\sum_{p=1}^{O} x_{ilp} + \sum_{p=1}^{O} y_{ip} + \sum_{p=1}^{O} z_{ip} = 1$ for $i = 1, \dots, N$ each farmer has to deliver their wheat to either a collection point or a production facility, or get it picked up by the trader

$\sum_{i=1}^{N}\sum_{p=1}^{O} x_{ilp} * A_i \leq CAP_l$ for $l = 1, \dots, M$ the harvests delivered to collection point l cannot exceed its capacity

$\sum_{l=1}^{M}\left(\left\lceil \sum_{i=1}^{N}\sum_{p=1}^{O} x_{ilp} * A_i \right\rceil\right) + \sum_{p=1}^{O}\sum_{i=1}^{N} z_{ip} * \lceil A_i \rceil \leq CAP_{trans}$

the total transportation done by the trader cannot exceed its transportation capacity

with

$x_{ilp} = 1$ if farmer i delivers to collection point l, from where it is transported to production location p, else 0

$y_{ip} = 1$ if farmer i delivers to production location p, else 0

$z_{ip} = 1$ if trader picks up from farmer i to production location p, else 0

A_i = amount of full truckloads of wheat supplied by farmer i (0.5, 1 or 1.5)

C_{farm} = costs of transporting truck load over 1 distance by the farmer = 120

C_{trad} = costs of transporting truck load over 1 distance by the trader = 60

C_{pick} = costs of picking up truck load over 1 distance by the trader = 100

CAP_l = capacity of collection point l, $CAP_1 = CAP_2 = 3$

CAP_{trans} = capacity of transportation by the trader = 7

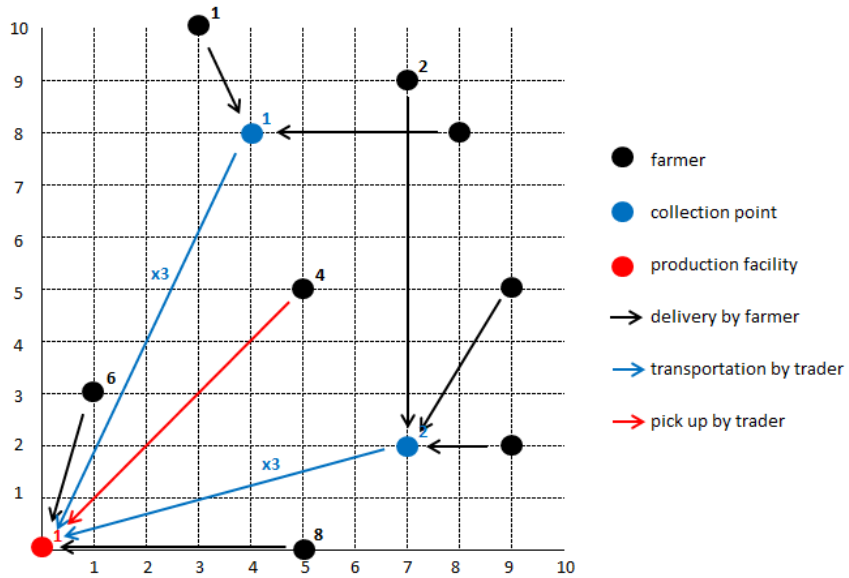
d(i, l) = distance between farmer i and collection point l

d(i, p) = distance between farmer i and production point p

d(l, p) = distance between collection point l and production point p

Furthermore, we assume the following amounts of full truckloads of wheat for the farmers:

i	A
1	1.5
2	0.5
3	1.5
4	0.5
5	1
6	1
7	1.5
8	0.5



The total costs equal: 9460

The solution to this step does not differ quite much from that of the precious step, step 5. One would expect that some of the trader's routes from step 5 would be changed into delivery routes for the farmers, and so is the case for farmers 6 and 8; their harvests are no longer picked up, but they have to deliver them themselves straight to the production location.

If we would increase the capacity of collection point 1 by 1 to a total of 4, we would get the same result as the solution to step 4, with one change. Farmer 8 would have to deliver its harvest himself, as the full transportation capacity of the trader is filled by transporting the harvests from both collection points to the production facility.

3.2.8. Overview

In the table below an overview of the different steps in the toy problem description is given. For each step the solution to the decision variables for each farmer is listed, as well as the value of the total costs.

		farmer								
phase	description	1	2	3	4	5	6	7	8	costs
step 0	current situation	col 1	col 1	col 1	col 1	col 2	prod	col 2	col 2	8100
↳ step 1	freedom of delivery	col 1	col 1	col 1	col 2	col 2	prod	col 2	prod	7620
↳ step 2	picking up	pick up	col 1	col 1	pick up	col 2	pick up	col 2	pick up	7300
↳ step 3	close collection point	pick up	col 2	col 2	pick up	col 2	pick up	col 2	pick up	8480
↳ step 4	uneven wheat harvests	col 1	col 1	col 1	col 1	col 2	pick up	col 2	col 2	9100
↳ step 5	collection point capacity	col 1	col 2	col 1	pick up	col 2	pick up	col 2	pick up	9280
↳ step 6	transportation capacity	pick up	col 1	col 1	col 2	col 2	prod	col 2	prod	9460

code	description	variable in model
col 1/2:	farmer transports to collection point 1/2	x
prod:	farmer transports to production location	y
pick up:	trader picks up at farmer	z

4. From model to practice

4.1. Introduction

In the previous chapter we used a toy problem to create models with increasing realism in order to optimise the logistical problem of getting the wheat harvests form the farmer to the trader. The steps of these models can now be applied to real life data. In doing so, two results are aimed for:

1. To validate the model. Do the theoretical savings from the subsequent steps of the toy problem correspond to the savings attained for the real life problem? Do the steps change the optimal solution significantly, or is the initial solution close to the subsequent optimums and does the model only increase in complexity without actually changing the end result?
2. To give an indication of possible savings. When the solution changes, so does the total costs of the network. The model can be used to give an indication of the total costs for each step with the real life data. Potential savings are interesting for both farmers and traders, which might want to capitalise on this and actually change the structure of their network. The insights of the possible savings within the steps can be used to provide a backbone for this decision making process.

The real life data of 2010 is used for the harvested amount from each farmer. It is assumed that the distance over which the wheat has to be transported is equal for all addresses within a four-digit postal code. For ease of modelling the harvests of the individual farmers are added up per four-digit postal codes. This results in 3454 unique farmers. In the remainder of this report, these totals will simply be referred to as the harvest of a "farmer". Through a data table the distances between any farmer, any collection point and any production facility (based on the respective postal codes) are calculated. Furthermore, the following costs per tonne transported over the corresponding distances are:

costs farmer		
km		
from	to	per tonne
0	20	€ 3.00
20	40	€ 5.40
40	60	€ 8.10
60	90	€ 12.15
90	120	€ 16.20
120	150	€ 20.25
150	180	€ 24.30
180	210	€ 28.35
210	240	€ 32.40
240	270	€ 36.45
270	300	€ 40.50
300	---	€ 45.00

costs trader		
km		
from	to	per tonne
0	20	€ 1.50
20	50	€ 3.00
50	100	€ 4.50
100	---	€ 6.00

costs pick-up		
km		
from	to	per tonne
0	20	€ 2.00
20	40	€ 3.60
40	60	€ 5.40
60	90	€ 8.10
90	120	€ 10.80
120	150	€ 13.50
150	180	€ 16.20
180	210	€ 18.90
210	240	€ 21.60
240	270	€ 24.30
270	300	€ 27.00
300	---	€ 30.00

These cost tables are combined with the previously constructed distance table to create new tables with the costs of transporting one tonne over every possible leg (combination of postal codes), and for each possible transportation method (farmer/trader/pick-up).

The simple solver used during the modelling of the toy problem quickly turned out to be unable to handle the much bigger dataset of the real life data. Therefore, a professional solving tool was selected: AIMMS. This program is used to calculate the consequences of the different steps as described below.

4.1.1. Step 0 – current situation

Recap: Farmers deliver their harvests to one of the trader's collection points or production locations (whichever is the nearest). The trader has to transport any of the wheat delivered to any of the collection points to the nearest production location.

Total costs: € 4,742,684

Results:

- 134 farmers deliver their harvest to a production location, 3320 farmers deliver to a collection point.
- Over 15.6 mln tonnekm are transported by the farmers, and over 22.3 mln tonnekm by the trader.

4.1.2. Step 1 – freedom of delivery

Recap: Instead of minimising only the first leg of transportation, the following route from the collection point to the production facility is also taken into account. The decision for the farmer to which collection point to deliver the harvest is thus based on the total costs of both transportation legs.

Total costs: € 4,178,793

Results:

- 1413 farmers deliver their harvest to a production location, 2041 farmers deliver to a collection point.
- Over 18.7 mln tonnekm are transported by the farmers, and over 18.1 mln tonnekm by the trader.

Comparison to previous step:

In this step around 40% of the farmers deliver their harvests directly to a production location; in the previous step this was less than 4%. This does force the farmers to transport around 20% more tonnekm, while decreasing the trader's total tonnekm by around 19%.

The total costs decrease by just over €349k.

4.1.3. Step 2 – picking up

Recap: In this step the trader is also allowed to pick up the harvests at the farmers and transport it directly to a production location. Since the costs of transportation by picking up are lower than the costs of delivering by the farmer, no farmer will deliver directly to a production location anymore.

Total costs: € 3,225,919

Results:

- 876 farmers deliver to a collection point, 2587 farmers have their harvest picked up by the trader
- Over 0.7 mln tonnekm are transported by the farmers, and over 8.1 mln tonnekm by the trader from the collection points, and over 24.2 mln tonnekm by picking up at the farmers.

Comparison to previous steps:

The trader transports the bulk of the harvest, as nearly 98% of all the tonnekm are on his account.

The total costs decrease by almost €953k.

4.1.4. Step 3 – close collection point

Recap: The feasibility of having a collection point open for business is taken into account. As having these collection points incurs a certain costs for the trader, the total result of the supply chain will improve if this factor is included in the calculation. However, the conclusions of the theoretical step 3 (chapter 3) is that closing a collection point is not a short term decision and that the costs of having it open is difficult to ascertain. However, we can calculate the increase in transportation costs when we limit the amount of collection points that is allowed to remain open. Note: The current situation is used as a starting point. The locations are fixed (cannot be moved), and no extra locations may be opened.

When we limit the amount of collection points that are allowed, we see the following results.

Total costs:

# collection points	total costs	index
34	€ 3,225,919	100.00
30	€ 3,225,919	100.00
25	€ 3,233,019	100.22
20	€ 3,239,683	100.43
15	€ 3,311,040	102.64
10	€ 3,316,668	102.81
5	€ 3,366,014	104.34
0	€ 3,412,677	105.79

We can see that the total transportation costs do not increase significantly when the number of allowed collection points decrease. This can be explained by the fact that the actual transportation cost of delivery by farmer and picking up by trader do not differ that much. It is only for the longer distances beneficial to make use of the collection points, so these points are now scarcely utilised.

4.1.5. Step 4 – uneven wheat harvests

Recap: This step was added to take any empty transportation space into account. It is assumed that the costs of transportation do not solely depend on the amount transported, but will also consist of a fixed component. A truck still has to traverse the total distance, with approximately the same time and effort, whether the truck is fully loaded or not.

However, the relevance of this factor in the used real life data is negligible. The dataset is totalised per postal code. Should the goal be to approach the actual current costs, then an average factor can be calculated and incorporated in the transportation costs per leg. Furthermore, any calculation based on actual quantities per farmer results in undesirable and volatile solutions over consequential time periods. The applicability of this factor in the real life model is unnameable.

4.1.6. Step 5 – collection point capacity

Recap: Previously the collection points had unlimited capacity. So, when the collection points are equipped with a limited capacity this could force the excess of transportation of wheat over these locations through a different route.

However, the collection points are in the current model not much utilised. Since most of the wheat is picked up by the trader, the collection point capacity is in no place stretched. In order to expect some changes in routings, the capacities should almost directly be put to zero. In this way the solution under step 3 is effectively recreated.

4.1.7. Step 6 – transportation capacity

Recap: As the trader does not possess an unlimited amount of transport capacity, this restriction can be put in the model. The trader has ownership of a limited amount of trucks, and has to make reservations for transportation capacity some weeks beforehand. The short term transportation capacity is fixed. Should this be exceeded by the demand for the trader's transport, then this will force certain farmers to deliver their wheat to a collection point instead of having it picked up.

In order to gain insight into the consequences of having a restricted transport capacity, we can take a look at reducing the amount of mln tonnekm available for the trader to "spend" on picking up. In step 2 it was calculated that the trader picked up wheat for a total of over 24.2 mln tonnekm, when we restrict this capacity we get the following results.

Total costs:

transport capacity (in mln tonne km)	total costs	index
25	€ 3,225,919	100.00
20	€ 3,369,543	104.45
15	€ 3,517,190	109.03
10	€ 3,728,037	115.57
5	€ 3,947,621	122.37
0	€ 4,178,793	129.54

The increase of the total cost from "no" capacity (solution from step 2), to zero capacity (solution from step 1) is relatively linear.

4.1.8. Results

When given free reins (compare step 2 with step 0), the model calculates a total savings of over € 1.5 mln, which comprises just under 32% of the total supply chain costs. Steps 3 through 6 restrict the possible solution and so the results worsen again. When taking a closer look at the calculated costs of the individual steps we can see that the biggest loss, or increase in costs, is realised in step 6. Over € 950k is spent again by reducing the transportation capacity of the trader.

5. Interpretation and consequences

5.1. Introduction

Now that the practice has been modelled, we can take a closer look at the results produced by the model. By analysing these results and the model itself, it is possible to examine to what extent the real-life situation might benefit from this optimisation. The consequences of the pre-made assumptions are also evaluated.

5.2. Model evaluation

The model is based on simplification of the real-life situation. The results obtained by this model provide an indication of the obtainable results of the real-life situation, but the following notions should be taken into account when projecting the model onto reality:

1. *Distribution of supply*

   The amounts to be transported are totalled per postal code in the model. The distances between different postal codes are averages; the actual distances will fluctuate around these values. Also, the number of farmers within a single postal code could influence the optimal decision for their particular situations. In the model, a single large farmer in one postal code is treated equally to multiple smaller ones in another (with the same total amount of harvest). When the supply chain is restructured, this could be taken into account. For instance by calculating different start-up costs for different transportation types, and considering the individual farmers instead of postal code totals.

2. *Timing of supply*

   The model does not consider the timing of the different harvested volumes. The transported quantities are the entire (year) volumes of the farmers. In reality, the demand for the transportation capacity is not distributed evenly over the year, but rather centred on the harvesting season. And within the season there are some peak capacity requirements, as shown in chapter 2. There is little flexibility to influence this as the goods are perishable.

3. *Costs of collection points*

   The effects on the transportation costs of having the (current) collection points remain open are calculated within the model. However, the costs of these collection points themselves are part of the entire supply chain, and should be taken into account when the real-life restructuring takes place. When considering the collection points, both the (yearly) operating costs and the once only costs of closing them have their influence on the setup. Note that closing a collection point may generate income (selling). While the operating costs can be put directly into the model, this is not easily done for once only costs (or profits) of closing. It can be done by recalculating them to a yearly impact, but it is better to consider each individual change in a business case. There, the consequences of either following or deviating from the model can be further investigated, weighed, and decided upon.

4. *Extra costs of shifts in solution*

   The model does not consider additional (once only) costs of changing the current situation. Perhaps some sort of planning department is required, or there is need for investing in extra transportation capacity or other infrastructure. Furthermore, the change itself will require time and effort form actors involved. The model provides an optimal solution, but the manner in which this solution is realised demands a detailed investigation in specific aspects. This should be done by drawing up detailed business cases for each required change.

These notions will only impact the actual (financial) results of model, but have limited influence on general direction or the idea of the solution itself. Thus, the improvements calculated and insights gained from the model remain valid. The individual changes and their consequences should be assessed separately. In case an impact is substantial, it might be wise to include this specific aspect into the model and to recalculate the optimal solution. However, special attention should be given on how to valuate once only costs versus periodical savings.

5.3. Business changes

In order to have the actors within the supply chain benefit from the proposed changes, some business processes currently installed will have to be adapted. Topics which need to be considered are:

1. *How can the supply chain savings be redistributed among all actors?*

   The model only takes the total transportation costs into account. Individual actors may be worse off in the proposed solution in comparison to the current situation. A division of the savings will have to take place to compensate those whose position declines.

2. *To what extent are actors prepared to actually change the current situation?*

   Even though the numbers add up to significant potential savings for the entire supply chain, the consequences for individual actors might be too much for them to handle. The actual, individual situations might not follow the general rules of thumb. There might be underlying causes which prevent individual actors to change, such as: extra costs, loss of autonomy, or even sheer stubbornness to change old habits. Even though these hurdles could be punished, the overall performance of the entire chain will wane.

3. *Should the setup be reviewed (on a one-year basis)?*

   The current proposed solution is tailored to historical data. When volumes change, so will the optimal solution. In an ideal situation this setup would be reviewed at least every year in order to make sure that the changing volumes do result in a changed (better) setup. What type of system should be put in place to monitor the performance, and on the basis of what arguments should the solution be changed? In other words: who would be the "owner" of this setup and what sort of responsibilities should this party have? Furthermore, the setup is based beforehand, based on predicted amounts. During the year these amounts may or may not be met. These deviations can be foreseen in some cases, and what should be done with this information?

6. Conclusions and recommendations

6.1. Conclusions

Now that we have finished modelling the problem and analysed the results and consequences of said model, we can answer the research question (and in doing so also provide the deliverables as mentioned in chapter 1.6):

Given a set of farmers and traders, how can a model be formulated to analyse and improve the performance of a harvest transport network between them?

While the original problem of the supply chain of the wheat harvest does seem complex at first sight, the model constructed and implemented in the previous chapters does provide valuable insight in potential savings. By simplifying the problem in a much smaller scale toy problem, the dynamics of this particular supply chain become clear.

Starting from this toy problem a simple model is drawn up. Step by step this model is expanded and more and more restrictions and boundaries are incorporated. Each step mimics an aspect of the real full scale problem. This process of building a model from the ground up and adding complexity along the way is laborious, but warrants robustness and ensures that the model is accurate. In the end, the final model is able to depict the full scale problem and identifies concrete savings to be made.

This result illustrates the potential of solid operations research. A concise approach to a real world problem reveals the dynamics within. When the cogs that make the clock tick are exposed, it is easy to identify which one to turn to attain the desired result. Thus it is possible to analyse a real world problem by using step by step modelling in operations research while imitating the problem on a smaller scale. It is even possible to make the model find the optimal solution itself, letting it decide which cogs to put into which position to obtain the optimal result.

However, it is impossible to model a complex problem without having to make some assumptions, or without some fencing off. This does impede on the trustworthiness of the final optimal solution. Some aspects are simply not taken into account, or deliberately limited to ensure workability of the model. By definition, it is hard to model soft constraints or complex value functions in operations research. The fact that our model provides a solution for every individual variable implies a certain degree of freedom and flexibility to change these in the real world. Perhaps this final level is of too much detail in order for the solution to be reliable. But then again, a similar approach can be done on a higher aggregated level. The implied hard and fixed results can be softened to provide an indication where the current situation can be improved upon.

6.2. Recommendations

This research aimed to provide numerical insights in the consequences of a change in wheat supply chain design. It comes up with an indication of potential savings which could be realised by shifting the decision making from the individual actors inside the chain, to an overview position. In order to complete the model and to be able to come to these figures, a couple assumptions had to be made. The results of this model can be strengthened by looking into these assumptions, and to expand or add to the model. For example: overhead costs are not taken into account. Closing (or opening!) collection points or production locations could be beneficial; but in order to calculate figures, actual costs have to be known.

But also softer aspects of this model require a closer look, as these raw results will have to be fine-tuned in order for them to be able to be used in the restructuring of the supply chain. To what extent are actors prepared to actually change the current situation? How can the supply chain savings be redistributed among all actors? Should the setup be reviewed on a one-year basis? How to deal with any fluctuation in amounts? So, even though this model provides a backbone of a more efficient situation and an estimation of the savings, the way of how to implement these specific changes, to what extent, and how to make certain that all actors reap its rewards, will have to be examined.

This research proves the concept of small scale, step by step model development in operation research. In order to translate the model to real life, to implement the decision changes and realise the expected results, a deeper understanding of the model will have to come alive among the actors involved. Business changes will have to be implemented in order to benefit from the proposed optimisation of the supply chain.

7. Epilogue

The model constructed in this thesis is tested with real life data. The company which has provided this data has already started a pilot of implementing the supply chain changes proposed by this investigation. Although no detailed calculation was made, the insight in the supply chain mechanics and potential savings led the trader to decide to start collecting the harvests. This culminated in a pilot project within Flevoland and the Noordoostpolder.

Initial results show great promise! The trader is able to organise a clear transportation plan and steady supply to its production plant. This has resulted in a substantial financial impact with benefits for all parties: the supply chain costs for the trader went down, and the price per tonne for the farmer went up. The only investment that had to be done by some farmers was to put down a concrete plateau from which the wheat could be picked up (in the few cases where this sort of facility was not already in place). The trader had to invest in a couple of trucks with mounted cranes to collect the harvest at farmers where no pick-up materiel (like shovels) was available.

8. Appendix A - Solver Models

8.1. Step 0 – current situation

This step minimises the costs for the individual farmers, so the actual costs for the entire chain is calculated within the constraint *totalcosts*. The actual decision variables are *FarmToColToProd(i,l,p)*, which is 1 if the harvest is delivered by farmer i to collection point l, and from there on transported to production location p, and *FarmToProd(i,p)*, which is 1 if farmer i delivers its harvest directly to production point p.

The parameters consist of the different types of transportation costs (for farmers and traders) and the different types of distances (between farmers, collection points and production locations). Note that a second production location has been modelled, but its large distance ensures no transportation to it.

```
SETS
  i in Farmer;                 // the farmers
  l in CollectionPoint;        // the collection points
  p in ProductionFacility;     // the production locations

PARAMETERS
  Distance1(i,l);              // the distance between farmers and collection points
  Distance2(l,p);              // the distance between collection points and production locations
  Distance3(i,p);              // the distance between farmers and production locations
  CostFarmer;                  // the costs per truckload per distance for transport by a farmer
  CostTrader;                  // the costs per truckload per distance for transport by a trader from a collection point

VARIABLES
  FarmToColToProd(i,l,p):{0,1};// if farmer i delivers to collection point l, and from there on to production location p, then 1 otherwise 0
  FarmToProd(i,p):{0,1};       // if farmer i delivers directly to production location p, then 1 otherwise 0
  TotalCosts : {0,inf};        // dummy to calculate total costs

CONSTRAINTS
  decisiondeliver(i):          // every farmer has to deliver either to a collection point, or to a production location
     sum[(l,p), FarmToColToProd(i,l,p)] + sum[(p), FarmToProd(i,p)] = 1 ;

  totalcosts:                  // this step, step 0, only minimises the costs for the farmers,
                               // this constraint calculates the total costs in the chain
    sum[(i,l,p), FarmToColToProd(i,l,p) * (Distance1(i,l) * CostFarmer + Distance2(l,p) * CostTrader)]
  + sum[(i,p), FarmToProd(i,p) * Distance3(i,p) * CostFarmer] = TotalCosts ;


MINIMIZE                       // the costs for farmers to deliver to collection points
                               // the costs for farmers to deliver directly to production locations
    sum[(i,l,p), FarmToColToProd(i,l,p) * (Distance1(i,l) * CostFarmer)]
  + sum[(i,p), FarmToProd(i,p) * Distance3(i,p) * CostFarmer]
    ;


SETSDATA
  Farmer : {i1..i8};
  CollectionPoint : {l1,l2};
  ProductionFacility : {p1,p2};

PARAMETERSDATA
  Distance1(i,l):
  i1 l1 3
  i2 l1 4
  i3 l1 4
  i4 l1 4
  i5 l1 8
  i6 l1 8
  i7 l1 11
  i8 l1 9
  i1 l2 12
  i2 l2 7
  i3 l2 7
  i4 l2 5
  i5 l2 5
  i6 l2 7
  i7 l2 2
  i8 l2 4;
  Distance2(l,p):
  l1 p1 12
  l2 p1 9
  l1 p2 9999
  l2 p2 9999;
```

```
Distance3(i,p):
i1 p1 13
i2 p1 18
i3 p1 16
i4 p1 10
i5 p1 14
i6 p1 4
i7 p1 11
i8 p1 5
i1 p2 9999
i2 p2 9999
i3 p2 9999
i4 p2 9999
i5 p2 9999
i6 p2 9999
i7 p2 9999
i8 p2 9999;
CostFarmer: 120;
CostTrader: 60;
```

8.2.Step 1 – freedom of delivery

This model has the same parameters and variables as the model from step 0. But this time the total costs of the entire chain are minimised, and not just those of the farmers.

```
SETS
  i in Farmer;                  // the farmers
  l in CollectionPoint;         // the collection points
  p in ProductionFacility;      // the production locations

PARAMETERS
  Distance1(i,l);               // the distance between farmers and collection points
  Distance2(l,p);               // the distance between collection points and production locations
  Distance3(i,p);               // the distance between farmers and production locations
  CostFarmer;                   // the costs per truckload per distance for transport by a farmer
  CostTrader;                   // the costs per truckload per distance for transport by a trader from a collection point

VARIABLES
  FarmToColToProd(i,l,p):{0,1};// if farmer i delivers to collection point l, and from there on to production location p, then 1 otherwise 0
  FarmToProd(i,p):{0,1};        // if farmer i delivers directly to production location p, then 1 otherwise 0

CONSTRAINTS
  decisiondeliver(i):           // every farmer has to deliver either to a collection point, or to a production location
     sum[(l,p), FarmToColToProd(i,l,p)] + sum[(p), FarmToProd(i,p)] = 1 ;

MINIMIZE
                                // the costs for farmers to deliver to collection points, and from there on to the production location
                                // the costs for farmers to deliver directly to production locations
    sum[(i,l,p), FarmToColToProd(i,l,p) * (Distance1(i,l) * CostFarmer + Distance2(l,p) * CostTrader)]
  + sum[(i,p), FarmToProd(i,p) * Distance3(i,p) * CostFarmer]  ;

SETSDATA
  Farmer : {i1..i8};
  CollectionPoint : {l1,l2};
  ProductionFacility : {p1,p2};

PARAMETERSDATA
  Distance1(i,l):
  i1 l1 3
  i2 l1 4
  i3 l1 4
  i4 l1 4
  i5 l1 8
  i6 l1 8
  i7 l1 11
  i8 l1 9
  i1 l2 12
  i2 l2 7
  i3 l2 7
  i4 l2 5
  i5 l2 5
  i6 l2 7
  i7 l2 2
  i8 l2 4;
  Distance2(l,p):
  l1 p1 12
  l2 p1 9
  l1 p2 9999
  l2 p2 9999;
  Distance3(i,p):
  i1 p1 13
  i2 p1 18
  i3 p1 16
  i4 p1 10
  i5 p1 14
  i6 p1 4
  i7 p1 11
  i8 p1 5
  i1 p2 9999
  i2 p2 9999
  i3 p2 9999
  i4 p2 9999
  i5 p2 9999
  i6 p2 9999
  i7 p2 9999
  i8 p2 9999;
  CostFarmer: 120;
  CostTrader: 60;
```

8.3.Step 2 – picking up

An extra variable is introduced: FarmPickUp(i,p) is 1 if farmer i has its harvest picked up and transported to production location p. The costs of picking up are captured in the parameter *CostPickUp*.

```
SETS
  i in Farmer;                  // the farmers
  l in CollectionPoint;         // the collection points
  p in ProductionFacility;      // the production locations

PARAMETERS
  Distance1(i,l);               // the distance between farmers and collection points
  Distance2(l,p);               // the distance between collection points and production locations
  Distance3(i,p);               // the distance between farmers and production locations
  CostFarmer;                   // the costs per truckload per distance for transport by a farmer
  CostTrader;                   // the costs per truckload per distance for transport by a trader from a collection point
  CostPickUp;                   // the costs per truckload per distance for transport by a trader from a farmer (pick up)

VARIABLES
  FarmToColToProd(i,l,p):{0,1};// if farmer i delivers to collection point l, and from there on to production location p, then 1 otherwise 0
  FarmToProd(i,p):{0,1};        // if farmer i delivers directly to production location p, then 1 otherwise 0
  FarmPickUp(i,p):{0,1};        // if farmer i has its produce picked up by production location p, then 1 otherwise 0

CONSTRAINTS
  decisiondeliver(i):           // every farmer has to deliver either to a collection point, or to a production location, or have it picked up
     sum[(l,p), FarmToColToProd(i,l,p)] + sum[(p), FarmToProd(i,p)] + sum[(p), FarmPickUp(i,p)] = 1 ;

MINIMIZE
                                // the costs for farmers to deliver to collection points, and from there on to the production location
                                // the costs for farmers to deliver directly to production locations
                                // the costs for traders to pick up from farmers
    sum[(i,l,p), FarmToColToProd(i,l,p) * (Distance1(i,l) * CostFarmer + Distance2(l,p) * CostTrader)]
  + sum[(i,p), FarmToProd(i,p) * Distance3(i,p) * CostFarmer]
  + sum[(i,p), FarmPickUp(i,p) * Distance3(i,p) * CostPickUp]   ;

SETSDATA
  Farmer : {i1..i8};
  CollectionPoint : {l1,l2};
  ProductionFacility : {p1,p2};

PARAMETERSDATA
  Distance1(i,l):
  i1 l1 3
  i2 l1 4
  i3 l1 4
  i4 l1 4
  i5 l1 8
  i6 l1 8
  i7 l1 11
  i8 l1 9
  i1 l2 12
  i2 l2 7
  i3 l2 7
  i4 l2 5
  i5 l2 5
  i6 l2 7
  i7 l2 2
  i8 l2 4;
  Distance2(l,p):
  l1 p1 12
  l2 p1 9
  l1 p2 9999
  l2 p2 9999;
  Distance3(i,p):
  i1 p1 13
  i2 p1 18
  i3 p1 16
  i4 p1 10
  i5 p1 14
  i6 p1 4
  i7 p1 11
  i8 p1 5
  i1 p2 9999
  i2 p2 9999
  i3 p2 9999
  i4 p2 9999
  i5 p2 9999
  i6 p2 9999
  i7 p2 9999
  i8 p2 9999;
  CostFarmer: 120;
  CostTrader: 60;
  CostPickUp: 100;
```

8.4.Step 3 – closing collection point

An extra variable is introduced: *OpenCol(l)*, which is 1 when a collection point is used/opened. In the goal function this variable is penalised with the costs associated to opening a collection point *CostOpenCol*. A constraint with the Big M ensures that when a harvest flows through a collection point, this collection point is opened.

```
SETS
  i in Farmer;                    // the farmers
  l in CollectionPoint;           // the collection points
  p in ProductionFacility;        // the production locations

PARAMETERS
  Distance1(i,l);                 // the distance between farmers and collection points
  Distance2(l,p);                 // the distance between collection points and production locations
  Distance3(i,p);                 // the distance between farmers and production locations
  CostFarmer;                     // the costs per truckload per distance for transport by a farmer
  CostTrader;                     // the costs per truckload per distance for transport by a trader from a collection point
  CostPickUp;                     // the costs per truckload per distance for transport by a trader from a farmer (pick up)
  CostOpenCol;                    // the costs of opening a collection point
  BigM;                           // large number

VARIABLES
  FarmToColToProd(i,l,p):{0,1};// if farmer i delivers to collection point l, and from there on to production location p, then 1 otherwise 0
  FarmToProd(i,p):{0,1};          // if farmer i delivers directly to production location p, then 1 otherwise 0
  FarmPickUp(i,p):{0,1};          // if farmer i has its produce picked up by production location p, then 1 otherwise 0
  OpenCol(l):{0,1};               // if collection point l is open (used), then 1 otherwise 0

CONSTRAINTS
  decisiondeliver(i):             // every farmer has to deliver either to a collection point, or to a production location, or have it picked up
     sum[(l,p), FarmToColToProd(i,l,p)] + sum[(p), FarmToProd(i,p)] + sum[(p), FarmPickUp(i,p)] = 1 ;

  openingcol(l):                  // when a harvest flows through collection point l, open it
     sum[(i,p), FarmToColToProd(i,l,p)] <=  (OpenCol(l) * BigM);

MINIMIZE
                                  // the costs for farmers to deliver to collection points, and from there on to the production location
                                  // the costs for farmers to deliver directly to production locations
                                  // the costs for traders to pick up from farmers
                                  // the costs of opening (using) a collection point
    sum[(i,l,p), FarmToColToProd(i,l,p) * (Distance1(i,l) * CostFarmer + Distance2(l,p) * CostTrader)]
  + sum[(i,p), FarmToProd(i,p) * Distance3(i,p) * CostFarmer]
  + sum[(i,p), FarmPickUp(i,p) * Distance3(i,p) * CostPickUp]
  + sum[(l), OpenCol(l) * CostOpenCol]   ;

SETSDATA
  Farmer : {i1..i8};
  CollectionPoint : {l1,l2};
  ProductionFacility : {p1,p2};

PARAMETERSDATA
  Distance1(i,l):
  i1 l1 3
  i2 l1 4
  i3 l1 4
  i4 l1 4
  i5 l1 8
  i6 l1 8
  i7 l1 11
  i8 l1 9
  i1 l2 12
  i2 l2 7
  i3 l2 7
  i4 l2 5
  i5 l2 5
  i6 l2 7
  i7 l2 2
  i8 l2 4;
  Distance2(l,p):
  l1 p1 12
  l2 p1 9
  l1 p2 9999
  l2 p2 9999;
  Distance3(i,p):
  i1 p1 13
  i2 p1 18
  i3 p1 16
  i4 p1 10
  i5 p1 14
  i6 p1 4
  i7 p1 11
  i8 p1 5
  i1 p2 9999
  i2 p2 9999
  i3 p2 9999
  i4 p2 9999
  i5 p2 9999
  i6 p2 9999
  i7 p2 9999
  i8 p2 9999;
  CostFarmer: 120;
  CostTrader: 60;
  CostPickUp: 100;
  CostOpenCol: 600;
  BigM: 9999;
```

8.5.Step 4 – uneven wheat harvests

The new parameter *Quantity(i)*, indicating the harvested quantity per farmer, has to be rounded up for the different types of transportation. The three constraints *totalfromfarm/2/3* force the new variables *FarmToColToPro2(i,l,p)*, *FarmToProd2(i,p)* and *FarmPickUp(i,p)* to do just that. These new variables substitute the old ones in the goal function.

And since the number of trucks delivering to a collection point does not have to equal the number of trucks transporting the total from there to a production location, the cost aspects are split up in the goal function.

```
SETS
  i in Farmer;                  // the farmers
  l in CollectionPoint;         // the collection points
  p in ProductionFacility;      // the production locations

PARAMETERS
  Distance1(i,l);               // the distance between farmers and collection points
  Distance2(l,p);               // the distance between collection points and production locations
  Distance3(i,p);               // the distance between farmers and production locations
  CostFarmer;                   // the costs per truckload per distance for transport by a farmer
  CostTrader;                   // the costs per truckload per distance for transport by a trader from a collection point
  CostPickUp;                   // the costs per truckload per distance for transport by a trader from a farmer (pick up)
  Quantity(i);                  // amount of wheat produces by farmer i, in truckloads
VARIABLES
  FarmToColToProd(i,l,p):{0,1};// if farmer i delivers to collection point l, and from there on to production location p, then 1 otherwise 0
  FarmToColToPro2(i,l,p):{0,inf};// integer number of trucks farmer i delivers to collection point l, and from there on to production location p
  FarmToProd(i,p):{0,1};        // if farmer i delivers directly to production location p, then 1 otherwise 0
  FarmToProd2(i,p):{0,inf};     // integer number of trucks farmer i delivers directly to production location p
  FarmPickUp(i,p):{0,1};        // if farmer i has its produce picked up by production location p, then 1 otherwise 0
  FarmPickUp2(i,p):{0,inf};     // integer number of trucks farmer i has its produce picked up by production location p
  NumberOfTruckCol(l,p):{0,inf};// integer number of trucks to transport from collection point l to production location p

CONSTRAINTS
  decisiondeliver(i):           // every farmer has to deliver either to a collection point, or to a production location, or have it picked up
     sum[(l,p), FarmToColToProd(i,l,p)] + sum[(p), FarmToProd(i,p)] + sum[(p), FarmPickUp(i,p)] = 1 ;

  totaltocollection(l,p):       // volume transported from collection point l to production location p, in # of truckloads rounded up
     sum[(i), FarmToColToProd(i,l,p) * Quantity(i)] <= NumberOfTruckCol(l,p);

  totalfromfarm(i,l,p):         // volume that flows from farmer i to collection point l, and from there on to production location p, in # of truc
    (FarmToColToProd(i,l,p) * Quantity(i)) <= FarmToColToPro2(i,l,p);

  totalfromfarm2(i,p):          // volume that farmer i delivers directly to production location p, in # of truckloads rounded up
    (FarmToProd(i,p) * Quantity(i)) <= FarmToProd2(i,p);

  totalfromfarm3(i,p):          // volume that is picked up from farmer i to production location p, in # of truckloads rounded up
    (FarmPickUp(i,p) * Quantity(i)) <= FarmPickUp2(i,p);

MINIMIZE
                                // the costs for farmers to deliver to collection points
                                // the costs for the trader to transport from collection point to production location
                                // the costs for farmers to deliver directly to production locations
                                // the costs for traders to pick up from farmers
    sum[(i,l,p), FarmToColToPro2(i,l,p) * Distance1(i,l) * CostFarmer]
  + sum[(l,p), NumberOfTruckCol(l,p)  * Distance2(l,p) * CostTrader]
  + sum[(i,p), FarmToProd2(i,p) * Distance3(i,p) * CostFarmer]
  + sum[(i,p), FarmPickUp2(i,p) * Distance3(i,p) * CostPickUp]  ;

SETSDATA
  Farmer : {i1..i8};
  CollectionPoint : {l1,l2};
  ProductionFacility : {p1,p2};

PARAMETERSDATA
  Distance1(i,l):
  i1 l1 3
  i2 l1 4
  i3 l1 4
  i4 l1 4
  i5 l1 8
  i6 l1 8
  i7 l1 11
  i8 l1 9
  i1 l2 12
  i2 l2 7
  i3 l2 7
  i4 l2 5
  i5 l2 5
  i6 l2 7
  i7 l2 2
  i8 l2 4;
  Distance2(l,p):
  l1 p1 12
  l2 p1 9
  l1 p2 9999
  l2 p2 9999;
```

```
Distance3(i,p):
i1 p1 13
i2 p1 18
i3 p1 16
i4 p1 10
i5 p1 14
i6 p1 4
i7 p1 11
i8 p1 5
i1 p2 9999
i2 p2 9999
i3 p2 9999
i4 p2 9999
i5 p2 9999
i6 p2 9999
i7 p2 9999
i8 p2 9999;
CostFarmer: 120;
CostTrader: 60;
CostPickUp: 100;
Quantity(i):
i1 1.5
i2 0.5
i3 1.5
i4 0.5
i5 1
i6 1
i7 1.5
i8 0.5;
```

8.6.Step 5 – collection point capacity

The total volume of the harvests delivered to collection points cannot exceed the capacity at these points. An extra restriction forces the *NumberOfTruckCol(l)* to be less than, or equal to this capacity *ColCap*.

```
SETS
  i in Farmer;                 // the farmers
  l in CollectionPoint;        // the collection points
  p in ProductionFacility;     // the production locations

PARAMETERS
  Distance1(i,l);              // the distance between farmers and collection points
  Distance2(l,p);              // the distance between collection points and production locations
  Distance3(i,p);              // the distance between farmers and production locations
  Distance4(l);                // the distance between collection points and production location 1
  CostFarmer;                  // the costs per truckload per distance for transport by a farmer
  CostTrader;                  // the costs per truckload per distance for transport by a trader from a collection point
  CostPickUp;                  // the costs per truckload per distance for transport by a trader from a farmer (pick up)
  Quantity(i);                 // amount of wheat produces by farmer i, in truckloads
  ColCap(l);                   // capacity of collection point l

VARIABLES
  FarmToColToProd(i,l,p):{0,1};// if farmer i delivers to collection point l, and from there on to production location p, then 1 otherwise 0
  FarmToColToPro2(i,l,p):{0,inf};// integer number of trucks farmer i delivers to collection point l, and from there on to production location p
  FarmToProd(i,p):{0,1};       // if farmer i delivers directly to production location p, then 1 otherwise 0
  FarmToProd2(i,p):{0,inf};    // integer number of trucks farmer i delivers directly to production location p
  FarmPickUp(i,p):{0,1};       // if farmer i has its produce picked up by production location p, then 1 otherwise 0
  FarmPickUp2(i,p):{0,inf};    // integer number of trucks farmer i has its produce picked up by production location p
  NumberOfTruckCol(l,p):{0,inf};// integer number of trucks to transport from collection point l  to production location p

CONSTRAINTS
  decisiondeliver(i):          // every farmer has to deliver either to a collection point, or to a production location, or have it picked up
     sum[(l,p), FarmToColToProd(i,l,p)] + sum[(p), FarmToProd(i,p)] + sum[(p), FarmPickUp(i,p)] = 1 ;

  totaltocollection(l,p):      // volume transported from collection point l to production location p, in # of truckloads rounded up
     sum[(i), FarmToColToProd(i,l,p) * Quantity(i)] <= NumberOfTruckCol(l,p);

  totalfromfarm(i,l,p):        // volume that flows from farmer i to collection point l, and from there on to production location p, in # of truc
    (FarmToColToProd(i,l,p) * Quantity(i)) <= FarmToColToPro2(i,l,p);

  totalfromfarm2(i,p):         // volume that farmer i delivers directly to production location p, in # of truckloads rounded up
    (FarmToProd(i,p) * Quantity(i)) <= FarmToProd2(i,p);

  totalfromfarm3(i,p):         // volume that is picked up from farmer i to production location p, in # of truckloads rounded up
    (FarmPickUp(i,p) * Quantity(i)) <= FarmPickUp2(i,p);

  collectioncapacity(l):       // the produce delivered at collection point l cannot exceed its capacity
     sum[(p), NumberOfTruckCol(l,p)] <= ColCap(l);

MINIMIZE
                               // the costs for farmers to deliver to collection points
                               // the costs for the trader to transport from collection point to production location
                               // the costs for farmers to deliver directly to production locations
                               // the costs for traders to pick up from farmers
    sum[(i,l,p), FarmToColToPro2(i,l,p) * Distance1(i,l) * CostFarmer]
  + sum[(l,p), NumberOfTruckCol(l,p)  * Distance2(l,p) * CostTrader]
  + sum[(i,p), FarmToProd2(i,p) * Distance3(i,p) * CostFarmer]
  + sum[(i,p), FarmPickUp2(i,p) * Distance3(i,p) * CostPickUp]   ;
```

```
SETSDATA
  Farmer : {i1..i8};
  CollectionPoint : {l1,l2};
  ProductionFacility : {p1,p2};

PARAMETERSDATA
  Distance1(i,l):
  i1 l1 3
  i2 l1 4
  i3 l1 4
  i4 l1 4
  i5 l1 8
  i6 l1 8
  i7 l1 11
  i8 l1 9
  i1 l2 12
  i2 l2 7
  i3 l2 7
  i4 l2 5
  i5 l2 5
  i6 l2 7
  i7 l2 2
  i8 l2 4;
  Distance2(l,p):
  l1 p1 12
  l2 p1 9
  l1 p2 9999
  l2 p2 9999;
  Distance3(i,p):
  i1 p1 13
  i2 p1 18
  i3 p1 16
  i4 p1 10
  i5 p1 14
  i6 p1 4
  i7 p1 11
  i8 p1 5
  i1 p2 9999
  i2 p2 9999
  i3 p2 9999
  i4 p2 9999
  i5 p2 9999
  i6 p2 9999
  i7 p2 9999
  i8 p2 9999;
  CostFarmer: 120;
  CostTrader: 60;
  CostPickUp: 100;
  Quantity(i):
  i1 1.5
  i2 0.5
  i3 1.5
  i4 0.5
  i5 1
  i6 1
  i7 1.5
  i8 0.5;
  ColCap(l):
  l1 3
  l2 3;
```

8.7. Step 6 – transportation capacity

In this step an extra constraint is introduced, based on the parameter *TransCap*. This constricts the amount of truck movements made by the trader.

```
SETS
  i in Farmer;                 // the farmers
  l in CollectionPoint;        // the collection points
  p in ProductionFacility;     // the production locations

PARAMETERS
  Distance1(i,l);              // the distance between farmers and collection points
  Distance2(l,p);              // the distance between collection points and production locations
  Distance3(i,p);              // the distance between farmers and production locations
  CostFarmer;                  // the costs per truckload per distance for transport by a farmer
  CostTrader;                  // the costs per truckload per distance for transport by a trader from a collection point
  CostPickUp;                  // the costs per truckload per distance for transport by a trader from a farmer (pick up)
  Quantity(i);                 // amount of wheat produces by farmer i, in truckloads
  ColCap(l);                   // capacity of collection point l
  TransCap;                    // capacity of transportation by the trader

VARIABLES
  FarmToColToProd(i,l,p):{0,1};// if farmer i delivers to collection point l, and from there on to production location p, then 1 otherwise 0
  FarmToColToPro2(i,l,p):{0,inf};// integer number of trucks farmer i delivers to collection point l, and from there on to production location p
  FarmToProd(i,p):{0,1};       // if farmer i delivers directly to production location p, then 1 otherwise 0
  FarmToProd2(i,p):{0,inf};    // integer number of trucks farmer i delivers directly to production location p
  FarmPickUp(i,p):{0,1};       // if farmer i has its produce picked up by production location p, then 1 otherwise 0
  FarmPickUp2(i,p):{0,inf};    // integer number of trucks farmer i has its produce picked up by production location p
  NumberOfTruckCol(l,p):{0,inf};// integer number of trucks to transport from collection point l  to production location p
```

```
CONSTRAINTS
  decisiondeliver(i):           // every farmer has to deliver either to a collection point, or to a production location, or have it picked up
     sum[(l,p), FarmToColToProd(i,l,p)] + sum[(p), FarmToProd(i,p)] + sum[(p), FarmPickUp(i,p)] = 1 ;

  totaltocollection(l,p):       // volume transported from collection point l to production location p, in # of truckloads rounded up
     sum[(i), FarmToColToProd(i,l,p) * Quantity(i)] <= NumberOfTruckCol(l,p);

  totalfromfarm(i,l,p):         // volume that flows from farmer i to collection point l, and from there on to production location p, in # of truc
    (FarmToColToProd(i,l,p) * Quantity(i)) <= FarmToColToPro2(i,l,p);

  totalfromfarm2(i,p):          // volume that farmer i delivers directly to production location p, in # of truckloads rounded up
    (FarmToProd(i,p) * Quantity(i)) <= FarmToProd2(i,p);

  totalfromfarm3(i,p):          // volume that is picked up from farmer i to production location p, in # of truckloads rounded up
    (FarmPickUp(i,p) * Quantity(i)) <= FarmPickUp2(i,p);

  collectioncapacity(l):        // the produce delivered at collection point l cannot exceed its capacity
     sum[(p), NumberOfTruckCol(l,p)] <= ColCap(l);

  transportationcapacity:       // the number of trucks used by the trader cannot exceed the capacity
    sum[(i,p), FarmPickUp2(i,p)] + sum[(l,p), NumberOfTruckCol(l,p)]<= TransCap;


MINIMIZE
                                // the costs for farmers to deliver to collection points
                                // the costs for the trader to transport from collection point to production location
                                // the costs for farmers to deliver directly to production locations
                                // the costs for traders to pick up from farmers
    sum[(i,l,p), FarmToColToPro2(i,l,p) * Distance1(i,l) * CostFarmer]
  + sum[(l,p), NumberOfTruckCol(l,p)  * Distance2(l,p) * CostTrader]
  + sum[(i,p), FarmToProd2(i,p) * Distance3(i,p) * CostFarmer]
  + sum[(i,p), FarmPickUp2(i,p) * Distance3(i,p) * CostPickUp]   ;

SETSDATA
  Farmer : {i1..i8};
  CollectionPoint : {l1,l2};
  ProductionFacility : {p1,p2};

PARAMETERSDATA
  Distance1(i,l):
  i1 l1 3
  i2 l1 4
  i3 l1 4
  i4 l1 4
  i5 l1 8
  i6 l1 8
  i7 l1 11
  i8 l1 9
  i1 l2 12
  i2 l2 7
  i3 l2 7
  i4 l2 5
  i5 l2 5
  i6 l2 7
  i7 l2 2
  i8 l2 4;
  Distance2(l,p):
  l1 p1 12
  l2 p1 9
  l1 p2 9999
  l2 p2 9999;

  Distance3(i,p):
  i1 p1 13
  i2 p1 18
  i3 p1 16
  i4 p1 10
  i5 p1 14
  i6 p1 4
  i7 p1 11
  i8 p1 5
  i1 p2 9999
  i2 p2 9999
  i3 p2 9999
  i4 p2 9999
  i5 p2 9999
  i6 p2 9999
  i7 p2 9999
  i8 p2 9999;
  CostFarmer: 120;
  CostTrader: 60;
  CostPickUp: 100;
  Quantity(i):
  i1 1.5
  i2 0.5
  i3 1.5
  i4 0.5
  i5 1
  i6 1
  i7 1.5
  i8 0.5;
  ColCap(l):
  l1 3
  l2 3;
  TransCap: 7;
```