Agricultural storage

Concepts and modelling

N.L.M. Grubben

Literature Survey

Ervaar innovatie.

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Agricultural storage
Concepts and modelling

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Abstract

In a biobased economy, for continuous operation of processes continuous streams of raw material is desirable. Since, most raw organic material streams from agricultural show seasonal fluctuation, a need for storage facilities is a fact. Zoomed in on the agricultural biomass that is supplying the food and non-food industries, the storage of high-valued products becomes even more important. In this literature study the concepts, and models used for the storage of agricultural produce are investigated.

The logistic network is an important factor in the biomass supply chain to food industries an biorefineries. In this network storage facilities are functional buffers that create a continuous stream of produce. In addition, also pre-processing and quality control are related to these storage facilities.

A suitable storage facility is the base to maintain a continuous stream of high quality agricultural products through the whole year. In this study, different types of facilities, such as bulk, box and sack, storage are described. Within these systems, we distinguish between blowing and suction ventilation.

The conventional way to maintain the quality of agricultural produce in a storage facility over a long period, is realized by climate control. In literature, a reasonable amount of studies on modelling of *potato* storage facilities can be found. Most researches focussed on the modelling of energy and mass (water content in air) balance, in a bulk storage. In these studies, the focus was on relative simple geometries, while assuming a homogeneous air distribution in the facility. An overview of these models of potato storage facilities is provided. A simple test-case is implemented in COMSOL 4.3 to demonstrate the potential use of these models in simulation studies.

In a follow-up study of this thesis, we will focus on the computation of temperature and humidity profiles in real-world storages, with different geometries and ventilation systems for (re)design and control.

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Wageningen University: for quality of life — N.L.M. Grubben
July 3, 2013

Chapter 1

Introduction

This thesis report presents is the first part of an MSc thesis project. The aim of this first part is to report the results of a literature study on the concepts and modelling of agricultural storage facilities. In this chapter first some background information will be given. In addition to this, the problem, objectives, research questions and approach will be presented.

1-1 Background

Agricultural products are playing an important role in live. From the beginning of time first for food and feed, but now-a-days agricultural products are also used as raw material. Agricultural products is one of the three main categories of biomass in the upcoming biobased economy (Yokoyama, 2008). In such an economy sustainable and renewable biomass sources that can be used as raw material is searched for. On the other hand, also the demand of agricultural products for food is growing under a growing world population. This requests for new cycles and processes to be able to supply the consumers, and as well the industry.

The new cycles and processes should be created at the production and processing sites and in between these industrial activities. At the production site new streams, of what is conventionally know as waste, could be interesting. In the process industry new abilities to process biobased materials could be created. In this new concept transport and storage are important factors, as new logistic concepts that make the biobased economy more interesting from both economical and ecological point of view.

Most agricultural products are season dependent, and to match the supply and demand of the consumers and industries, storage of these products is important. The storage period can differ from days, to weeks, to several months. It is important to keep the product quality at a certain level, to provide good quality products through the whole year. Therefore, long term storage is challenging process under the influence of the environment and internal processes.

The climate in the storage facility directly affects the quality of the products in the storage. Consequently, by controlling the climate in the storage, one aims for a good quality control. In literature, many papers on modelling of the processes that are related to climate control of the agricultural storages can be found. In practice, often, experimentally collected information is used to design and control the storage facilities. To get more insight in the modelling of agricultural storage facilities, for designing and control of these systems this literature survey is done. This survey is the first part of a 60 ECTS MSc project. Overall, the aim is to investigate the relations between mathematical process models and different geometries of the storage facilities. With this knowledge, in the second part of the MSc project, simulation studies can be done, and it allows further research on the design, model reduction and control of the systems is possible.

1-2 Problem formulation

Biomass is a renewable product. The availability is an important factor in the usage and consumption of biomass. The production process of several biomass types are season dependent and is causing a non-continuous stream of biomass. Especially, in the processing of agricultural products for food, feed, chemicals, energy and materials, the season dependency is playing an important role. Food is one of the first needs of the human population, requiring a continuous stream of food through the whole year. As mentioned above, an upcoming biobased economy becomes active on the market of the agricultural products. And likewise, as in the food industry, a continuous stream of biomass for continuous operations in the processing industry is desired.

With this non-continuous and season dependent production of biomass, and the need for a continuous stream of biomass for the process industry, we can make the following problem statement:

- The need for and the importance of storage facilities for biomass in a biobased economy and for food is rising

1-3 Objectives

One of the goals of this literature thesis research includes the relation between the storage of biomass and the usage in a conventional, and in a biobased economy. This can be seen as the top layer. An other goal, a layer beneath it, is to get insight in storage possibilities for biomass with the highest production rates in the Netherlands. Under this layer we end up with the physical modelling of storage facilities, which plays an important role in the control of indoor climates of high-valued agricultural products, such as potatoes. The last layer in this research will be the first findings on an implementation of a storage model, in COMSOL 4.3. Hence, the objectives of this research are:

- To present an inventory of the storage facilities for the high-valued agricultural products

- To investigate indoor climate models defined for (re)design and control of agricultural storage facilities
- To implement a relatively simple model for high-valued product storage in COMSOL

Research questions Storage of biomass is not something new. However, storage facilities are becoming more sufficient, more complex and more efficient. The first two research questions related to the concepts of storage facilities are:

What is the role of storage in a biobassed economy?
What kind of concepts are used for the storage of agricultural products?

Two other research questions are related to the modelling of the climate controlled agricultural storage facilities. A physically-based model is a good starting point for model-based design and control of a storage facility. Therefore, it is necessary to know which model can describe the physics well enough. This leads to the third question:

Which models have been provided and used for design and control of the high-valued product storage?

An important entry for the model are the in- and outputs. In boundary control strategies the in- and outputs of the model characterize the model boundaries. Or the other way around, the model boundaries depend on the model in- and outputs. This results in the last research question:

How are the model boundaries coupled to the geometry of storage facilities?

1-4 Approach

Through this literature study a systematic approach is followed to find the answers on the research questions and accomplish the objectives. This research starts very broad and zooms further into the different subjects. The first and broadest subject is the biobased economy and we end up by zooming, through all the layers, with the different types of models for potato storage facilities, see figure 1-1.

Roughly speaking the research start with the investigation of the role of the storage facility in a biobased economy. Second, the concepts available in literature are investigated. This second step is followed by a literature study on, and a classification of models used for agricultural storage, with an explanation of the most important physics in these systems. Finally, a implementation of a potato storage model in COMSOL is described.

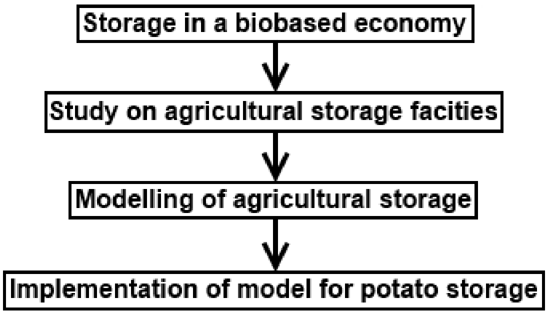

Figure 1-1: Structure of the this thesis.

1-5 Outline of the thesis

This report is the first part of 60 ECTS MSc project. In this part, a literature survey on concepts and models for storage is presented. In the next part, a detailed research on the modelling of a potato storage will be done. Hence, for part two first the concepts and knowledge of models need to be investigated.

In chapter 2 the concepts behind a biobased economy are investigated, with respect to the biomass types.

In chapter 3 we zoom in on the logistic options for the different biomass types. This will be done from both the biomass producer, and from the processing point of view.

In chapter 4 the focus is on the agricultural product, because this is one of the most important biomass types for the world wide population. This chapter zooms further in on the storage concepts of agricultural products.

In chapter 5 the most important concepts and steps to model a storage facility are highlighted. The research basically focusses on the models used for potato storage facilities. First, the laws of conservation are described. Second the most important constitutive laws that contribute to the storage system are explained. At last, an inventory of the models available in literature is presented and evaluated.

Chapter 6 contains a description of the implementation of a simplified model in COMSOL. The first experiences and implementation steps form the bases for part two of this thesis project.

In chapter 7 the conclusions with respect to the research questions are presented. This chapter also included a discussion on the results.

Chapter 2

Food and non-food agri-material

From the beginning of time agricultural products were used for food. The most agricultural crops are season dependent. To provide through the whole year the products should be stored for later consumption. Nowadays, crops are not only seen as a product for food, but also other applications of agricultural (by-)products became interesting. In this new trend the biobased economy plays an important role. Also for this application, a continuous stream of high quality products is desirable.

This chapter first describes the upcoming biobased economy. Followed by a classification of different types of biomass, and there composition. And ends with a investigation of the biomass classification from the biomass processing point of view.

2-1 Biobased economy

A biobased economy is an economy that is focusing on the usage of biomass as raw material rather than the usage of fossil raw material. The advantage of a biobased system is that the biomass is a renewable resource. In a biobased economy, a closed loop system is created where the biomass has a central position, figure 2-1. They are not longer only the basis for food and feed, but also a crucial product for the production of materials, chemicals, fuels and energy. We will make a clear distinction between the food/feed and non-food stream. However, for both the streams there is an overlap in usage of biomass for biomass products. To end up with such an economy, the production of these products has to grow. Growth can be realised if new forms of cooperation, joint effort, and innovation will be generated in whole the cycle.

2-1-1 Biomass classification

Biomass contains all materials with a biological nature. Several classifications on different categories of related biomass can be made. Focusing on storage of biomass a proper classification based on the recourse of different types of biomass can be made. In this case three main categories can be distinguished (Yokoyama, 2008), (Demirbas, 2001),

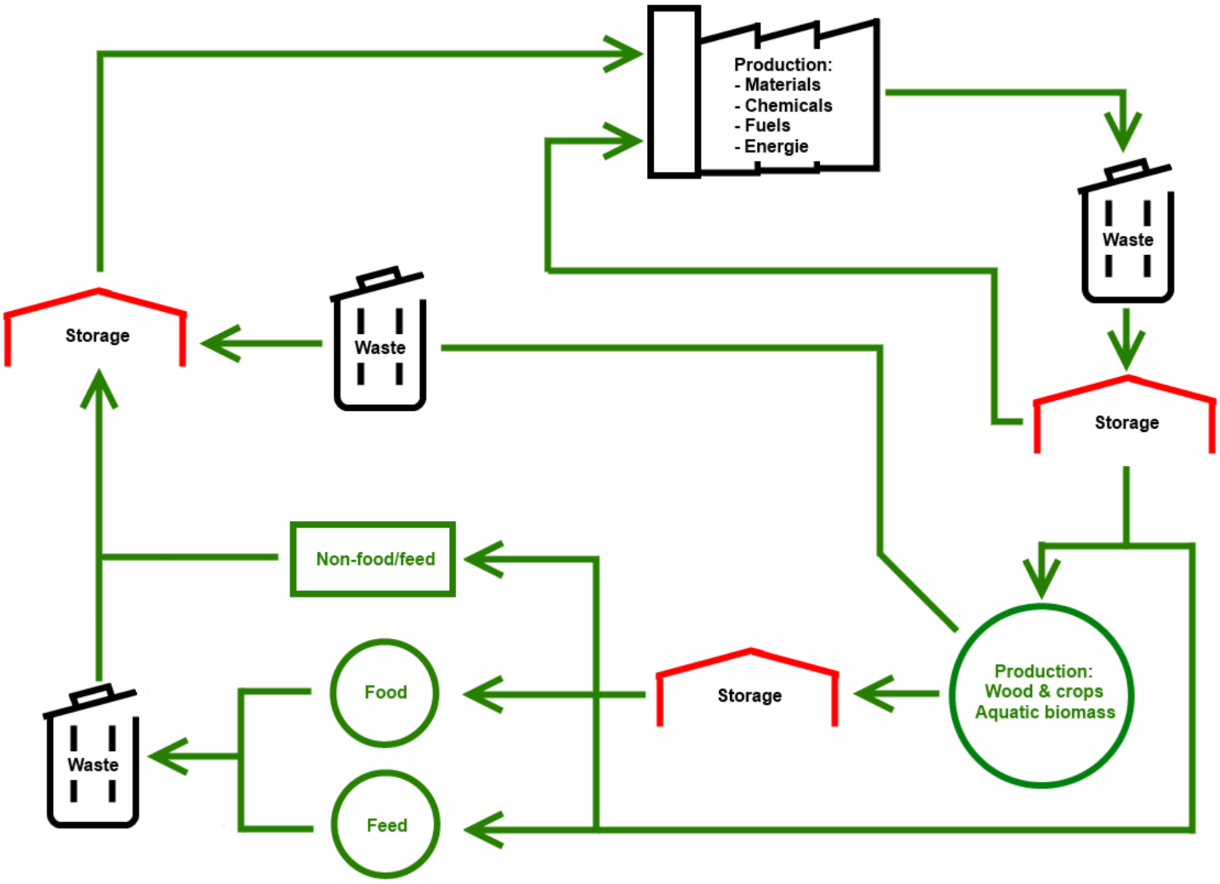

Figure 2-1: Closed Biobased economy loop. With three types of biomass production, at the forest/farm, aquatic production, and waste production. The waste is produced at three locations in the loop. Also, there are several storage facilities, where the biomass is stored for short or long terms.

1 Aquatic plants and algae

2 Waste/by-products

3 Wood and Agricultural products

Aquatic plants and algae is a category separated from the other two, because of the unique structure and production opportunities.

In a biobase economy waste/by-products is not a properly used term. In a biobased economy some kinds of waste could be rearranged into usable biomass. This rearrangement has three main categories (Koppejan et al., 2009):

- **Primary residue** is biomass that is a by-product of the main product.
- **Secondary residue** are the by-products that arise in the industrial process.
- **Tertiary residue** is biomass that arise after usage of products.

Wood and agricultural products are product that are produced for industrial purposes to produce energy, materials, chemicals and fuels. Also the conventional food and feed stream is covert in this category.

Table 2-1 provides an overview with some examples in every biomass category. In the category agri-products the conventional food products are not included.

Table 2-1: Different kind of biomass (Koppejan et al. (2009), Vis (2002), www.biobasedeconomy.nl)

Aquatic plants and algae	Waste/by-products primary	Secondary	Tertiary	Wood and agri-products
algae	straw	potato peels	Municipal Solid Waste	energy corn
water weed	prunning waste	low quality potato's	wood residuals	oilseeds crops
	hay	beet pulp	refinery sludge	grasses
	manure	animal fat	waste water	sugar crops
				wood

2-1-2 Biomass composition

For the three different kinds of biomasses there can be made a separation between first, second and third generation of biomass (Evenblij, 2010). The first generation biomass are the products that are produced for direct usage for the food and non food streams. The biomass in the second category are the residual streams of the first generation products. This means that these by- products, are the waste products of the first generation biomass products. The third generation biomass is not focusing on the conventional agricultural and wood products, but is a collection of new techniques to produce usable material out of green products, like algae and seaweed.

If the composition of the biomass of the first and second generation is taken into account there are three main streams of biomass products (Koops and Sanders, 2005) :

- Biomass from sugar and starch crops
- Oil crop biomass
- Lignocelluslosic biomass

Until so far, the third generation biomass is used to get al sorts of new usable materials out of all kinds of biomass. In addition to the three main components, the crops/products in the three, last mentioned, categories do have other useful substances, like amino acids, protein, grease, cellulose, hemicellulose and lignine. Minerals and numerous other components come in small quantities. The different composition of crops allow the use of biomass in as well the food as the non food industry. For the processing of the biomass into materials, chemicals, fuels and energy, the concentration of these components are an important factor. Consequently, for the food and also the non food streams a high quality product is desirable. This means from the moment of obtaining the biomass until the processing into other material a low as possible quality loss is pursued.

2-2 Classification biomass processing

The biomass is processed into different types of products like, food, feed, materials, chemicals, fuels, power and heat. These different products can be organized by the same usage types, food/feed and non-food. For the processing point of view a wider distinction than just food, non-food and feed can be made. We may also distinguish between produced volumes and market price. In that case there are four categories; biochemicals, biomaterials, bioenergy and the food/feed. These categories could be ordered in a logical way. Two important stimulants of a biobased economy are the social- and market price aspects. In theory these should be in balance. Up to now this is not the case, because in the upcoming biobased economy there are several subsidy compromises to stimulate some specific products. Hence, there are two different ways to order the four categories biochemicals, biomaterials, bioenergy and food/feed:

- From social point of view (Hoeven and Reinshagen, 2011) the most valuable biomass (feed- and food-stock) products should be used for the production of the products that have an big relevance (highest rank in the pyramid) for the humanity, de-pictured in figure 2-2 on the left.
- From economical point of view (Langeveld, 2010) the product with the highest market price should be reflected against the market volume, de-pictured in figure 2-2 on the right.

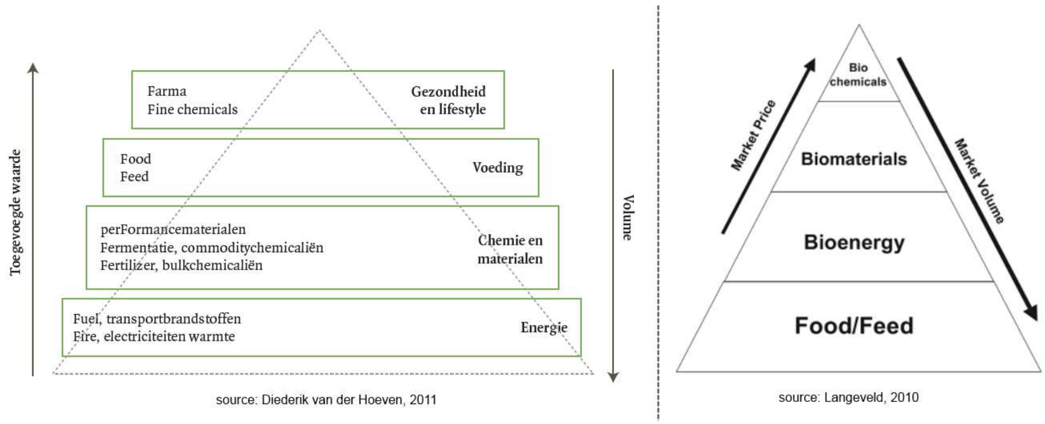

Figure 2-2: Two different classifications bases on social and economical aspects. Left the social pyramid with in the top the category that uses the most important produced biomass(after Hoeven and Reinshagen (2011)). On the right the economical based pyramid with in the top the processed biomass with the highest market value. If the biobased is in balance the two pyramids should be identical, and so the most important biomass processing process contains the highest market price (after Langeveld (2010))

From the processing point of view the four categories biochemicals, biomaterial, bioenergy and food/feed can be grouped as three main categories: Bio-based products, bioenergy and food/feed, where bioenergy can be produced in different forms: fuels, power and heat. The bio-based products contains two types of products: bio-based materials and bio-based chemicals.

Chapter 3

Logistic network of biomass in a bioeconomy

In most situations, the biomass of the first generation products for processing in the energy materials, chemicals or fuels is not interesting for farmers (Elbersen et al., 2011). The production of biomass for food is in general more profitable (Voort et al., 2008). The second generation biomasses is already more available, but not always optimal exploited. For the processing of this type of biomass there are some logistic challenges that are different from the fossil raw material.

- season depended biomass production
- spread production area of biomass
- small quantity residuals biomass from main product
- relatively low mass density and high moisture content
- relatively low energy density

These five biomass properties are of big influence of the usage of biomass as a feedstock. Furthermore, these properties have a strong relationship with the harvest, collecting, storage and (pre-)processing of the biomasses. The season dependency of biomass will cause a high stream of biomass at one short period of time. To provide the industry and consumers the whole year around, the biomass has to be stored. Because most biomasses are spread over one or more area's, the products should be transported from location to the storage or processing location. For the storage and transport of biomass the relative low mass-, energy density and high moisture content are negative properties. Hence, a relatively large amount of space is needed in the storehouses and transportation facilities. For the different types of biomass there should be an optimal logistic trajectory. The biobased economy is an upcoming concept. Because of this fact, for most of the applications there is not yet a specific logistic plan.

Some biomass products are already used for decades for the production of materials, energy, chemicals and fuels. These products like Municipal Solid Waste (MSW) and materials for the wood industry have already such a logistic network. The knowledge of these networks are a basis for the new upcoming biomass networks and hence providing a good starting point for an optimal economical solution.

In this chapter first some logistic related matter is investigated. After this investigation we are zooming in on the logistic chain, into the biomass storage. For all of the three biomass categories storage facilities are described.

3-1 Logistics

The logistic chain of all kinds of products stream is of big importance for the cost and efficiency of the whole cycle (Beamon, 1998). Especially from the point of end-product production like energy, materials, chemicals and the food and feed in a biobased economy (Kumar and Sokhansanj (2007), Mol et al. (1997), Mansfeld (2009)). The most important factors are the interaction between the transport and storage, and the distances between the production and processing facility.

3-1-1 Former biomass logistics

Formerly biomass consisted out of food/feed and waste of the consumers. No advanced chemical plants where jet invented and so all the food wast was used as feed and all the organic waste was used as fertilizer. At a certain moment industrial plants were growing, and more waste was produced by the population. In most of the countries a collective waste collection was initiated. In the Netherlands this was around the beginning of 20^e century. These wastes were collected and composted outside the city. When the cities became bigger and bigger the transport cost rose, so alternatives like burning ovens where build in the cities. In the sixties, the waste production was explosively growing. The burning ovens did not have enough capacity and so still a lot of the waste, like crops but also plastics, was dumped at landfills. In the intermediated years, until the nineties, the communities became more aware of the problems, and possibilities to re-use, recovery and recycling of the waste. So regional territories that processed the wastes by composting, burning and still dumping at this recycle centres were created (Visser, 2001). Consequently, transport plays a big role in the landfill logistics. There is always a trade-off between the costs and the social aspects, leading to small scale storages at the consumer. Subsequently the costumer wastes are transported to a landfill or to other processing place.

3-1-2 Biobased biomass logistics

Several logistic plans are used in the biomass production and processing cycle. In the following, three different logistic approaches are distinguished. The main idea behind this distinction is the difference in storage place: at the farm or forest, intermediate storage or storage at the processing facility. These options are de-pictured in figure 3-1. These logistic concepts are investigated for the bioenergy (power plants) and also for the biorefinery case, see Rentizelas et al. (2009) and Bowling et al. (2011) respectively. For the biorefinery case the intermediate storage is also used for possible pre-treatments.

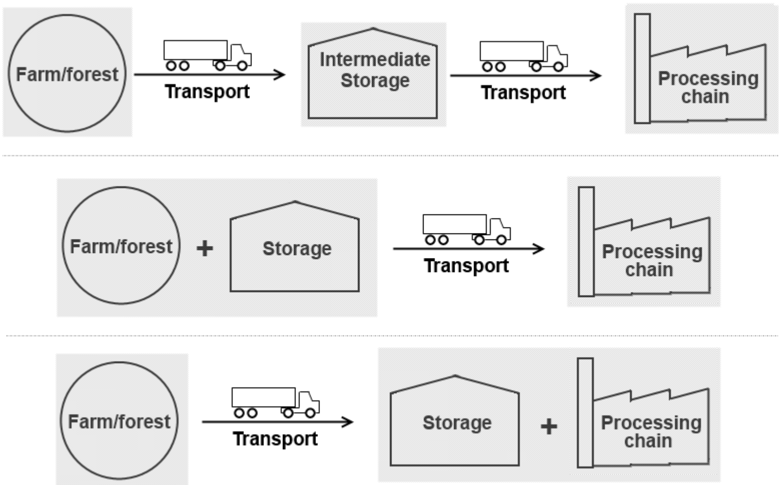

Figure 3-1: Three logistic concepts for the processing chain of biomass.

In the first approach, the biomass is harvested at the farm or forest. Then transported to an intermediate storage, and in a later stage transported to the power plant. Several (local) intermediate storages should be available between the processed location and the processing chain of the biomass. This intermediate storage has the advantages that several biomasses can be collected and possibly preprocessed.

In the other two cases the biomass is only transported once. In case two, the biomass is directly stored at the location where the biomass is harvested. Consequently several store places need to be available. Some products can be stored in the outside air and hence the field or forest itself can be used. A disadvantage is that the field should be available for a longer period of time. Hence, the field can not be used for production. Other products need to be stored in storehouses, because they can not handle the fluctuations in the natural climate. Hence, several storehouses should be build spread over the area where the crops are growing. For every different type of biomass a separated storage need to be available.

In the last case, the storehouse is build next to the power plant. Directly after harvesting the biomass is transported to the power plant and stored at that location. The advantage is that the products are collected at one storage. Table 3-1 summarizes the negative and positive aspects of the different logistic concepts.

Table 3-1: The advantage and disadvantage of the three logistic concepts.

The logistic concept	**advantage**	**disadvantage**
intermediate storage	- possibility for preprocessing - collection different types of biomass	- twice transportation - regional bases
producer + storage	- transportation once - spread distribution of crops to the processor	- one storage for every biomass type - various quality in biomass
storage + processor	- all biomass directly at one place - use of (waste) power for pre-process	- long distance transport -

3-1-3 Logistic concepts

All three logistic options has positive and negative influences on the whole logistic chain of the biomass. The logistic trajectory for the three particular categories (defined in paragraph 2-2) bio-energy, bio-base products and food/ feed, are different. Also the different sorts of biomass for the processes plays an important roll.

For the case of bio-energy, where fuel is produced out of straw, coppice or miscanthus the transportation cost are relative high. The mass density compared to the volume is very low. The transport cost can rise up to 55 percent of the total cost until the biomass reaches the power plant (Allen and Browne, 1998). From point of view of the power plant the option of an intermediate storage probably would not be the best option. The disadvantage is that transporting the biomass twice causes extra cost or transportation. Using an intermediate storage stage may add $10 - 20\%$ to the delivered costs, as a result of the additional transportation and handling costs (Rentizelas et al., 2009).

For the bio-based products the case of an intermediate storage is considered as a possible place for more than only storage. This intermediated place should be a place where several types of biomass should be collected, stored and possibly pre-processed. If the whole biomass producing/processing cycle is taken into account, including the variety of biomass products, the different intermediated pre-processing places and the central processing facility, the best option seems to be the one where the biomass is collected over several distributed locations, like in figure 3-2 (Bowling et al., 2011).

For the conventional food and feed industry all three logistic concepts are used. From the view of a biobased economy one particular concept becomes more interesting, where ecology is an important component. Likewise for the bio-based products chain, the combined intermediated storage place with additional functions becomes an interesting concept. This intermediate storage is again meant for the storage, collection of biomass and (pre-)processing of some

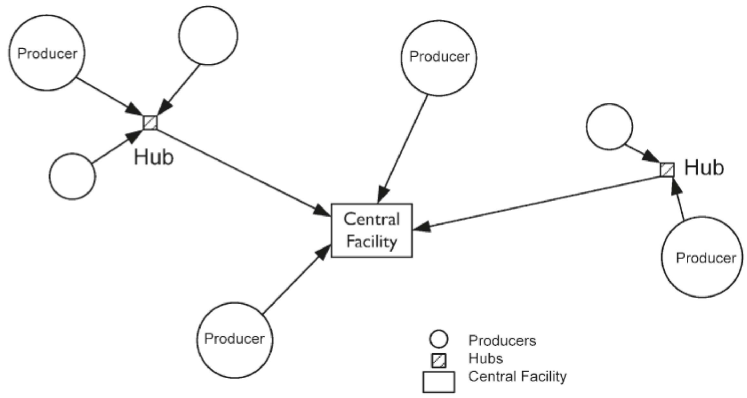

Figure 3-2: The schematic representation of the logistic concept with the intermediate facility(hub) Different kinds of biomass is transported and collected on regional base before it is transported to the central facility. Also the option of direct transportation to the central facility is de-pictured (Bowling et al., 2011)

biomass that belongs to the food and feed chain. Some investigation on such concepts were already done by (Annevelink et al., 2003). They tested some different sized configurations on a regional base, like in figure 3-3. The advantage of this concepts is that also on small scale, if the whole chain is considered, that is from production to re-use of wastes it is economically and ecologically an interesting concept. This concept saves on transport, energy and fertilizer.

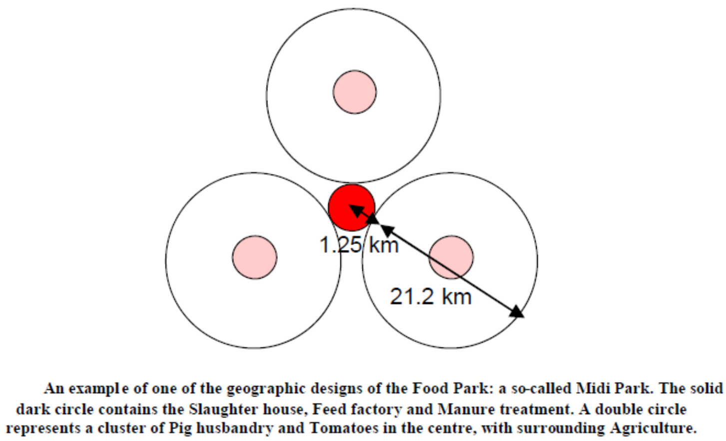

Figure 3-3: Schematic representation of a regional intermediate processing concept (Annevelink et al., 2003)

3-1-3-1 Practical working concept

The previous section pointed out that an intermediate storage becomes more interesting in a biobased economy. In such economy the intermediate storage facility becomes a multifunctional facility, where is taken care for the collection of different types of biomass, storage and when needed the pre-processing of the biomass. This facility is typically organised on a regional basis and can be interpreted in different ways. For example, an earlier mentioned concept, the multifunctional intermediate facility Food park (Annevelink et al., 2003).

A more detailed concept, that is already in operation, is a so called biomass yard. The principle of a biomass yard is the collective collection of different types of biomasses form a specific area. The place of such a yard is at the power plant or at an intermediated place between production and processing of the biomass. A biomass yard can have several tasks, depending on the collection of the types of biomass, the main task can be (Annevelink, 2009):

- Regional collecting point for several types of biomass
- Storage, and buffering for a constant stream to the power plant
- Logistic cost optimality
- Efficient scaling, and so aim for a profitable investment cost of the pre-processing
- Control over the biomass streams of specific circuit
- Quality control of the biomass that goes to the processing facility

This logistic concept comes from the traditional wood industry. An other concept, which is comparable to a biomass yard, is the MSW and green wast collection. Actually, a biomass yard is not a new concept. But a longer existing concept with a new name; Arjan Brinkmann(dir. Branche Vereniging Orgnanische Reststoffen): "A biomass yard is a synonym for a longer existing concept called 'processing yard for organic residues'." (Coenen-Sinia, 2011) In the Netherlands already 49 biomass yard are spread over the country, see figure 3-4. The main biomass products that are taken in are wood residues, crop residue, consumers green residues. The main products that are produced are fuel chips and shrips, but also compost and ground/-soil improving products.

3-2 Storage of biomass

For the storage of biomass two different storage cases can be distinguished: open and closed storage systems. For the storageof biomass in a biobased economy the role of a CO2 neutral system is playing a big role. Consequently, the hole logistic network, including the storage, has to been seen as one subsystem, where the consideration between transport cost, and storage are important factors. The main reason for storage is to have a constant flow of products. In a biobased economy this is preferable, to get a constant energy or material production. For the food industry this is needed to satisfy the consumers need, the need of supply of food through the whole year. In this storage process the quality of the product is of most importance.

The biomass product: aquatic plants, waste/by-products, and wood and agricultural products are categorized on type of origin. From a storage point of view it is a little bit harder to specify the best storage facility for the three categories, because within these categories there is a large diversity of biomass.

Figure 3-4: Several Biomass yard's are spread all over the Netherlands. These yard's are used for storage of biomass for regional basis. Also the production out of biomass is often done on these yards (source: www.biomassawerven.nl).

3-2-1 Storage of aquatic plants and algae

Algae and aquatic plants can be used for the food and non-food industry. For the growing process water is needed. Hence, a logical option is to use open oceans, inland seas or make facilities on land. The most optimal way to control the whole growing process is on land. For the production on land of aquatic biomass open and closed systems exist. The open systems need relative more space compared to the closed systems. To get the end product that can be used for further processing there are four important factors (Newby, 2011):

- Harvest and de-watering
- Drying
- Storage
- Transport

For long term storage, specimens can be preserved in liquid, dried, or made into a permanent microscope mount. Because of these different types of storage structures there are several ways to store this kind of biomass. For instance, in tanks, silo's or in a conventional pile.

3-2-2 Storage of waste/by-products

This category contains a wide spread diversity of biomass types. Hence, the harvest, storage, transport and possible intermediate operations are very different. However, the biomass are released at similar resources. The primary by- products are residues produced by the main products, hence at the farm or in the forest. The secondary by products arises from industrial processes. And the most tertiary products arise after usage of products, hence produced by the consumers and industry.

For most of the products in the primary and tertiary categories the residues consist of small quantities, spread over a wide area. Because the amount of different biomass products, different storages for every individual biomass product have been introduced. However, for the collection and storage of grouped products, facilities like biomass yard's and regional collecting places are discussed. A distinction can be made between solid and liquid biomasses. Both can be stored in and outdoor.

Waste/by-products consisting out of solid biomass can be stored in piles, because of the solid structure. It depends on the components in the biomass, that are interesting for further processing, and on the further processing cycle how the waste/by-products are stored. Because of the wide diversity of biomass, from straw to municipal solid waste, all kind of storage is possible. Often used storages are simple piles in nature or indoor piles. Also storage in boxes, containers or as bales is an option.

The liquid biomass types are biomass like refinery sludge, waste water and manure. Also these types of biomass contains valuable nutrients for the non-food industry, these nutritious substances can be used for the fertilization of the crops on the field. This kind of biomass is mostly stored in tanks or in basins.

3-2-3 Storage of wood and agricultural products

The storage of these two products can be split up into woody biomass and agricultural product storage.

3-2-3-1 Storage of woody biomass

Woody biomass is spread over the whole biomass chain, in the forest but also as industrial or consumers waste. For the production of wood, the wood should be transported to an storage facility in the forest, intermediate storage or direct to the processing facility. Two main methods to store wood can be defined:

- as a trunk pile
- as chip bulk

The storage of chips in the outside air, and so on the harvest location, is only save for a couple of days. The chipped woody material that is stored in bulk needs forced ventilation to prevent heating in the bulk and the growing of mould, and consequently quality loss. So most chips are stored at a biomass yard or at the processing facility. For the later processing, it is necessary that the moisture content of the chips is low. Since it cost a lot of energy to dry the chips (Boosten et al., 2009) it is better to dry the wood as much as possible before it is used in the chipping process. This can be realised by storing the wood for a while, as trunk piles. These piles can be made at the harvest location or at intermediate storage facilities between the harvest location and the processing facility.

3-2-3-2 Storage of agricultural biomass

The chain of agri-material, and so the availability of biomass, depends very strongly on the crops, climate and harvest-time (Sokhansanj et al., 2006). Some crops can be easily stored in the outside air, while for other crops the quality degreases dramatically in the same situation. Also the climate where the crops are produced does have a strong influence on the quality of the product in the storage process. The best place of the storage depends on the sort of biomass and the kind of processing facility. As mentioned before, in a biobased economy the concept of a closed chain becomes more interesting. Concepts like the Food park are become more economically and ecologically efficient (Annevelink et al., 2003).

For agricultural products, it is not immediately clear what the best storage option is. A distinction can be made between the indoor and outside storage, likewise in the other categories. An important factor, in the outdoor facility on land, is that the field most of the time is not available for a long time storage, because the field should be prepared for the next crop growing activities (Rentizelas et al., 2009). For high valued biomass products the quality is of big importance. Hence, often these products are stored in climate controlled facilities. In these storages the products can be stored for longer time, in piles, sacks, boxes or in other package material.

In the upcoming biobased economy, where the conventional food products also can be used as raw material, the availability of this kind of biomass becomes more interesting. Even more interested as it already was with the growing demand on food, for the growing world wide population. To provide the whole year around, products of good quality, the storage of this kind of biomass becomes more and more interesting.

Chapter 4

Storage of agri-material

In chapter 3 the importance of storage of agricultural biomass is pointed out. For the storage of agricultural material, first is investigated which of the biomass is used most in this upcoming biobased economy. On bases of these knowledge, further investigation on storage of the more important type of agricultural biomass is done. This is followed by the description of first the outdoor, and second the indoor storage concepts.

4-1 Major agricultural crops

The world's most produced crops are mainly food products. Table 4-1 gives an overview of the most produced agricultural products world wide, in West-Europe and in the Netherlands. For the Netherlands the top five is mainly consisting of food products. There is not jet a market for the production of potatoes used for other purposes beyond consumption or seed potatoes. Also, for the sugar beats, energy corn and wheat this is not the case. In the Netherlands the potato is the most produced agricultural product, but also in West-Europe the potato has a large contribution to the food production.

Table 4-1: Major agricultural crop production (based on produced tonnage in 2011)

	World wide	West-Europe	Netherlands
1	Suger cane	Sugar beats	Potato
2	Maize	Wheat	Sugar beats
3	Rize	Potatoes	Onions
4	Wheat	Maize	Wheat
5	Potato	Barley	Tomatoes

Focusing on the products that are of most importance in the Netherlands and are produced in the agricultural sector, we are left with potato, sugar beats, unions, wheat and tomatoes.

The fruits, and so tomatoes, are not taken into account in this specific research because it is a fruit product and is produced in the greenery sector. The fruits has an other, softer and more softer structure as the other agricultural products in table 4-1. An other important produced biomass in the Netherlands is flower bulb. High sales values are related to this sector, and from storage point of view it can be treated more or less the same as potatoes and unions. But formally, bulb is produced in the greenery sector, and so not included in this research.

4-2 Conventional storage

There are different ways to store agricultural products. The two basic methods to storage agri-material is in- and outdoor storage (Ooster van 't, 1999). Where indoor storage allows more advanced controllers. For the two main methods of storage there are several ways to realise the storage. For outdoor storage this is on a pile or in a clamp silo, and for the indoor storage we distinguish made use of bulk, box and sack storage(see also figure 4-1).

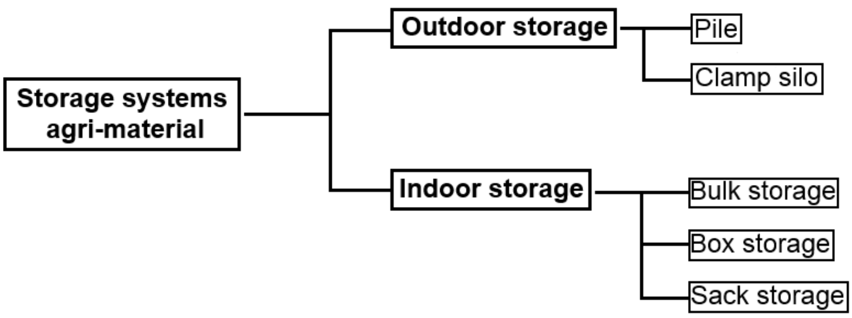

Figure 4-1: Several types of storage are available for the most produced field crops in the Netherlands.

Outdoor storage An outdoor storage is meant for products that can handle large temperature fluctuations. For most of the food products this type of storage is used only for a short time period. Most of the time these storages rely on natural ventilation.

Indoor storage For products that are sensitive for temperature and vapour fluctuations, often an indoor storage is used. In such a storehouse the temperature and other natural influences on the products can be controlled to keep a high quality product. In these storehouses often forced ventilation is used to control the atmosphere of the storehouse.

In the past years, different systems were developed to control the storage process of the products. In all these systems there are exchanges between product and the surrounding air. A distinction can be made between two different kinds of heat exchange (Beukema, 1980):

- Convective cooling : Heat transfer directly from product to air. So, cold air streaming through a pile of product.

- Conductive cooling : Conduction through some solid material. So, cold air is streaming along a pile of products and by convection heat is transfer between product and air, and a cooling effect by the conduction from the outside to the inside of the pile.

4-2-1 Convection

Especially in the convective cooling case there are two different modes of convection, namely natural and forced convection.

In the case of natural convection, there is convection between the product and the surrounding. The natural convection is caused by a change and difference in the temperature, density and pressure between the air and the product. These differences are caused only by natural non forced changes in these three factors.

When forced convection is taking place, a forced change in temperature, density and pressure between the product and the surrounding air is created. So an external source is used to transport energy and mass. With this type of convection one can affect the energy and mass transport between the air and the product.

4-2-2 Cooling

An important factor that has influence on the quality of agricultural products, is the temperature. A distinction can be made between passive and active cooling of the products.

In case passive cooling is used, only out- or inside air can be used for the ventilation of the storage. The system is restricted to the temperatures of the out- and inside air. This can be a limited factor in hot areas or for storage over a longer period. The only control is reventilation rates, which enforces the mixing of ambient air with air from inside the storage.

Active cooling uses an external mechanical cooling installation, like a heat exchanger. In this case, one is capable to control the air temperature with this external source. This allows the ventilation of the storage with fresh outside air, with a higher temperature then is objected to be optimal, while keeping the temperature in the storage at a desired level (Eeckhout and Boussery, 2004). The cooling mechanism circulates cooling fluid though the heat exchanger. Heat is extracted from the air in the vaporizer where the refrigerant becomes a vapour. Subsequently, a compressor compresses the vapour. Under high pressure the hot refrigerant is pumped to a condenser that contains air or water with the surrounding temperature, there the heat will be exchanged from refrigerant to the surrounding air or water, and the refrigerant condensates, but is still under high pressure. Then when the pressure is slowly decreased, a certain amount of colder refrigerant is released, what results in a cooler temperature of the refrigerant.

4-2-3 Air injection

The conventional way to regulate the forced convection is with mechanical fans. These ventilators create a certain air flow so that an over- or under pressure between the different planes in a 3D box containing the agricultural material. The pressure contains two components, static and dynamical pressure.

For a homogeneous air distribution, it is necessary to create a homogeneous pressure at the blowing or suctions site of the tuber pile. If uniform airflow channels are considered the air velocity will decrease proportional to the length of the channels. Consequently, the intake of the duct should have a wider cross-section than the end of the channel. To create the pressure difference by the ventilators there are two working principles:

- Direct air injection into a channel
- Homogeneous distributed air injection by a pressure chamber.

Two examples of bulk system distribution systems are de-pictured in figure 4-2. However, the working principle for other kinds of systems like box storage is more or less the same. In the case with a pressure chamber, a homogeneous divided air pressure is guaranteed, before the air goes through the pile of product. The advantage is that there is some reduction in efficiency by composing the pressure compared by the direct air injection into the channels (Eeckhout and Boussery, 2004).

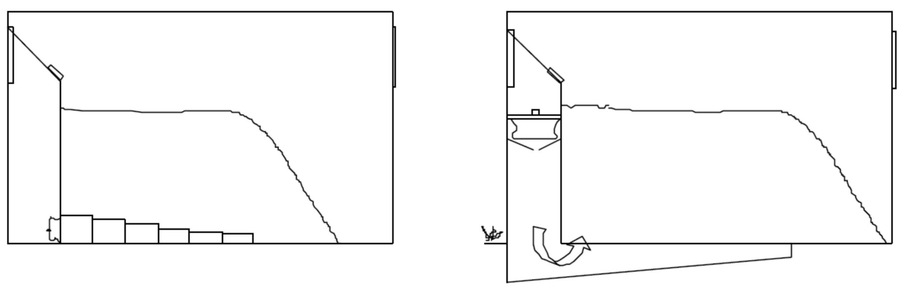

Figure 4-2: Two different types of air distribution systems. Left; duct where the pressure is composed, on the right the system were in a pressure chamber a homogeneous pressure is composed and distributed through the pile (Eeckhout and Boussery, 2004)

4-3 Outdoor storage

The outdoor storage is a simple way of storage. These storage systems can be used for all of the four main agricultural products in the Netherlands. This kind of storage is based on making a pile of the products in the outside air. The control of the climate in the product pile is limited. Two types of outdoor storage principles are distinguished:

- Spherical/cylinder and square shaped pile

- Clamp silo

These storage methods are typically used for storage of the product over a relative short period, for like starch potatoes, sugar beats and wheat. Corn and grass is also stored for longer time in such systems.

4-3-1 Pile

The spherical/cylinder shaped pile is one way to make a pile, de-pictured on the left in figure 4-3. This pile has for every different kind of product other dimensions. The height and angle of the pile depends on the repose angle of the tuber or other kind of product. An other way is the square pile, this is a pile that is square and so higher piles can be realised, because of the bigger pile width that can be reached. The natural confection in the middle of the pile is less that in a spherical shaped pile. In a warm climate this could lead to heating in the middle of the pile, while in colder climates the change on loss in quality due to frost is limited(up to a certain temperature).

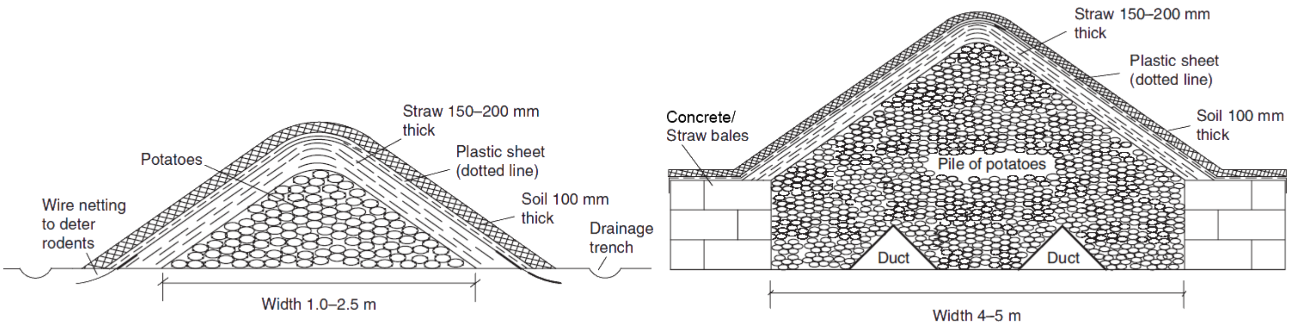

Figure 4-3: On the left a spherical pile with coverage is de pictured. For both systems these piles are use for different types of agricultural products. On the right the Clamp silo pile with some coverage, after Pringle (2009)

4-3-2 Clamp silo

One other way of outdoor storage is in a horizontal silo, like the right picture of picture 4-3. In this case the pile is surrounded by straw or concrete blocks. With this kind of walls a higher pile can be build up. In figure 4-3 an example of a potato pile is de pictured. There are also two air ducts for the forced direct air injection. Also other kinds of products like grass and corn or other products can be stored in this way.

These spherical-, square- and clamp piles can be covered with some material, to prevent the products in the pile against rain and frost. For a covered potato pile the right figure 4-3 gives a good reflection of such an coverage. Also for sugar beats these piles are often used in the Netherlands. Different types of coverage can be used (Naaktgeboren, 2012). Depending on the weather there can be made use of simple plastic covers to advanced 'breathing' coverage materials like duster. -

4-4 Indoor storage systems.

For the indoor storage, three main methods to store agricultural products can be defined:

- Bulk storage
- Box storage
- Sack storage

These indoor storage systems are mostly used for relive longer storage periods, because the potential control of the indoor environment. The bulk storage is mostly used for storage of big quantities of product, like potatoes, unions and wheat. The investment cost are generally lower than for box storage. In box storage the handling of smaller quantities is much easier. This kind of storage is mainly used for smaller quantities or products that needs more care, like seed-potatoes, wheat, flower bulb and unions. The limited pile up height in a box prevents high pressures on the products. But the handling of the boxes requires more care. This is also the case with sack storage. Most of the sack storage facilities are now-a-days used for cases where the handling cost of sack stored products is relative low, like in India (Pringle, 2009).

Bulk storage systems typically use duct injection or a pressure chamber. In box storage systems it is more likely to make use of a pressure chamber, the air between the boxes itself, are actually acting as a lot of 'small' duct through which the air is transported. For sack storage there is only flow along the products possible.

4-4-1 Bulk-system

In a bulk storage facility the products are captured together and put on one large pile. This method is used outdoors, but also in storehouses. To control the indoor atmosphere two conventional ventilation systems are used:

- ventilation ducts
- full grid floor storage

4-4-1-1 Ventilation ducts

Now-a-days, commonly three used ventilation ducts, two kinds of above duct and one underfloor duct types, are used (Pringle, 2009) see figure 4-4) These systems work often with direct air injection of a fan. But also a pressure chamber can be used (Xu et al., 2002). An important property of these duct systems is the ratio between the mutual distances of the ducts and the hight of the pile. For an optimal pressure development in the ducts, the ducts should have a decreasing cross section over the length of duct. The advantage of the above floor ducts is the relative simple building construction, and the cleaning after usage. A disadvantage is the work needed to install the ducts during storage loading, and the de-installation of the ducts after unloading the store. An other disadvantage for the above ground duct systems, is that a wheel loader can not be used to unload the storage.

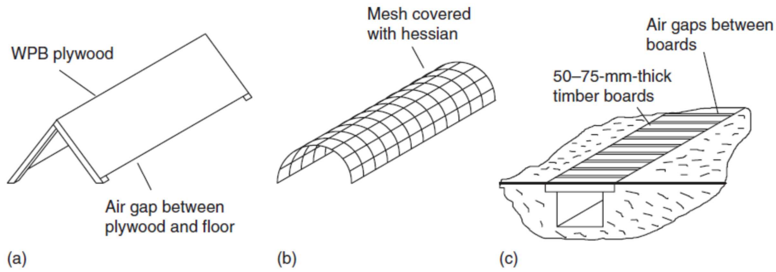

Figure 4-4: three different types of ducts, (a)wooden A-frame duct, (b)metal circular duct, (c) underfloor duct (Pringle, 2009).

4-4-1-2 Grid floor

In a fully grid floor the whole floor is build up as slatted concrete pieces like in figure 4-5. In the earlier days it was constructed of wooden pieces. Under the entire grid floor a basement is lying, and so actually large ducts that are lying direct next to each other are constructed. Hence the floor allows an equal distribution of air. Only 600 millimetres from all the 4 walls there are no grids in the floor. This is because the resistance of the concrete walls is lower as the potato resistance. A rule of thumb is that the sum of the grid spacings are two and a halve to three times as big as the air inlet of the floor, because in bulk storage the ratio potato coverage on the concrete floor is two thirds (Eeckhout and Boussery, 2004). A disadvantage of a fully grid floor for potatoes and unions is the problematic cleaning of the space under the slatted concrete pieces. For grain storage also full grid floors can be used. For this application the slates are made very narrow, and mostly these kind of floors are placed in a silo.

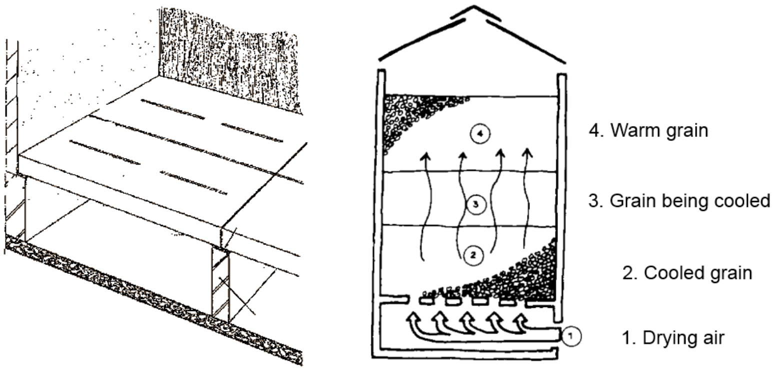

Figure 4-5: Schematic representation of grid floor in a store house left: after Ooster van 't (1999) and on the right a grid floor in a silo for drying grain, after Lucia and Assennato (1994)

4-4-2 Box storage

The storage of products in boxes has some advantage above the loose bulk storage. Working with boxes is more flexible compared to loose bulk storage (McRae, 1985). Every box or row can be treated differently therefore, more flexibility by the in- and out-take of the product is created. The hight of the box is also the maximum hight of the potatoes, so a smaller pressure caused by the product weight. A disadvantage is the high investment costs on boxes. Also, the box size, in some cooling systems, can be the restrictive factor for air injection. Different box store systems are used in the agricultural sector:

- Flow through the boxes
  - Drying wall
    - Blowing ventilation
    - Suction ventilation
  - Tunnel ventilation
    - Blowing ventilation
    - Suction ventilation
- Flow along the boxes
  - Flow-along ventilation

4-4-2-1 Drying wall

The main idea of the drying wall is the injection of air through the opening frame of the pallet. There are different types of drying wall systems. Different combinations for the injection through the frame openings and different types of pressure room configuration are applied.

Blowing ventilation In figure 4-6 the three different combinations of blowing ventilation for drying wall systems are shown. The left system uses single injection. The air is injected in the bottom of the pallet box. The bottom, the left and right side of the pallet are closed, so the air flows in the horizontal direction and is released only to the top of the box sides. The picture in the middle of 4-6 presents the double injection system. This system has boxes with open pallet bottoms only closed on the left and right sides. The air is injected in the openings frame of the above box of a set of two boxes, and the air flow in up- and downward stream. In both cases the openings frames, in the pallet, of the last column with boxes, should be filled up for an optimal composition of the pressure. Systems that uses an open wall structure (see most right picture in figure 4-6) are applied, as well.

Suction ventilation The principles of suction ventilation for the drying wall system are comparable with the blowing ventilation systems. The main difference is the low pressure in the pressure temperature, in stead of a higher pressure. This will result in a air flow from the boxes into the pressure chamber(see figure 4-7) in stead of a flow from the pressure chamber into the boxes.

Different configurations as pressure chamber can be used, see figure 4-8. The most simple one is rectangular shaped. The other two configurations do have a better pressure composition. The configuration, presented in the middle of figure 4-8 needs a extra air conductor blade to compose the right pressure. The most right configuration, in figure 4-8, first pressed the air downstream and by the pressure pushes it to the top boxes.

Figure 4-6: Three different air injection combinations for a drying wall configuration. The left uses single box injection, the system in the middle uses one injection point for two boxes and the most right system has an open injection structure, left: after Eeckhout and Boussery (2004) and right: after Pringle (2009))

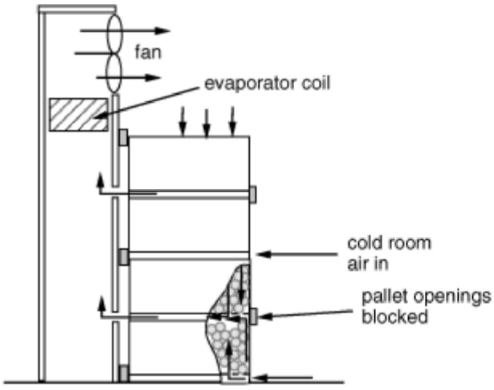

Figure 4-7: Suction ventilation applied in a drying wall system (Thompson, 2004).

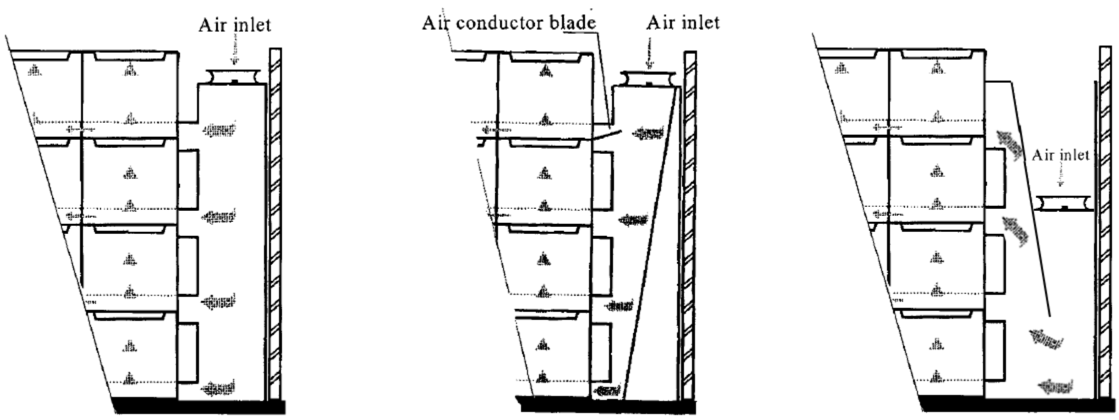

Figure 4-8: Three different pressure chamber configurations, (left: classical version; middle: a configuration with equal pressure at all ducts; right modern version) (Ooster van 't, 1999)

4-4-2-2 Tunnel ventilation

The principle of tunnel ventilation with boxes is that a tunnel between a row of boxes is created. The boxes are placed in two rows next to each other with a spacing in between, the so called tunnel (see figure 4-9). The used boxes should have an open structured side walls, so the air flows from the out- to the inside of the boxes. The front and top side of the tunnel spacing, between the boxes, is blocked with a tarp or bellows, to create a pressure difference. On the end of the tunnel, a ventilation creates the under- or over- pressure. Also for this system different kinds of pressure chamber, comparable to the wall ventilation systems can be used. The length and hight of the rows is depending on the intermediate spacing between the two rows.

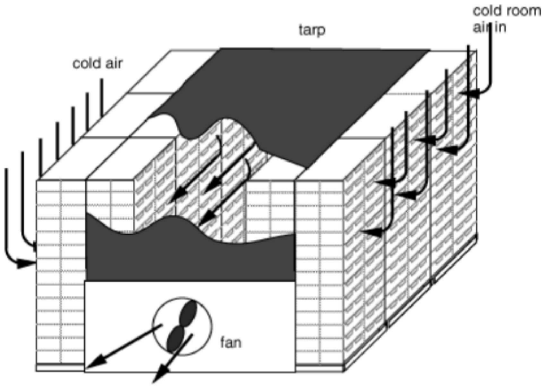

Figure 4-9: Tunnel ventilation system (Thompson, 2004).

Blowing ventilation In the blowing tunnel ventilation system an overpressure, in the pressure chamber, and between the box rows is created. The front and top side are covered with an compressed air bag. This bag is kept under pressure while the ventilation system is processing. The pressure chamber is now operated at overpressure and the air flows from the fan though the spacing between the box rows away though the boxes with product.

Suction ventilation The configuration of a suction ventilation for boxes in the tunnel ventilation system, is the same as for the blowing system. Suction ventilation in a tunnel system is based on creating an under-pressure at the suction chamber, what normal would be the pressure chamber. So now the air flow goes the other way around. The air is flowing from the outside of the boxes to the fan, like in figure 4-10.

4-4-2-3 Flow-along ventilation

The flow-along ventilation system is a relative simple system. The system is blowing air over the top of the box rows. Hence, the spacing between the top box and the roof is acting like a ventilation duct. This spacing should be around 10 percentage of the hight of the total building height (Scheer, 1996). The cold air is transported to the end of the row, and there it is pussed downwards. Hence a air circulation, like in figure 4-11 is created.

If boxes in the middle of the storage are placed, the only way the air can flow, is through the boxes back to the ventilation system. This system circulates cold air over the top boxes of the storage, the top layer of potatoes become colder then the other potatoes in the storage. Once the system stops cooling the hotter air of the rest of the potato pile will have a natural

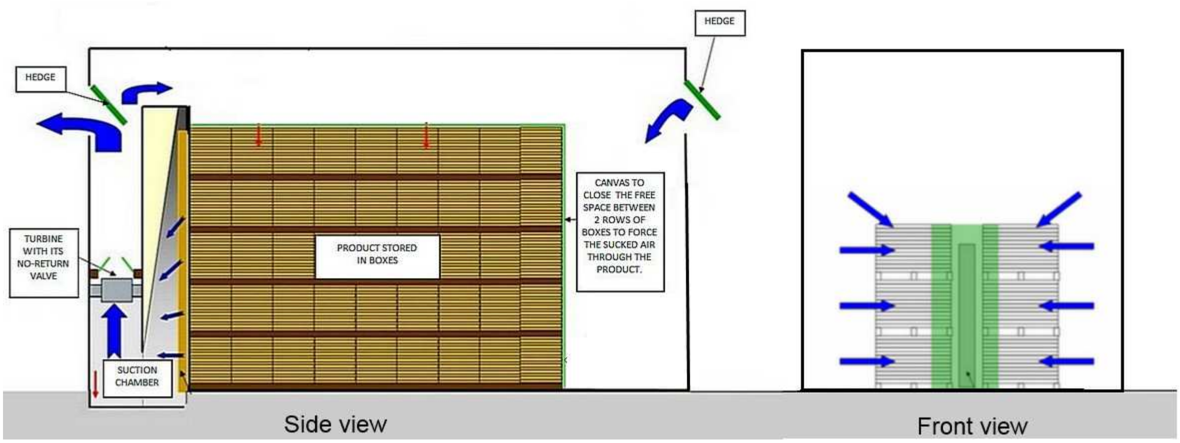

Figure 4-10: Suction wall ventilation system. With two rows of boxes with a certain distance between them, that is blocked with canvas at the front and top site (source: www.onions-potatoes.com).

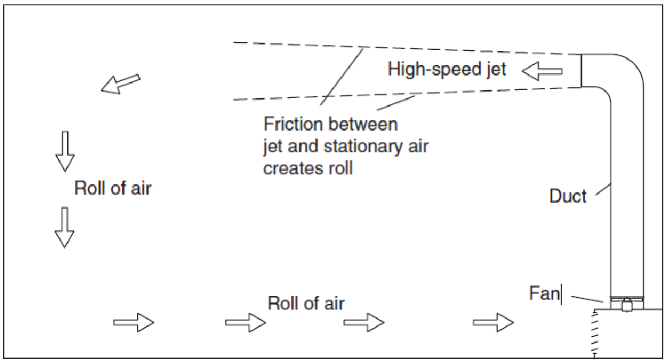

Figure 4-11: Overhead ventilation (Pringle, 2009).

flow upwards. Hence, this system should never cool with an air temperature that has a big difference compared to the pile temperature, else condensation will occur when the cooling process stops.

Two different configurations are de pictured in figure 4-12. On the left picture, the spacing between the ventilation system and the first row of boxes is blocked in horizontal direction. The air cannot flow directly from the air outlet back to the intake, or to the spacing between the ventilation system and the boxes. On the right an open structure where the air can flow everywhere but is forced above the boxes.

4-4-3 Sack storage

Sack stored products are easy to handle. In general, the disadvantage of storage in sack's is the amount of handling work. That is the reason these storage systems are often used in countries with low employee costs. The way of storing the sack products is by keeping the temperature and humidity on a certain level, by the flow along principle. Typically, the

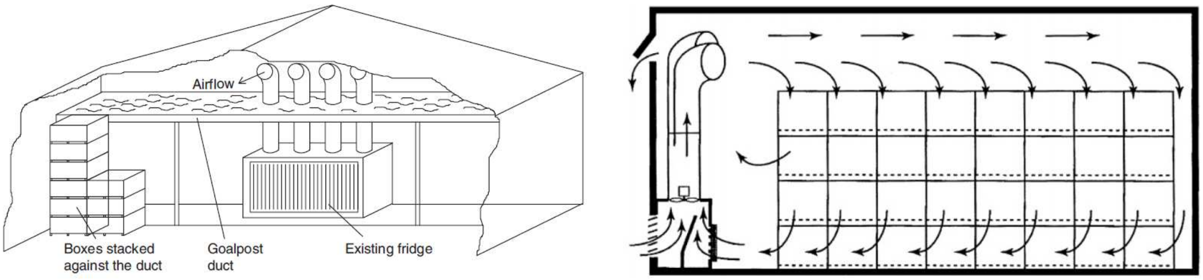

Figure 4-12: Two different configurations of the flow-along ventilation system, left: after Pringle (2009) and right: after Ooster van 't (1999)

storage has several levels where the sacks are stored in small series of piles. The level floors are of porous material and the target is to have a homogeneous climate in the storage. The floors are functioning as a large ventilation duct (see figure 4-13).

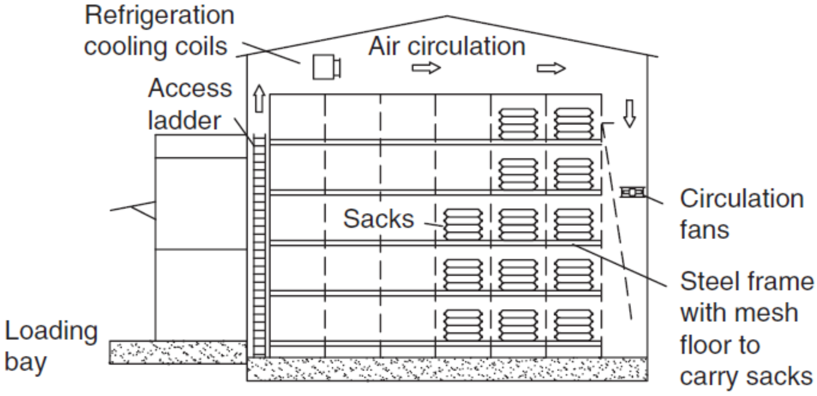

Figure 4-13: A sack store house (Pringle, 2009).

Chapter 5

Modelling agricultural storage

To model a storage with agricultural produce, different choices with respect to the model definition have to be made. The main difference is in the complexities of the storage models. Several components, like spacial distribution and process dynamics are the fundamentals for a realistic physical model. Besides these components, the definition of the system boundaries, are important model components to define for the modelling of the storage. A good definition, interpretation and identification of these components are the base for a working mathematical model. If the physical system is modelled very detailed, often the model becomes very complicated. This has disadvantages for the computations involved in the simulation of the mathematical model and for the controller design. The modelling of a physical system can be defined in three steps:

- Process definition
- Model boundaries
- Model structure

In the following chapter these three steps will be treated in chronological order. In the model structure a detailed description of the transport phenomena and process definitions is stated. This is followed by detailed overview of the models defined in the literature. At last some remarks on these models is given.

5-1 Process definition

The physicals system is usually considered as a dynamical process. For a storage facility the driving components of this process are the products in the facility, the air between the products, the air in the shafts and the environment around the storage. These components affect the systems behaviour, and the control of the system. The four process components and the controlling part have each their own domain (Verdijck, 2003), de-pictured in figure 5-1:

- Product, the specific agricultural product in the store.
- Direct domain, the air between the product in the bulk, box or sack.
- In-direct domain, the air in the facility, like in the ducts and pressure chamber, sensors/actuators.
- Environment, the domain outside the facility.
- Control domain, the domain that is capable to influence the process behaviour.

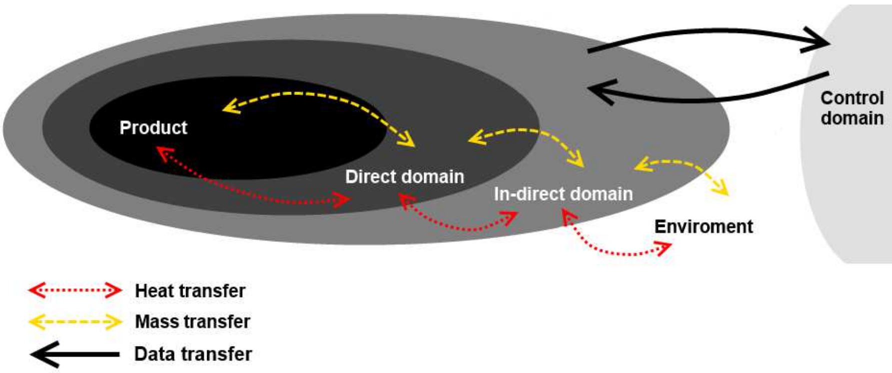

Figure 5-1: The five different domains that characterise the controlled physical system. The arrows are representing the interaction between the different domains.

In a dynamical agricultural storage system interaction between the different domains is taking place. This interaction can be covered in mass, energy and momentum equations. From thermodynamic point of view there are two basic transfer mechanisms, conduction and radiation. A third important energy transfer of heat is caused by convection. This is not a thermodynamic property but an empirical based property that is specific related to heat transfer (Moran, 2006). Besides the energy transfer in the form of heat, also transfer of mass is taking place. The relation of the velocity and the density of gas, fluid or solid are covered by the law of conservation of momentum. Since the products are living mechanisms, the processes that take place in and between these products, have influence on the quality and consequently also on the heat and mass transfer.

The main processes that are taking place in the product domain, are respiration and evaporation (Beukema et al. (1982),Verdijck (2003)). In the direct domain the air between the product is the dominant factor. In this domain, convection is playing an important role in the interaction between the air and the products. The in-direct domain is also characterised by air, the air that is flowing in the ducts. An other important components for the control of the process, like sensors, contribute in this domain. The environment is a very broth domain, a lot of processes are taking place, but in general only the temperature and moisture , and the corresponding interactions, are taken into account. The control domain contains all the parts that are needed to control the climate in the storage system. With this knowledge a clear distinction can be made by the different flows:

- Energy flow in the form of heat

- Mass flow

These two flows are the base of the physical model (Ofoli and Burgess, 1986). To model these phenomena a distinction between the transport and generation of the heat and mass can be made. As stated above, the transportation of the heat and mass can take place in product and air, so the product, direct, in-direct and environment domains. The production terms are taking place in the product domain, but will influence the direct, in-direct and environment domains.

5-2 Model boundaries

In section 4-4 the agricultural indoor storage systems are discussed. A clear distinction between bulk and box storage is stated. For the modelling procedure of the heat and mass transport in the storage, the difference between the two systems concern only the different scales. Assuming that the air by ventilation is distributed homogeneous;y, the configuration of the ventilation duct is negligible for now. Hence, it is assumed that the parameters for the heat and mass balances acting more or less the same, for the different bulk- and box systems (Lukasse et al., 2007). For a more detailed description of the box storage, every box could be taken as one system of its one.

An overall model can be defined as de-pictured in figure 5-2 (left). This is a system with an in- and outflow of the environment. The air streams into an air room where the in- and outside air are homogeneously mixed and ventilated into a air channel. From this air channel the air flows by the forced convection through the product, to the top of the storage.

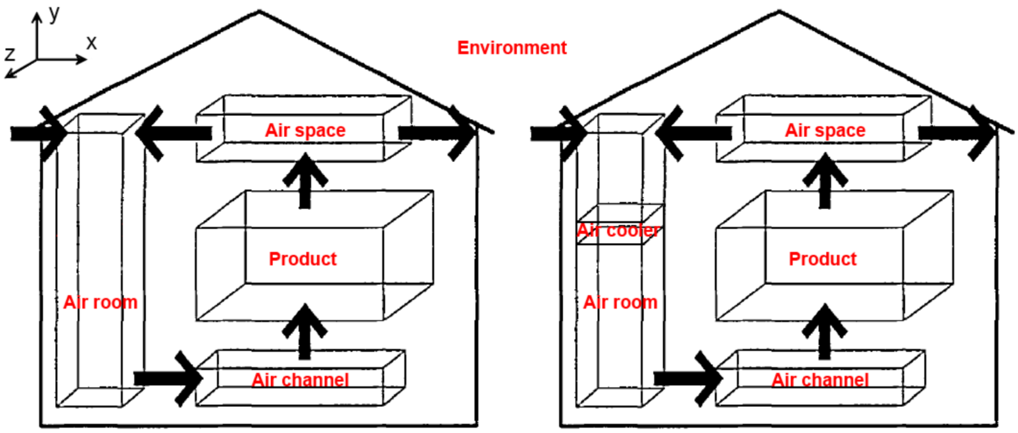

Figure 5-2: On the left, a standard configuration for a storage model without cooled air. On the right, a storage model with air cooling, after Verdijck et al. (1999).

This model can be simplified from 3-D to 2- or 1-D. A 2-D model configuration is de-pictured in figure 5-3. As the model contains heat and mass balances this configuration can be used for both bulk and box systems. If a cooling installation is used, the air is direct cooled down to temperature T_c.

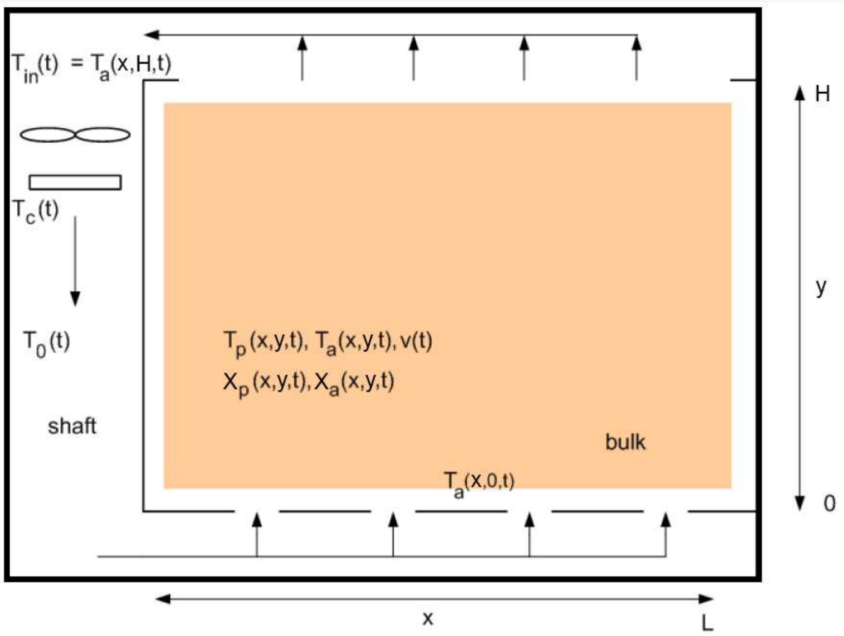

Figure 5-3: 2-D model of a agricultural storage facility (Mourik, 2008)

5-3 Model structure

The complexity of the model is related to the modelled states, the processes that are taken into account and the spatial configuration. Like in figure 5-4, actually three main approaches to build the model states, defined with the (spatial) parameters, can be defined (Amos, 1995).

A lumped parameter model is taking into account one- or more zones in the spatial directions, where a zone is defined as a layer of air with produce. If one zone is considered, the storage facility to an ideally mixed room with temperature, moisture- and CO_2 content as states. If more zones are taken into account, the model becomes more realistic, because there are several layers over the vertical plane. For every zone, a set of ordinary differential equation represent the behaviour of the state.

An even more realistic model is obtained by a fully spatial distributed system. The states, and the parameters that influence them, has a certain degree freedom in the Cartesian co-ordinate system. This system can be represented in three different spatial configurations, in 1-D, 2-D and 3-D. The more realistic, but more, complicated models can be represented by partial differential equations for the different conditions.

Data-base (mechanistic) modelling, as an alternative to physical model, starts from black box modelling. Using real time data a model in the form of a continues-time transfer functions is aimed for. The model is acceptable, if the obtained ordinary differential equations explaining the data well and has a structure that is relevant to the physical system.

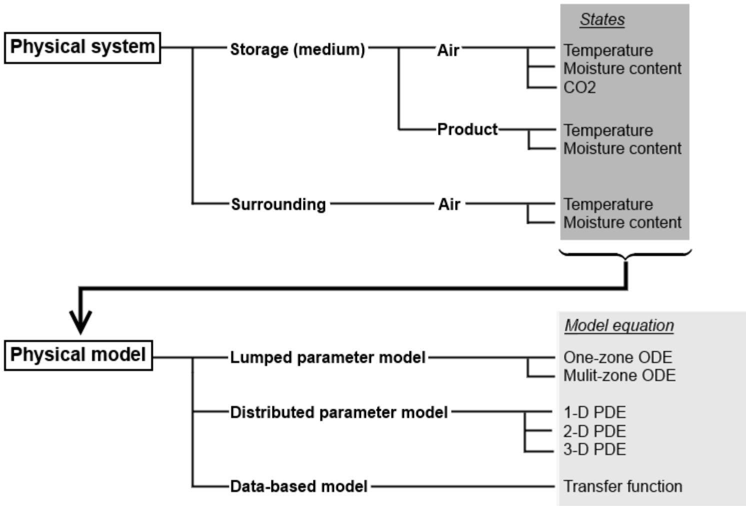

Figure 5-4: The physical system can be convert to a physical model in several ways, also the different choices of states like temperature, moisture and CO_2 are possible

5-3-1 Laws of conservation

A theoretical model description, provides a mathematically simplified notation of the real physical system. For the storage models, where transport of momentum, mass and energy is an important factor, we making use of the laws of conservation. These laws cover the transport, production and forces related of mass, energy and momentum. A general equation for the conservation of a certain amount of 'X' can be derived. This equation describes the reactions responsible for the process in the physical system. This general equation is the base for the state equations that describe the process, and is stated as follows:

$$\underbrace{\frac{\text{accumulation of X}}{\text{unit time}}}_{\text{Time-variant state}} = \underbrace{\frac{\text{flux(X into system - X out of system)}}{\text{unit time}}}_{\text{transport}} + \underbrace{\frac{\text{reaction of X}}{\text{unit time}}}_{\text{production}} \tag{5-1}$$

These laws of conservation are used as well for the lumped parameter models as for the spatial distributed models (Beek et al., 1999). In case of lumped models, only the macroscopic properties are important factors; no insight in the distribution on a spatial plane or point. Hence, only macro-balances could be defined for the conservation laws for mass, energy and other properties of interest. If a control volume in a lumped model is considered, a basic mass or heat balance can be stated as:

$$V\frac{dX}{dt} = \phi_{v,in}X_{in} - \phi_{v,out}X_{out} + Vr_X \tag{5-2}$$

Where V represents the volume of the system. The flux of X in- and out of the system is denoted by $\phi_{v,in}$ and $\phi_{v,out}$. For the heat and mass balance, the reaction of X is represented by the volumetric production r_X. For the momentum balance the production term r_X is interpreted as forces.

For specific heat, mass and momentum balances, with subscript m represents a medium like the product or air, the following equations can be defined:

$$\rho_m V_m C_{p,m} \frac{dT_m}{dt} = \phi_{v,in} \rho_m C_{p,m} T_{m,in} - \phi_{v,out} \rho_m C_{p,m} T_{m,out} + V r_T \tag{5-3}$$

$$\rho_m V_m \frac{dX_m}{dt} = \phi_{v,in} \rho_m X_{m,in} - \phi_{v,out} \rho_m X_{m,out} + V r_X \tag{5-4}$$

$$\rho_m V_m \frac{dv_{i,m}}{dt} = \phi_{v,in} \rho_m v_{i,m,in} - \phi_{v,out} \rho_m v_{i,m,out} + \sum F_i \tag{5-5}$$

For the heat balance (5-3), the derivative of the temperature T is taken. The mass balance (5-4) starts with is the time derivative of mass X. For the momentum equation (5-5) the momentum per unit volume, ρv, is taken. Since, momentum has direction and size we end up with three components (Cartesian coordinates) of momentum. The production is stated as the sum of the forces $\sum F_i$ in a certain direction i.

At a more detailed level, processes at micro scales are active. On this scale smaller volume elements are defined, as subsystems of the whole system. By this volume element the spatial distribution is taken into account. With these micro-balances the distribution of the system quantity is represented. To introduce the spatial distribution, the micro-balance is represented in terms of partial differential equations(PDE). By this representation a 3-D model environment can be created. These PDE's can only be solved analytically for relative simple situations. Hence, for more complex systems, these calculations with PDE's are very time consuming. The accumulation of X per unit of time is now depending on the fluxes at three spatial coordinates x, y and z. The basic accumulation formula can be defined for the micro scale case as follows:

$$\frac{\partial X}{\partial t} = -\frac{\partial \phi''_x}{\partial x} - \frac{\partial \phi''_y}{\partial y} - \frac{\partial \phi''_z}{\partial z} + r_X \tag{5-6}$$

The flux density of X on this scale is considered as a static and convective transport term, and is given by:

$$\phi''_n = v_n X - (\text{constant}) \frac{\partial X}{\partial n} \tag{5-7}$$

Where n are the directions x, y and z. In the term X, v_n represents a velocity in a certain direction. Later on, this is generalized to the vector case, where $\vec{v}$ represents a vector with the velocities in the specific directions. After substituting (5-7) in (5-6) a more detailed formulation is provided:

$$\frac{\partial X}{\partial t} = -\frac{\partial v_x X}{\partial x} - \frac{\partial v_y X}{\partial y} - \frac{\partial v_z X}{\partial z} + c\frac{\partial^2 X}{\partial x^2} + c\frac{\partial^2 X}{\partial y^2} + c\frac{\partial^2 X}{\partial z^2} + r_X \tag{5-8}$$

$$\frac{\partial X}{\partial t} = -v_x \frac{\partial X}{\partial x} - v_y \frac{\partial X}{\partial y} - v_z \frac{\partial X}{\partial z} + c\frac{\partial^2 X}{\partial x^2} + c\frac{\partial^2 X}{\partial y^2} + c\frac{\partial^2 X}{\partial z^2} + r_X \tag{5-9}$$

In compact notation:

$$\frac{\partial X}{\partial t} = -\vec{v} \cdot \nabla X + c \cdot \Delta X + r_X \tag{5-10}$$

Where $\vec{v} = [v_x \; v_y \; v_z]^T$, the gradient operator (nabla) $\nabla = \left[\frac{\partial}{\partial x} \; \frac{\partial}{\partial y} \; \frac{\partial}{\partial z}\right]^T$ and the Laplacian operator (operator with second derivatives) $\Delta = \left[\frac{\partial^2}{\partial x^2} \; \frac{\partial^2}{\partial y^2} \; \frac{\partial^2}{\partial z^2}\right]^T$.

The expression for the accumulation of X can also be denoted in terms of a convective derivative. This Lagrangian derivative denotes the derivative with respect to a spatial coordinate system:

$$\frac{DX}{Dt} = c\frac{\partial^2 X}{\partial x^2} + c\frac{\partial^2 X}{\partial y^2} + c\frac{\partial^2 X}{\partial z^2} + r_X \tag{5-11}$$

$$\left[\frac{\partial}{\partial t} + \vec{v} \cdot \nabla\right] X = c \cdot \Delta X + r_X \tag{5-12}$$

For the heat, mass and momentum balance the following standard formulas (5-13), (5-14) and (5-15) can be defined.

$$\rho_m C_{p,m} \frac{\partial T}{\partial t} = -\rho_m C_{p,m} \vec{v} \cdot \nabla T + \lambda \cdot \Delta T + r_T \tag{5-13}$$

$$\rho_m \frac{\partial X}{\partial t} = -\rho_m \vec{v} \cdot \nabla X + \rho_m \mathbb{D} \cdot \Delta X + r_X \tag{5-14}$$

$$\rho_m \frac{\partial v_i}{\partial t} = -\rho_m \vec{v}_i \cdot \nabla v_n + \rho_m \nu \cdot \Delta v_i + \frac{\partial p}{\partial i} + \sum F_i \tag{5-15}$$

In the balance for the temperature the thermal conductivity λ is multiplied by the Laplacian of the temperature. In the mass-balance case the Laplacian is multiplied by the diffusion coefficient $\mathbb{D}$, and in the momentum equation the kinetic viscosity ν is used for this constant. Note that the time derivative is taken with respect to i, so three time derivatives are obtained. Therefore, three momentum equations are obtained in direction i, $i = [x \; y \; z]$ and within these balance equations, $n = [x \; y \; z]$, is taken to the corresponding derivative. In (5-14) the production term is split into two terms, the sum of the forces, and the derivative in direction i of the pressure.

5-3-2 Distinction in phases

In the process description presented above, a distinction is made between the spatial description options for the model. In this description a clear distinction between different states of phase is not yet stated. So, these models are called one-phase models. In general, one can distinguish between the gas and solid phase of the modelled bulk. The bulk could be modelled as a porous medium as in figure 5-5. In this case, a two-phase model is obtained. Two different balance equation for both of the different phases should be defined.

In equation 5-16 the stagnant solid phase equation is represented and the moving gas phase is defined in equation 5-17 (Beukema, 1980).

$$(1-\epsilon)\frac{\partial X_p}{\partial t} = (1-\epsilon)\lambda_p \cdot \Delta X_P + r_p + (1-\epsilon)\xi A(X_p - X_g) \tag{5-16}$$

$$(\epsilon)\frac{\partial X_g}{\partial t} = -\vec{v} \cdot \nabla X_g + (\epsilon)\lambda_g \cdot \Delta X_g + r_g + (1-\epsilon)\xi A(X_p - X_g) \tag{5-17}$$

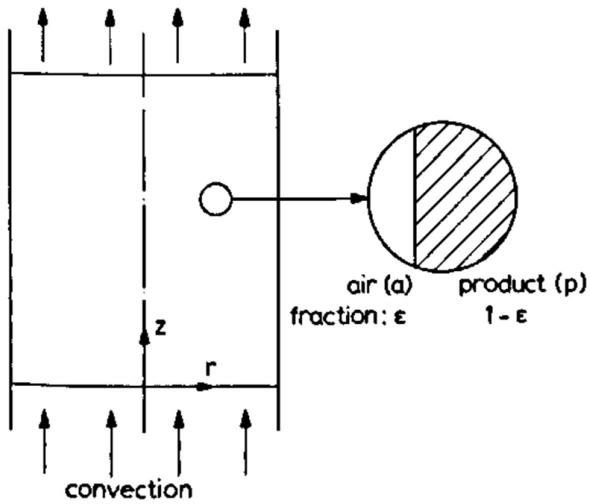

Figure 5-5: The bulk in described in a two-dimensional coordinate system as a porous medium (Beukema, 1980).

Between these two different phases some interaction should be taken into account. The last term in both the equations 5-16 and 5-17 represents this interaction. In the case of heat transfer, ξ represents the heat transfer between solid and gas (to be discussed later). In the case of mass transfer ξ represents the mass transfer coefficient (Beukema et al., 1982). The porosity is defined by ϵ.

5-3-3 Transport

The transport of mass and heat is already introduced in the beginning of section 5-3. This transport is denoted as the in- and output fluxes of the control volume. Typically, transport is state dependent. In every different balance of the state, influences of these transport phenomena are playing a role. For every state the transport terms are defined as the flow multiplied by the specific in and output of the state variable. This is the base of the flux representing the transport phenomena. This can be multiplied or divided by constants, depending on the notation of the state and structure of the model. In a state space notation for a lumped model the following equation is defined for the heat and mass transports:

$$\frac{\partial X}{\partial t} = \phi(X_{i,in} - X_i) \tag{5-18}$$

For the micro-balance, where the spatial distribution is taken into account, the expressing for the transport can be defined as:

$$\frac{\partial X}{\partial t} = -\frac{\partial \phi''_x}{\partial x} - \frac{\partial \phi''_y}{\partial y} - \frac{\partial \phi''_z}{\partial z} \tag{5-19}$$

Where the flux ϕ''_n is defined as in (5-7).

5-3-4 Production in heat and mass balance

The accumulation of X in the system, as defined in equation 5-1, is partly derived by the production of a certain amount of X. In the heat and mass balance, the production term is presented as r_X, where the subscript X denotes the dependency on the defined amount of X. Different production phenomena are acting on the physical system. Some processes dominate the mass and heat balances. If the system is in steady state, conduction and respiration contribute most to the system behaviour (Lukasse et al., 2007). If this is not the case, each of the following processes should be taken into account (Beukema et al. (1982), Lukasse et al. (2007), Ooster van 't (1999) and Verdijck et al. (1999)):

- Conduction
- Radiation
- Convection
- Evaporation
- Respiration

These process are explained in more detail beneath. A physical overview of these processes in a bulk with potatoes, is de-pictured in figure 5-6.

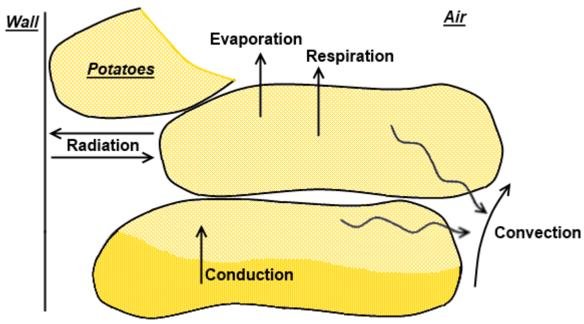

Figure 5-6: The processes that are taking place in the bulk of potatoes.

5-3-4-1 Conduction

Conduction is the transfer of energy in the form of heat on molecular scale. Heat is transferred from the molecules with a higher energetic level to molecules to neighbour molecules with a lower energetic level. This transfer can take place in solids, liquids and in gases. Taking a plane in consideration, the rate of heat transfer in x direction on that plane is defined as Q_x. Q_x depends on the specific plane area, A, and the corresponding gradient of the temperature T in the the x direction. Multiplying this area and temperature gradient with the thermal conductivity constant the energy transfer by conduction can be determined as follows:

$$\dot{Q}_x = -kA\frac{dT}{dx} \tag{5-20}$$

The relationship holds under the condition that the temperature varies linearly in x direction over a total length L:

$$\dot{Q}_x = -kA\frac{T_2 - T_1}{L} \tag{5-21}$$

5-3-4-2 Radiation

Radiation is the energy transfer of heat by photons or electromagnetic waves. These photons travels relative freely through the air between two surfaces. Where the molecules by conduction travels relative short distances $\sim 0.65\mu m$ (Mills, 1999), the photons responsible in the radiation process can travel relative large distances. The transmission and absorption of the thermal radiation are caused by solid surfaces, gases and liquids. The rate of emission of radiation is defined by the Stefan-Boltzmann law. The Stefan-Boltzmann constant, σ, gives the rate of radiation of a surface A. The rate of energy emission $\dot{Q}_e$, can be determined by multiplying the constant σ with the surface, surface temperature T_b to the power four and the emissivity ε, so that:

$$\dot{Q}_e = \varepsilon\sigma A T_b^4 \tag{5-22}$$

If radiation between two real surfaces is taken into account, one usually models this kind of surfaces as a so called gray surface (Mills, 1999). This will give a realistic emittance of the real situation. The rate of heat flow between two gray surfaces with a certain geometry depends on temperatures, emittance, and geometry and is given by:

$$\dot{Q}_{12} = A_1\mathbb{F}_{12}(\sigma T_1^4 - \sigma T_2^4) \tag{5-23}$$

Where $\mathbb{F}_{12}$ is a transfer factor depending on the emittance and geometry. If the area A_1 is small compared to area A_2 or surface two is nearly a black surface (so all incident radiation is absorbed), the transfer coefficient can be simplified to be only the emittance of surface one:

$$\dot{Q}_{12} = A_1\varepsilon_1(\sigma T_1^4 - \sigma T_2^4) \tag{5-24}$$

This expression can be linearised under the assumption that the temperatures T_1 and T_2 are nearly the same:

$$\dot{Q}_{12} \simeq A_1\varepsilon_1\sigma(4T_m^3)(T_1 - T_2) \tag{5-25}$$

Where T_m is the mean temperature of T_1 and T_2. For ε_1, σ and $(4T_m^3)$ constant we obtain the following equation:

$$\dot{Q}_{12} \simeq A_1 h_r(T_1 - T_2) \tag{5-26}$$

5-3-4-3 Convection

Convection can be interpreted as transport of energy by bulk motion of a medium. It is deduced from momentum transport, where a volume with a mass and velocity can transport momentum. In addition to this, also mass transfer, between a surface and bulk motion is interpreted as convection. In this report the convection of heat and mass is considered, and can also be called mass and heat transfer of a bulk motion.

Convection of energy, is now interpreted as the energy transport between a (solid) surface and a bulk motion of a liquid or gas. In this process a bulk motion of air with temperature T_a is flowing along a surface A with temperature T_s. Then, by effect of conduction the heat is transferred to the bulk with the lowest temperature. The amount of heat transfer is directly related to an empirical parameter, the heat transfer coefficient h. This coefficient relates the flow pattern near the surface to the bulk flow. As stated before a distinction between natural and forced convection could be made. If a forced flow is acting on the bulk matter, the heat transfer coefficient is usually higher then in the case where natural convection is acting on a surface A. With these knowledge the rate of energy transfer due to convection can be stated as:

$$\dot{Q}_c = Ah_c(T_s - T_a) \tag{5-27}$$

The heat transfer coefficient h_c depends on the flow of the medium. For laminar flows the heat transfer coefficient is proportional related to the thermal conductivity. For a turbulent flow the heat transfer coefficient depending strongly on the velocity (Mills, 1999). The transfer coefficient can be defined by experimental data. This expression for h_c can be defined as a function that depends on the Nusselt number(Nu):

$$h_c = \frac{Nuk}{L} \tag{5-28}$$

This number is experimentally defined for different flow configurations (Whitaker, 1972). This Nusselt number is a function of the Reynolds number(Re) and the Prandtl number(Pr), which are functions of velocity, specific volume, thermal diffusivity and dimension of the medium. For flow through packed beds the Nusselt number can be defined as (5-29),

$$Nu = (0.5Re^{1/2} + 0.2Re^{2/3})Pr^{1/3} \tag{5-29}$$

$$20 < Re < 10^4 \tag{5-30}$$

$$0.5 < Pr < 20 \tag{5-31}$$

With the corresponding Reynolds and Prandtl numbers (Mills, 1999)

Convective mass transfer is comparable to convective heat transfer, only now mass in stead of energy is transported between a surface and bulk motion of a liquid or gas. A frequently used notation for the mass transfer, in terms of species 1, is given by:

$$j_{1,s} = \eth_{m1}(m_{1,s} - m_{1,a}) \tag{5-32}$$

Where $\eth_{m1}$ is the mass transfer coefficient, and m the mass fraction.

The mass transfer coefficient $\eth_{m1}$, likewise as the heat transfer coefficient, is depending on a empirical expression. For the mass transfer coefficient the Sherwood number (Sh) can be defined. This expression is obtained by replacing the Prandtl number, in the Nusselt number (5-29), by the Schmidt number. Now the expression for the mass transfer coefficient can be defined as follows:

$$\eth_m = \frac{Sh\rho\mathcal{D}_{ab}}{D} \tag{5-33}$$

Where $\mathcal{D}_{ab}$ is the diffusion coefficient and D a diameter. For gasses the Schmidt number is in the same range of the Prandtl number and so $Sc \approx Pr$. Consequently, the expression of Sherwood is similar to the Nusselt number, and the implementation of Sherwood is simular to (5-29)-(5-31).

Overall heat transfer coefficient. For conduction, radiation and convection an overall heat transfer coefficient can be considered. All the parameters in equation (5-21), (5-26), (5-27), can be seen as a thermal resistance R. Consequently, these equations can be states as in equation follows:

$$\dot{Q}_{conduction} = \frac{-\kappa A}{L}(T_2 - T_1) = \frac{1}{R}(T_2 - T_1), \text{with} \quad R = \frac{L}{\kappa A} \tag{5-34}$$

$$\dot{Q}_{radiation} = A_1 h_r (T_2 - T_1) = \frac{1}{R}(T_2 - T_1), \text{with} \quad R = \frac{1}{h_r A} \tag{5-35}$$

$$\dot{Q}_{convection} = A h_c (T_2 - T_1) = \frac{1}{R}(T_2 - T_1), \text{with} \quad R = \frac{1}{h_c A} \tag{5-36}$$

The total heat transfer from these parallel processes is then defined as:

$$\dot{Q}_{total} = \frac{A(T_i - T_o)}{R} \tag{5-37}$$

Where

$$R = \frac{L}{\kappa A} + \frac{1}{h_c A} + \frac{1}{h_r A} \tag{5-38}$$

5-3-4-4 Evaporation

Evaporation is the transformation of a liquid into vapour. Evaporation is caused by two different phenomena. One is at the boiling point of the liquid, where vapour with liquid and the other takes place at the surface of the liquid. The evaporation phenomenon that is considered in this report, is the evaporation of water at a surface of agricultural produce. In this case, evaporation is caused by a difference in vapour concentration at the surface area and the adjacent air. The evaporation is induced by the released energy of the motion of molecules that bump into each other. If the moisture content in the surrounding air is lower as in the produce, the water in the produce is evaporated by the released energy. Hence, the rate of evaporation depends on the temperature, pressure and the humidity of the produce and surroundings.

Different expressions for the evaporation can be found, because mass transport can be described by different driving forces. A general notation uses the evaporative or latent heat flux, and is based on mass transfer (5-32). By multiplying (5-32), with the enthalpy of vaporization h_{fg}, the evaporation can be described by:

$$\dot{Q}_{evap} = \eth_{m1}(m_{1,s} - m_{l,a})h_{fg} \tag{5-39}$$

If the processes and so the parameters related to the evaporation are lumped together, a simple expression can be found. The total heat flow by evaporation, in a more lumped notation, can be calculated by multiplying an evaporation coefficient with an area and a ratio of the heat and mass transfer coefficient. This ratio can be derived from the governing equations of fluid dynamics (Steeman et al., 2009). A lumped notation for evaporation is given by:

$$\dot{Q}_{evap} = - \bigtriangleup H_L G \tag{5-40}$$

Where a latent heat of vaporization $\bigtriangleup H_L$, is multiplied by the total mass flow exchange at the surface G.

5-3-4-5 Respiration

Respiration is a biochemical transformation process. In living products energy is produced by oxidation of organic matter. This production is caused by reactions in the living organism. These processes convert the nutrients (that are the important factor in the quality of the product), into adenosine triphosphate, heat, CO_2 and water:

$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O + (ATP + Heat) \tag{5-41}$$

This process dependence on the temperature of the product itself, if the product is in steady state condition. For potato tuber Lukasse et al. (2007) expressed the respiration in terms of a second-order polynomial in the product temperatures $T_{product}$:

$$Q_{resp} = p_{resp,1} - p_{resp,2}T_{product} + p_{resp,3}T_{product}^2 \tag{5-42}$$

Where $p_{resp,i}$, defines respiration constants. Also simplifications of 5-42 are used, so a first-order polynomial or only a respiration constant.

5-3-5 Production in momentum balance

The production terms in the momentum equations like, (5-5) and (5-15) are defined as forces. The term $\sum F_i$ is the sum of the forces that contribute to the momentum balance, defined in a certain direction i. The interpretation of the production term, as force, follows from the fact that momentum is the product of mass and velocity. For systems with flow, two typical forces as production terms can be defined:

- Pressure force
- Potential force

5-3-5-1 Pressure force

The pressure force was already introduced in (5-15) as:

$$F_{pressure} = \frac{\partial p}{\partial i} = \nabla p \tag{5-43}$$

Where p is the pressure acting in a specific direction i, on a volume in the mesh. The pressure gradient describes the directions of the greatest rate of pressure difference at a particular point.

5-3-5-2 Potential force

Potential forces are the forces caused by the gravitational acceleration g. Gravity acts on every element, so on all the atoms and molecules. The potential force is like the pressure force defined as the force per unit volume:

$$F_{potential} = \rho g \tag{5-44}$$

If the defined volume is at rest, the potential and pressure force acting on the volume, should be in balance. So the sum of the both forces should be equal to 0:

$$-\nabla p + \rho g = 0 \tag{5-45}$$

5-4 Model classification

In the literature quite some modelling work on the storage of food products has been presented. In the first place, our interest is in models used for the storage of potatoes. These models are strongly related to models that describe transport phenomena in a porous medium. Table 5-1 provides a overview of recent models that are developed for transport phenomena in a porous medium, and in particular; for potatoes in a bulk.

Most of the models defined in literature (Table 5-1) are describing the transport, heat and moisture production in a facility. Some of them are also used for controlling the states in the storage facility (see e.g. Keesman et al. 2002; Marchant et al. 1994; Verdijck et al. 1999; Mourik et al. 2012; Gottschalk 1996; Price et al. 1999) or for the modelling of a controlled storage facility (see Nahor et al. 2004). A good modelling and control structure is provided by Verdijck and van Straten (2002). Other control methods, with more or less the same mathematical models, are defined in Mourik et al. (2010), Verdijck (2003), Verdijck and Tijskens (2003), and Gottschalk et al. (2003). Also some optimisations related articles are published (see Lukasse et al. 2009; Verdijck et al. 2005).

In recent years, many CFD simulation studies on the post-harvest processes were performed. A recent review of these CFD simulation studies is given by Ambaw et al. (2013). Verboven et al. (2006) gives the basics and advantage of different CFD modelling methods. A more dated review with CFD overview is provided by Wang and Sun (2003). CFD models are described by Xu and Burfoot (1999), Chourasia and Goswami (2007), Nahor et al. (2005), Mohan and Talukdar (2010), Desta et al. (2004) and Kondrashov (2007).

Somewhat less related to the field of interest are models that describe the processing in a potato or porous medium for a certain application. Typical applications are: pre-cooling (Ansari, 1999), drying (Simal et al. 1994; Wang and Brennan 1995; Mohan and Talukdar 2010), effect of temperature on the sugar content (Hertog et al., 1997), moisture loss for bulk potatoes (Misener and MacDonald, 1975), modelling changes in rheological properties (Solomon and Jindal, 2007), transfer of spherical fresh produce (Hayakawa and Succar, 1982), resistance in potato bulk (Irvine et al., 1993), calculation of the heat transfer (Varga and Oliveira, 2000) and heat transfer coefficient calculation during frying (Erdogdu and Dejmek, 2010)

In table 5-1 not all models are directly suitable for the modelling of temperature and humidity profiles in a bulk of potatoes that is subjected tot natural and forced convection. The models that will not be further explored are presented in Table 5-2.

Table 5-1: Overview of models, describing transport phenomena in a potato bulk.

Lumped parameter	1-D	2-D	3-D	DBM
Misener and Shove (1976)	Ofoli and Burgess (1986)	Brugger (1979)††	(Beukema et al., 1983)	Price et al. (1999)
Marchant et al. (1994)	Gottschalk (1996)	Beukema et al. (1982)	Wang and Touber (1990)	Desta et al. (2004)
Amos (1995)	Verdijck et al. (1999)†	Royer and Flores (1994)	Xu and Burfoot (1999)	
Keesman et al. (2002)	Ooster van 't (1999)	Kondrashov (2000)	Xu et al. (2002)	
Nahor et al. (2004)	Mourik (2008)†	Alvarez et al. (2003)	Nahor et al. (2005)	
Lukasse et al. (2007)	Mourik et al. (2012)		Verboven et al. (2006)	
			Chourasia and Goswami (2007)	
			Kondrashov (2007)	

†*: More dimensional distribution of the product model*
††*: Not available*

The models, in Table 5-1, that are interesting for this research are described in some more detail. These models are interesting, because of the combination of the model structure and the used application. The Tables 5-3, 5-4, 5-5 and 5-6 provide an overview of the processes that are taken into account in the balance equations, in the corresponding models.

In the previous section the processes occurring in the bulk are defined. For the overview of the models we use the definitions introduced before. To keep the notation in the tables as simple as possible shorthand notations are used. By "transp." we meant the transport terms. "Cond." meant conduction, by "rad." the radiation is meant. The convection of heat and mass, we use the notation transfer of heat and mass, "evap." means evaporation and "resp." should be interpreted as respiration. When momentum balances are included in the models, extra columns for the pressure gradient and for potential force, as F are introduced.

Table 5-2: Structure overview of models used for porous medium bulk models

Reference	remark
(Misener and Shove, 1976)	Model for consecutive processes for potato drying
(Marchant et al., 1994):	A flow along model
(Amos, 1995):	Focused on apple storehouses
(Nahor et al., 2004):	A controlled atmosphere tested with apples
(Mourik, 2008):	Only temperature distribution model
(Mourik et al., 2012):	Only temperature distribution model
(Royer and Flores, 1994):	Simulation of porous medium only natural convection
(Alvarez et al., 2003):	Two dimensional, not evaluated with potatoes
(Beukema et al., 1983):	Only a temperature distribution model
(Wang and Touber, 1990):	Refrigerated flow along model
(Xu et al., 2002):	Uses same equations as (Xu and Burfoot, 1999)
(Nahor et al., 2005):	Multiple configurations, flow along model
(Verboven et al., 2006)	Models for refrigerated food

Table 5-3: Model overview, Lumped model

	State	$\frac{\partial S}{\partial t}$	transp.	cond.	rad.	transfer heat	evap.	resp.
(Keesman et al., 2002) 0-D	T_a	S	+			+		
	X_a	S	+				+	
	T_p	S				+	+	+
(Lukasse et al., 2007) 0-D	T_a	S	+	+		+		
	X_a	S	+				+	
	T_p	S				+	+	+
	X_p	S					+	+
	CO_2	S	+					+

S*: modelled state,* +*: used terms in the corresponding state equation*

Table 5-4: Model overview, 1-D

	State	$\frac{\partial S}{\partial t}$	transp. $\frac{\partial S}{\partial x}$	transp. $\frac{\partial^2 S}{\partial x^2}$	cond.	transfer heat	transfer mass	evap.	resp.
(Ofoli and Burgess, 1986) 1-D	T_a	S	+			+		$+^{\dagger}$	
	X_a	S	+					$+^{\dagger}$	
	T_p	S				+		$+^{\dagger}$	+
	X_p	S					+		
(Gottschalk, 1996) 1-D	T_a		+			+		+	
	X_a		+				+		
	T_p	S	+			+		+	+
	X_p	S					+		
(Ooster van 't, 1999) 1-D	T_1		+			+			
	X_a		+				+	+	
	T_p	S		+	+	+		+	+
(Verdijck et al., 1999) 1-D	T_a	S	+			+		+	
	X_a	S	+					+	
	T_p	S		$+^{*}$		+		+	+
	X_p	S						+	+

S*: modelled state, + : used terms in the corresponding state equation,*
**: 2-D temperature profile,*
†*: influence of evaporation on control volume where the second derivative of mass w.r.t time is taken*

Table 5-5: Model overview, 2-D

	State	$\frac{\partial S}{\partial t}$	transp. $\frac{\partial S}{\partial x}$	transp. $\frac{\partial S}{\partial y}$	transp. $\frac{\partial^2 S}{\partial x^2}$	transp. $\frac{\partial^2 S}{\partial y^2}$	cond.	rad.	transfer heat	transfer mass	evap.	resp.	$\frac{\partial P}{\partial X}$
(Beukema et al., 1982) 2-D	T_a		+						+				
	X_a	S	+			+				+			
	T_p	S			+	+		+	+		+	+	
(Kondrashov, 2000) 2-D	T_a	S	+	+	+	+			+				
	X_a	S	+	+	+	+				+			
	T_p	S			+	+			+		+	+	
	u_x	S	+	+									+
	u_y	S	+	+						+			+
	T_{g1}	S	+		+	+							
	T_{g2}	S		+	+								
	T_{g3}	S			+	+							

S*: modelled state, +: used terms in the corresponding state equation,*
T_{gi}*: conduction related to the construction of the store,*
u_x*: equation of motion of air in a pile for mixed convection*

Table 5-6: Model overview, 3-D

			transp.							transfer					
	State	$\frac{\partial S}{\partial t}$	$\frac{\partial S}{\partial x}$	$\frac{\partial S}{\partial y}$	$\frac{\partial S}{\partial z}$	$\frac{\partial^2 S}{\partial x^2}$	$\frac{\partial^2 S}{\partial y^2}$	$\frac{\partial^2 S}{\partial z^2}$	Cond.	heat	mass	evap.	resp.	$\frac{\partial P}{\partial X}$	force
(Xu and Burfoot, 1999) 3-D	ρ_a	S	+	+	+						+				
	$\rho_a v_a$	S	+	+	+									+	R
	E_a	S	+	+	+	+	+	+							
	X_a	S	+	+	+	+	+	+			+				
	E_p	S				$+^\dagger$			+	b		b	+		
	X_p	S				+					b				
(Chourasia and Goswami, 2007) 3-D	ρ_a	S	+	+	+						+				
	$\rho_a v_a$	S	+	+	+									+	+
	E_{ap}	S	+	+	+	+	+	+				+	+	+	
	X_a	S	+	+	+	+	+	+			+				
(Kondrashov, 2007) 3-D	T_a	S	+	+	+	+	+	+		+					
	X	S	+	+	+	+	+	+			+				
	T_p	S				+	+	+				+	+		
	U_{fil}	S	+	+	+						+			+	R
	T_g	S	+	+	+	+	+	+							

S*: modelled state,* +*: used terms in the corresponding state equation,*
b*: exposed in boundary condition,*
†*: The derivative of states related to diffusivity and conductivity,*
R*: aerodynamics resistance*

5-4-1 Explanation defined models

To complete the overview of the storage models, a summary of the models presented in Table 5-3, 5-4, 5-5 and 5-6 will be given. For every model a clear description of the aim of the article will be given, completed with a table with the modes and assumptions made on the model.

(Keesman et al., 2002) presents a physical model of a storage facility, that is used later on for a receding horizon optimal controller(RHOC) for this facility. The model contains relevant aspects of the process from climate control point of view. Also the mixing ratio of in- and outside air is taken into account. Before implementation of the model for RHOC, a model reduction step, using singular perturbation theory, is accomplished.

Table 5-7: Modes and assumptions (Keesman et al., 2002)

Modes	Assumptions
Natural flow Forced ventilation	- Uniform distribution of temperature and moisture content - Ventilation duct volume is neglected - Respiration rate and density of products are constant - Ventilation heat is neglected - Relative humidity of air can be >100% - Transpiration heat is completely withdrawn from the product - Mixing ration of the out- and inside air linearly depends on the valve opening

(Lukasse et al., 2007) provides a physical model to predict climate dynamics in ventilated bulk-storage of agricultural produce. They present the modelling procedure and present the model in a well-ordered model presentation. A zonal decomposition is used and the process and transport terms are represented in a matrix-vector notation.

Table 5-8: Modes and assumptions (Lukasse et al., 2007)

Modes	Assumptions
Natural flow	- Analysis of flow in zones the spatial distribution of minor importance
Forced ventilation	- Perfect mixed air flow
Cooling	- Evaporation may be neglected if one is only interested in steady state temperature-distribution - Heat exchange through the walls

(Ofoli and Burgess, 1986) describes a mathematical model for stored potatoes from thermodynamic point of view. An extensive overview to the eventually state equations is produced. Afterwards the model is tested by data from of ventilated cooling of a porous bed of potatoes.

Table 5-9: Modes and assumptions (Ofoli and Burgess, 1986)

Modes	Assumptions
Natural convection Forced convection Cooling	- Product and water content are in thermal equilibrium - Constant mass of product - Thermal conduction between particles neglected - Neglected change in product volume - Constant velocity along the bin

(Gottschalk, 1996) provides a one-dimensional mathematical model for a potato pile. Heat and mass transfer between different layers of potatoes are defined. In this article the model is used to design a fuzzy controller. This controller should keep the temperature at a certain level, and cool the stack to a certain temperature.

Table 5-10: Modes and assumptions (Gottschalk, 1996)

Modes	Assumptions
Natural flow Forced convection Cooling	- The air flow is incompressible - The air flow is non-viscous, i.e. free of internal friction - The bulk material is homogeneous - The air flow stream lines are parallel to the ground level(Zones)

(Ooster van 't, 1999) describes a model for only the potato stack, with distributed dynamic balance equations for the transport processes within the stack. The potato temperature, air temperature and air humidity are described using a finite element method. The physical system is divided in finite elements that are interconnected by nodes, each node contains an energy or moisture balance. For a linear static calculation of each element and corresponding state equations, a matrix-vector element equation is defined.

Table 5-11: Modes and assumptions (Ooster van 't, 1999)

Modes	Assumptions
Natural flow	- Only the potato stack is considered - Uniform distribution of temperature and moisture content in y and z direction - The load vector contains independent state variable terms and can be completed by adding elements for ventilation, heat loss to the surrounding or by forced cooling and heating.

(Verdijck et al., 1999) presents an industrial potato storage process. The model contains the relevant processes on micro and macro scale. The system is modelled with the intention to use the model to develop a model-based process controller.

Table 5-12: Modes and assumptions (Verdijck et al., 1999)

Modes	Assumptions
Forced ventilation Natural flow	- Constant potato volume - Uniform distribution of the potatoes in space - Uniform air stream - Constant specific heats, so temperature independent - Moisture and temperature profiles inside the potatoes and heat conduction in the air phase can be neglected.

(Beukema et al., 1982) defines a two-dimensional two-phase model of the cooling and storage process of agricultural products in a cylindrical container. The work provides insight in the influence of natural convection, self-heating and cooling.

Table 5-13: Modes and assumptions (Beukema et al., 1982)

Modes	Assumptions
Forced ventilation Natural convection Cooling	- Same assumptions ass in a fixed bed catalytic reactor - Include natural convection due to low air velocity - Pseudo steady state in the air-phase - Physical properties of the system are constant - Local differences of velocity of natural convection are neglected - Condensation occurs in a thin water film on the total product surface - The equilibrium water vapour concentration is assumed to be equals to the saturated water vapour

(Kondrashov, 2000) proposes a model of coupled heat and moisture exchange in a agricultural storehouse. The environmental temperature is set at -25 degrees Celsius. The configuration is well described. This model is used for simulations to provide temperature profiles in a potato bulk.

Table 5-14: Modes and assumptions (Kondrashov, 2000)

Modes	Assumptions
Natural convection Forced convection	- Uniform velocity distribution - humidity of air supplied is 100%

(Xu and Burfoot, 1999) presents a three-dimensional model for CFD simulations. They use a bed of potatoes to predict and measure the temperature profiles during forced cooling. The model contains six basic equations for the air, potatoes and the interaction between the two.

Table 5-15: Modes and assumptions (Xu and Burfoot, 1999)

Modes	Assumptions
Forced ventilation cooling	- No shrinkage - Laminar flow through the bulk - Uniform velocity, temperature and moisture profiles at the inlet - Axial symmetry assumed

(Chourasia and Goswami, 2007) develops a three-dimensional model, which is used for a CFD simulation. They simulate transport phenomena in a heat and mass generating porous medium covered in a sack. They tested the model in a cooled and natural convective environment.

Table 5-16: Modes and assumptions (Chourasia and Goswami, 2007)

Modes	Assumptions
Natural convection	- Temperature and moisture differences in one single potato did not require modelling
Cooling	- An single bag is conforms to a rectangular shape when it is laid flat on the ground

(Kondrashov, 2007) developes a model that describes the heat and moisture transfer in a potato pile where only natural convection is considered.

Table 5-17: Modes and assumptions (Kondrashov, 2007)

Modes	Assumptions
Natural convection	air velocity of 0.12 m/s

5-4-2 Remarks on the overview

In all the different model classifications in Tables 5-3 - 5-6 different models are defined. Some of these can be used to simulate the behaviour of the physical system, in the second part of the thesis. The interesting physical systems are the bulk systems, drying wall and the tunnel ventilation. Especially, for the box systems the investigation on blowing and suction could be interesting.

To investigate the non-homogeneities in a storage facility, the lumped models are not suitable. The data-based mechanistic models are also not suitable, because these models need experimental data from specific facilities. Hence, it is hard and not sufficient to get a model that is universally usable for different geometries. The distributed parameter models are the most suitable ones for (re)design and boundary control.

To end up with a representative model for long period storage, important processes and transport terms, like in most 2-D and 3-D models should be included. In all the distributed parameter models spatial distribution terms like diffusion and conduction are used. So, for a first implementation in COMSOL, a general 1-D transport term and complete balance with the process dynamics of corresponding state is used. The models of Kondrashov (2007, 2000) and Xu and Burfoot (1999) contain a complete set of transport and process terms, Lukasse et al. (2007) provide a model for the respiration and evaporation rates. In principle, the spatial distribution can then be easily extended to 2-D and 3-D.

Chapter 6

Implementation

In this chapter a basic implementation of a agricultural storage facility will be described. The ultimate purpose of the simulation is to couple the process states to different geometries of a real storage facility. After simulation the predicted spatially distributed temperature, mass and momentum profiles in a specific storage facility will be obtained. The PDE's will be implemented in COMSOL 3.4, that solves the PDE's with a finite element method. The aim of this chapter is to get a first impression of the simulations with COMSOL, and is the start for the second part of the MSc project, as described in the Introduction.

The aim is to run three different simulations. First a 1-D model is implemented, followed by a 2-D model and as last a 3-D model is implemented. First the implementation options are discussed. Second a description of the implemented model, and the model boundaries to set up the simulation, are described. Third the assumptions on the model will be given. At last the COMSOL implementation, and some results will be given.

6-1 Implementation options

For a CFD simulation of systems with flow, now-a-days several programs, like Solid-Works, Ansys and COMSOL can be used. For the simulation of systems with flow and internal production, like the potato pile, in general these programs provide two implementation options:

- Standard packages, that cover the physics of the system
- Mathematical environment, in which the relevant transport phenomena can be specified.

Standard package For the standard package the mathematical description and the different relations within the states are already implemented as partial derivative equations. The user only should enter the coefficients in the PDE's. For a system with a momentum, energy and mass balance COMSOL provides, respectively, three standard physic packages namely, Darcy's law, heat transfer in porous media and species transport in porous media.

For the implementation of the boundary conditions, also different standard packages are already predefined. These boundary conditions can be related to the implemented geometry. Different boundary conditions, like inlet/outlet, thermal insulation, inflow/outflow can be used. In these boundary condition packages, the user only has to specify the variables and coefficients. For instance, for the inflow heat flux, the user only has to select the line, or area, on which this can occur, a specific heat flux in [W/m^2] and the corresponding external temperature.

The standard implementation options has the advantage that all the mathematics are already implemented. The definer should only think about with package he should use, and which parameters he wants to implement. However, this method has also disadvantages. One disadvantage is the lack of insight on the implementation of the balance equations, and how the relations in a balance are coupled. Because the equations of the model are already implemented, the possibility to change some equations is not very efficient. For instance the porous media packages has the disadvantage that it has only one state for the temperature. Hence, for a two-phase system, two different implementations for the heat transfer and as well for the species transport in porous media should be defined. For the modelling of systems that have an internal heat source, like the respiration and evaporation processes in potato storage systems, no standard physics are defined, but has to specified as boundary conditions. Consequently, the standard physic packages are not the most efficient way to model potato storage.

Mathematical environment In the mathematical environment, a mathematical model can be implemented in different interfaces that contain standard (predefined) mathematical equations. The most extensive one is the coefficient PDE form, defined in COMSOL as:

$$e_a \frac{\partial^2 S}{\partial t^2} + d_a \frac{\partial S}{\partial t} + \nabla \cdot (-c\nabla S - \alpha S + \gamma) + \beta \nabla S + aS = f \tag{6-1}$$

$$\nabla = \left[\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z} \right] \tag{6-2}$$

Where S is the state, and the other variables can be defined as constants or as an equation.

The specification of the boundary condition is comparable to the implementation of the boundary conditions when using the standard packages. To define boundary conditions, first the areas or lines should be selected in the predefined geometry. For each of the boundary condition, some general mathematical equations are available that can be specified by the user. For instance, if the state equation is defined in terms of a temperature balance with the variable quantity, T_a in [K], the user can implement a flux or source with the following mathematical relation:

$$-\, n \cdot (-c\nabla T_a - \alpha T_a + \gamma) = g - qT_a \tag{6-3}$$

Where g should be defined in [m· K/s] and q in [m/s]

The advantage of this implementation method is that the balance equations can be implemented as basic formulas, as described in the models in Chapter 5. No unwanted concessions on the model have to be made, to put them in the standard physical form. All the relations are in line with the balance equations and the user has full insight on how the PDE's are coupled to each other. The disadvantage of this way of implementation is the time it cost to implement every single PDE.

Because of the advantages, described above, we use the mathematical environment instead of standard packages to implement the test-case model in COMSOL.

6-2 Test-case model description

For the test-case the physical model is simplified to a certain level. Only the dominant state, at a certain time instant, of the physical system is taken into account. The simulations were focused on long time storage, while neglecting the first months of storage. So the product is already in the state of long time storage. This means that no processes that occur directly after storage are taken into account. This is to keep certain processes, like evaporation, respiration, and fluctuations in temperature and mass within small ranges. With this simplification we neglect for instance drying of the potatoes, where the potato peel, and the related evaporation rates, changes a lot.

6-2-1 Model structure in COMSOL

In the test-case the energy transfer ins the dominant state. Hence, only the temperature balances for air and potato are taken into account, which leads to a two phase temperature balance. The solid phase is related to the potato, and the gas phase to the air in the potato pile. Ultimately, we are interested in the potato temperature. However, because of forced ventilation, the air and the interaction between the air and potato can not be neglected. We suppose the medium is incompressible over the storage period. The implemented balances is two-phase like the equations 5-16 and 5-17 (Beukema, 1980), ad mainly based on the model of Kondrashov (2007) and Lukasse et al. (2007) and Keesman et al. (2002). Hence, the system is described by:

$$\frac{\partial T_a}{\partial t} = -\frac{1}{(1-\epsilon)} v \cdot \nabla T_a + \nabla \left(\frac{\lambda}{\rho_a C_{pa}} \nabla T_a \right) + \frac{\alpha_c F_m}{\rho_a C_{pa}(1-\epsilon)} (T_p - T_a) \tag{6-4}$$

$$\frac{\partial T_p}{\partial t} = \nabla \left(\frac{\lambda}{\rho_p C_{pp}} \nabla T_p \right) - \frac{\alpha_c F_m}{\rho_p C_{pp} \epsilon} (T_p - T_a) + \frac{R}{\rho_p C_{pp} \epsilon} \tag{6-5}$$

Where the F_m is the specific surface of a mount defined as follows (Lukasse et al., 2007):

$$F_m = \frac{\pi d_p^2}{(1/6)\pi d_p^3} \epsilon \tag{6-6}$$

The coefficient of convective heat transfer between the potatoes and ventilation air is given by (Kondrashov, 2007):

$$\alpha_c = 0.05 d_p + \frac{7.27 v^{0.67}}{d_p^{0.33}} \tag{6-7}$$

And the respiration rate as constant rate (Keesman et al., 2002):

$$R = 4680000 [J/m^3 day] \tag{6-8}$$

For the description and nominal values of the implemented variables see Table 6-2.

For now, natural convection is not playing a role and the forced convective flow is assumed to be constant in time and space. Hence, v is constant and:

$$\phi = Av \tag{6-9}$$

6-2-2 Model configurations

The first model, 1-D, is set on a 2-D domain, where only the distribution in vertical direction is considered. Furthermore, only forced convective flow in vertical direction is considered, as shown on the left in figure 6-1. An external flow $Q = \phi$ is injected in the bulk with a temperature $T_a(0,t)$. No flux or flow in horizontal direction is considered so we end up with a 1-D model.

In the 2-D model the same conditions, external flow and injection temperature as in the 1-D model are applied, completed with a extra dimension and boundary condition. In this case also fluxes in horizontal direction are possible. An extra boundary condition is put on one vertical side of the x-y plane, namely, it has the same temperature as the injected air(see figure 6-1, middle panel).

In the last simulation the same conditions as the 2-D model is used, but again a dimension is added, so we end up with a 3-D model like the right panel in figure 6-1. This means that it is expected to have fluxes in three dimensions.

6-2-2-1 Boundary conditions and initial conditions

In COMSOL different boundary conductions, like a Neumann, Dirichlet, or mixed boundary conditions and even periodic boundary conditions can be applied on lines or planes. For the horizontal boundaries, at $y = 0$ and $y = H$, the same conditions for 1-D, 2-D, and 3-D models are used. In the balance of the potato temperature no internal fluxes or sources were applied at the boundaries. Hence, in none of the simulations fluxes or sources are applied, see Table 6-1. For the temperature balance, at the boundary at $y = 0$, a Dirichlet boundary condition is applied. The air at that point has a certain temperature. Consequently at the lower boundary:

$$T_a(x, 0, t) = T_{in} \tag{6-10}$$

In the 1-D and 2-D configuration this is applied to the horizontal line at $y = 0$, and in the 3-D case on the x-z plane at $y = 0$. At the top of the configuration, so at $y = H$ also a Dirichlet

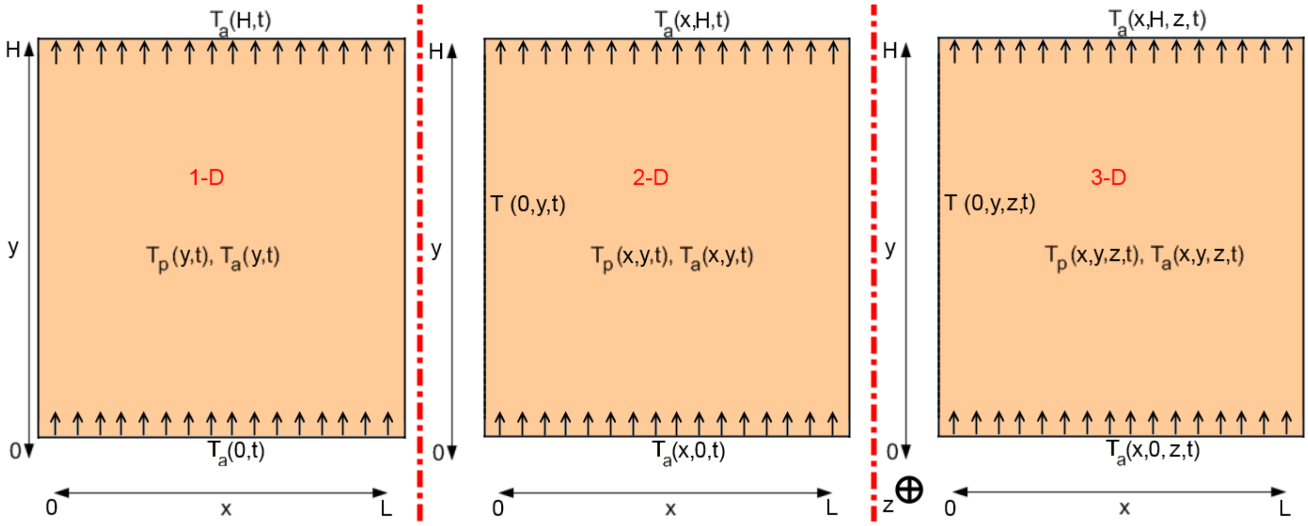

Figure 6-1: The implemented models.

boundary condition is applied. At this line, in 1-D and 2-D and plane in 3-D, the temperature of this boundary should be the same as the air temperature at this upper boundary. This is specified as:

$$T_a(x, 0, z, t) = T_a(x, 0, z, t) \tag{6-11}$$

On the vertical boundary in the 1-D case no fluxes will occur. Hence, zero fluxes are stated as boundary conditions in the 2-D plane. In the 2-D configuration, at the left vertical boundary at x=0 a Dirichlet boundary condition is applied. This line has the same temperature as the air at the horizontal boundary, T_{in}. In the 3-D implementation the Dirichlet boundary condition with the temperature, T_{in} is stated on the left $(x = 0)$ y-z plane, see figure 6-2 For the other vertical planes, the two x-y planes and y-z plane at $x = L$, no Dirichlet or Nuemann conditions are applied. All these boundary conditions are shown in Table 6-1.

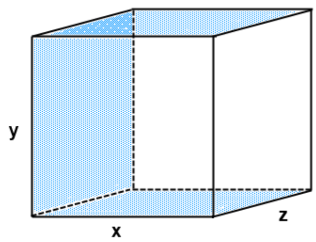

Figure 6-2: The 3-D configuration, on the blue shaded planes Dirichlet boundary conditions are applied.

For the bulk temperature, which is composed of the potatoes temperature T_p(x,0) and the air temperature T_a(x,0), a initial temperature of 279.15 [K] is applied. The applied flow is based on the forced convective dilution rate of 100 m^3/h air per m^3 potatoes. For bulk storage a average bulk hight is four meters. This means a dilution rate of 400 [m^3 air/ m^3 product/ hour]. For the cubic configuration of our simulations, this results in a air velocity in the bulk

Table 6-1: Boundary conditions

	Boundary	Boundary condition T_a	Boundary condition T_p
1-D	x=0	$-c\nabla T_a = 0$	$-c\nabla T_p = 0$
	x=1	$-c\nabla T_a = 0$	$-c\nabla T_p = 0$
	y=0	$T_a(x,0,t) = T_{in}$	$-c\nabla T_p = 0$
	y=1	$T_a(x,0,t) = T_a(x,0,t)$	$-c\nabla T_p = 0$
2-D	x=0	$T_a(0,y,z,t) = T_{in}$	$-c\nabla T_p = 0$
	x=1	$-c\nabla T_a = 0$	$-c\nabla T_p = 0$
	y=0	$T_a(x,0,t) = T_{in}$	$-c\nabla T_p = 0$
	y=1	$T_a(x,1,t) = T_a(x,1,t)$	$-c\nabla T_p = 0$
3-D	x=0	$T_a(0,y,z,t) = T_{in}$	$-c\nabla T_p = 0$
	x=1	$-c\nabla T_a = 0$	$-c\nabla T_p = 0$
	y=0	$T_a(x,0,z,t) = T_{in}$	$-c\nabla T_p = 0$
	y=1	$T_a(x,1,z,t) = T_a(x,1,z,t)$	$-c\nabla T_p = 0$

of:

$$\frac{1}{1-\epsilon} \cdot \frac{400}{3600} = 0.32[m/s] \tag{6-12}$$

The inlet temperature and the temperature of the line/plane at $x = 0$ in the 2-D and 3-D case are defined as: $T_{in} = 278.55$ [K].

6-2-3 Model assumptions

For this implementation the following assumptions are made:

- Forced convective flow in vertical direction
- Energy transfer is the dominant process
- Potatoes are already in long-term storage state
- Homogeneous distribution of bulk material
- Density of product and air (incompressible) are constant

6-2-3-1 Parameters

For the simulation we implemented the parameters as presented in Table 6-2.

6-2-4 Simulation results

A simulation of the test-case system over a period of 24 hours was conducted, see for the results Figures 6-3 - 6-7. On the horizontal line at y=0 a temperature of $T_a(0,t) = 278.55$ is applied. At y=1 the the boundary has the temperature T_a(x,1,t). For all of the three

Table 6-2: Model parameters in simulation study

Symbol	Description	value	unit
C_{pa}	Specific heat	1005	[J/kg K]
C_{pp}	Specific heat	3600	[J/kg K]
d_p	Diameter	0.052	[m]
F_m	Specific surface of the mount	78.48	[m^2/m^3]
T_{in}	Injection temperature	278.55	[K]
v	Air velocity	0.11	[m/s]
ϵ	Bulk porosity	0.654	[-]
λ_a	Thermal conductivity air	0.025	[W/m K]
λ_p	Thermal conductivity potato	0.4	[W/m K]
ρ_a	Density of air	1.269	[kg/m^3]
ρ_p	Density of potato	1080	[kg/m^3]

simulations using the, 1-D, 2-D and 3-D models, six plots are discussed below. The first two plots in figure 6-3 show the profiles at start time (t=0), the second plots (figure 6-4) after five hours (t=18000 seconds) when the top layer of the air and potatoes is cooled down 0.2 to 0.3 Kelvin, and after 13 hours (t=46800 seconds) when the temperature is more or less homogeneous 278.55 Kelvin in the 1-D and 2-D test case, and after nine hours (t=32400) in the 3-D case.

First the results of the 1-D case simulated are shown in the figures 6-3, 6-4 and 6-5. In the plot at t=0 the air temperature in already cooled down a bit by the initial condition of the temperature at y=0. The potato temperature is homogeneous 279.15 Kelvin.

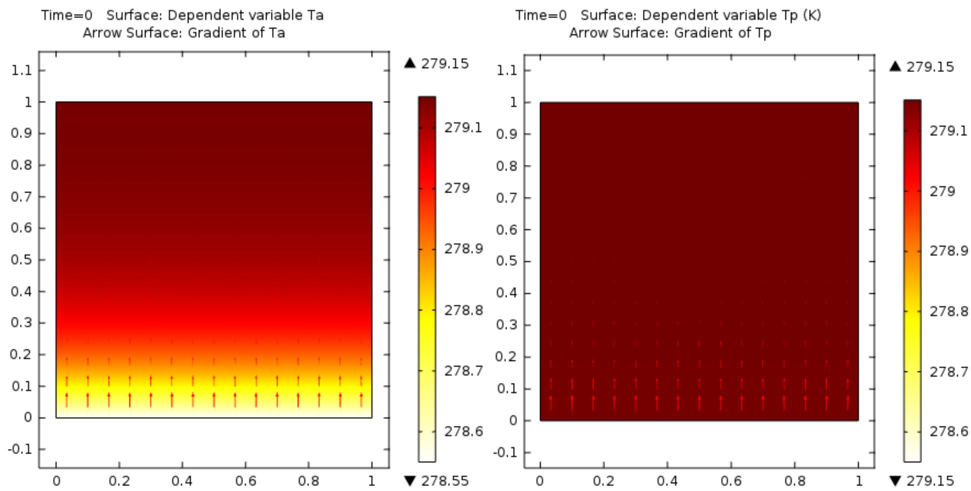

Figure 6-3: 1-D simulation at t=0 (left: the air temperatures, right: the potato temperatures)

At time t=5 hours the temperature of the potatoes in the upper layer of the potato pile, at y=1, is almost cooled down with 0.3 (figure 6-4). At this stage the air temperature at y=1, is 0.05 less, and so the potato temperature is still cooled down. The difference in potato and air temperature at every place in the bulk is small, what causes a small cooling rate.

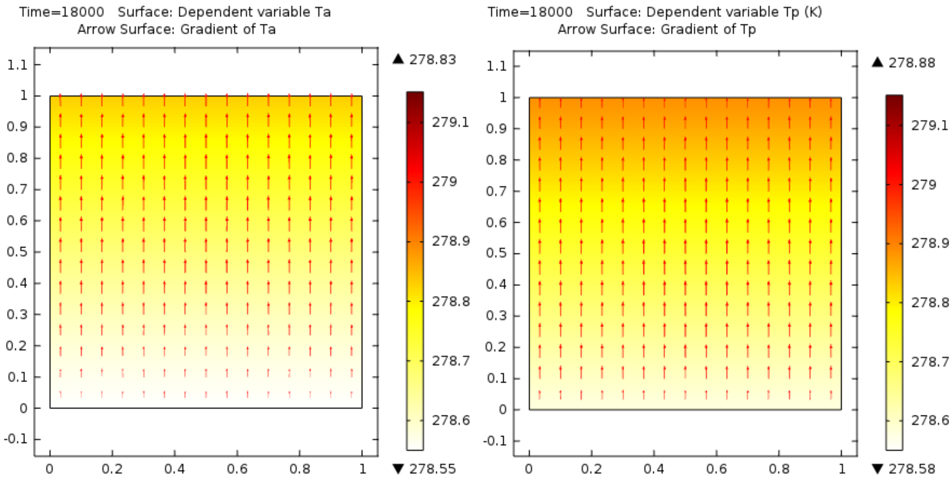

Figure 6-4: 1-D simulation at t=5 hours (left: the air temperatures, right: the potato temperatures)

After 13 hours the temperature of the potatoes is almost cooled down uniformly to the desired temperature of 278.55 (Figure 6-5).

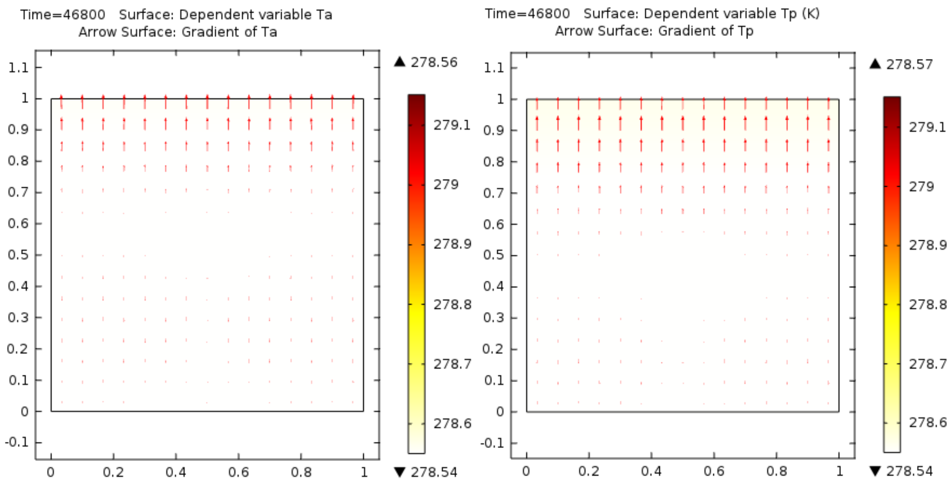

Figure 6-5: 1-D simulation at t=13 hours (left: the air temperatures, right: the potato temperatures)

The results of the 2-D and 3-D simulations are shown in figures 6-6 and 6-7, respectively. The same behaviour as in the simulation of the 1-D case can be seen. In the 2-D case the lower wall temperature at x=0 has only influence on the bulk in the range of x=0 to x=0.1. In the 3-D simulation this lower temperature is diffusing a little bit more into the bulk. However it is not very differing from the 2-D plot. In the 3-D case the time it causes to cool down the bulk homogeneous to 275.55, is shorter compared to the 1-D and 2-D case.

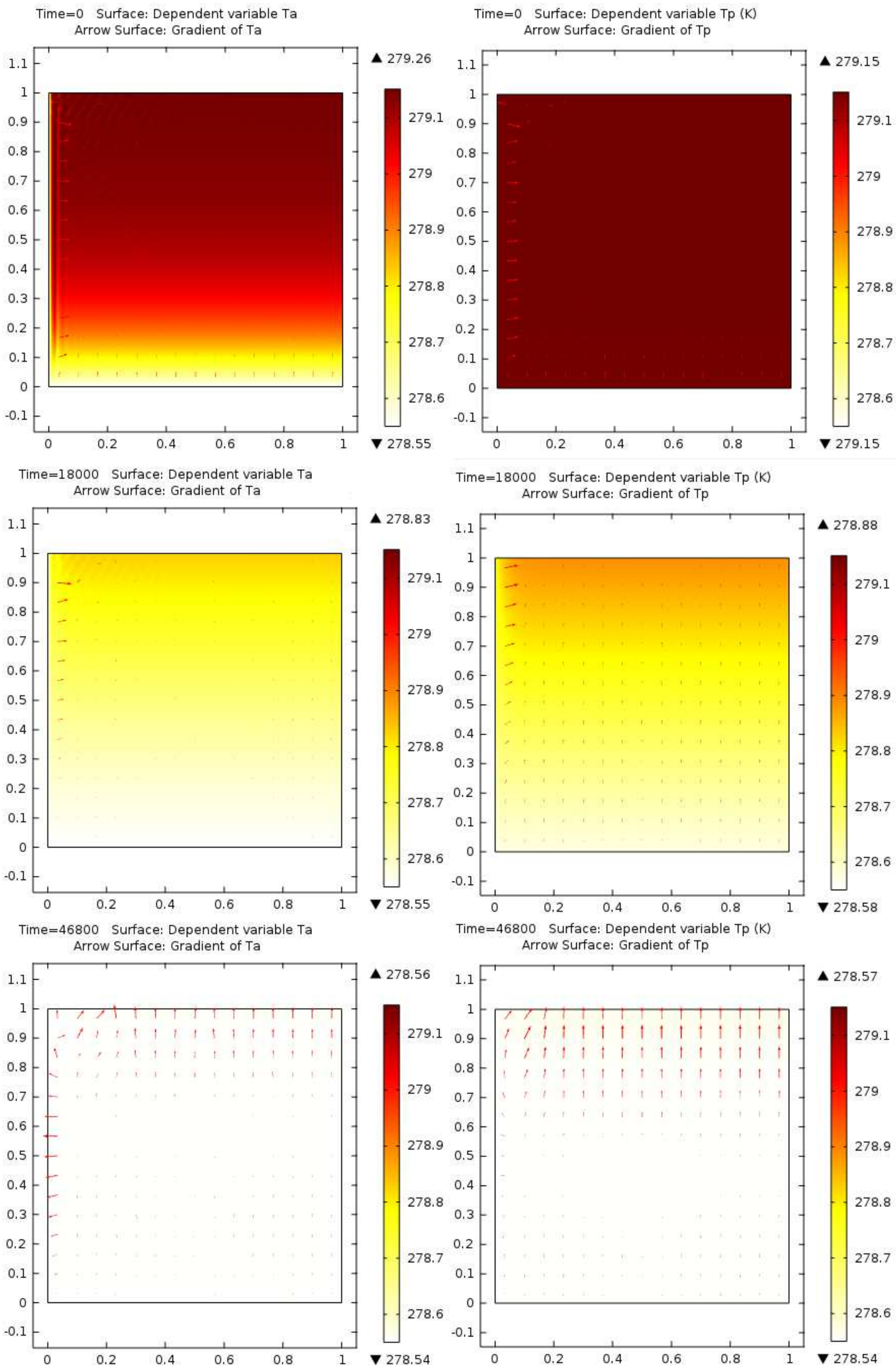

Figure 6-6: 2-D simulation at t=0, t=5 and t=13 hours (left: the air temperatures, right: the potato temperatures).

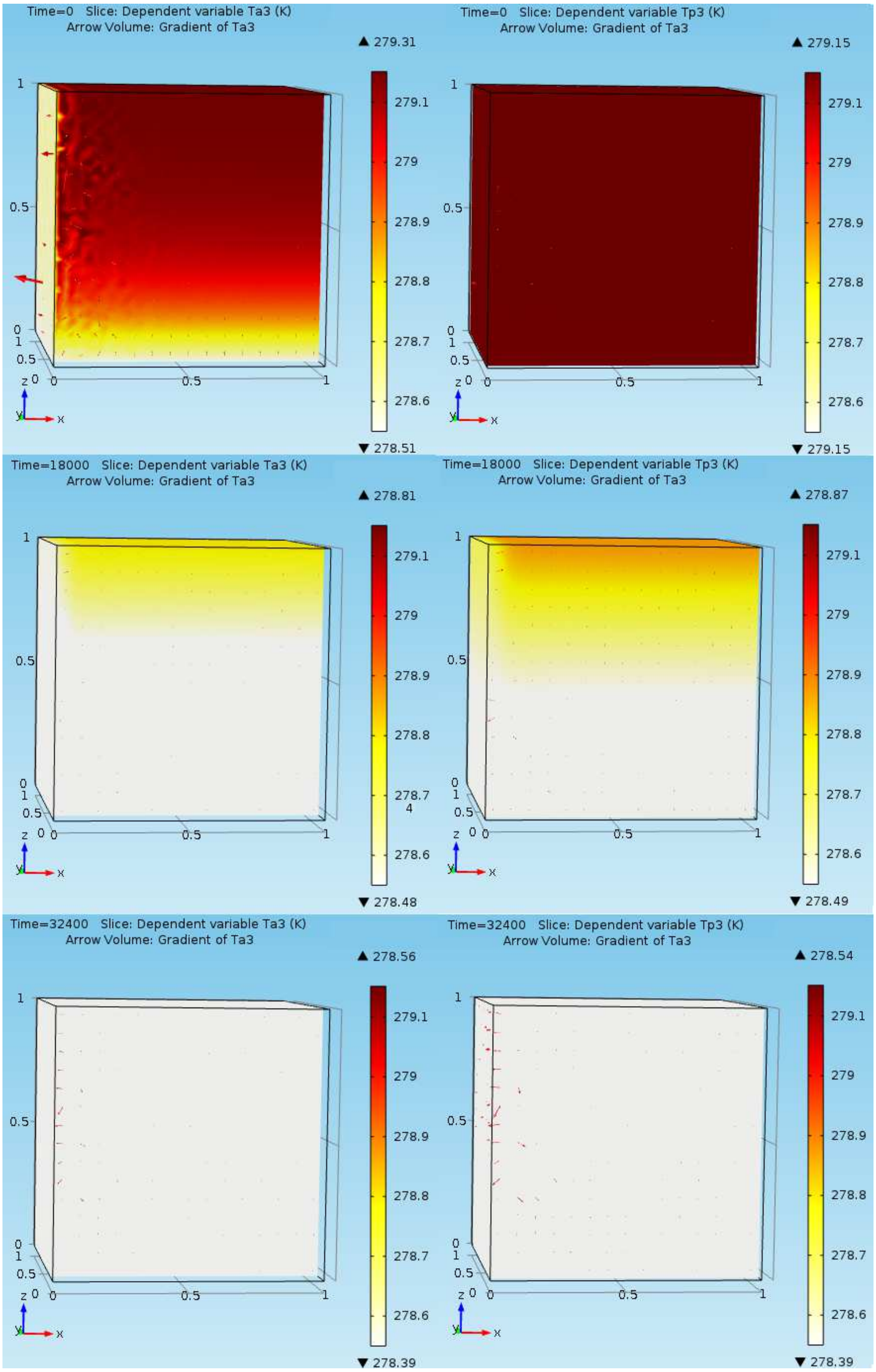

Figure 6-7: 3-D simulation at t=0, t=5 and t=9 hours (left: the air temperatures, right: the potato temperatures).

6-2-5 Interpretation of simulation results

For the 1-D simulation case appropriate results are obtained. The temperature of the air is always a fraction cooler as the potato temperature. This temperature difference, between the air and potato, becomes smaller as time increases. It seems to be a non-linear relation between the cooling of the temperature of the potato in time. This is due to the non-linearities in the systems. This also hold for the 2-D and 3-D configuration.

In the simulation of the 3-D case the time it causes to cool the potato temperature homogeneous to 278.55 is four hours shorter as in the 1-D and 2-D case. This can have several causes, like the extra dimension that is added. Hence, it is possible that the program is able to calculate the homogeneous distribution in a other way, as in the 1-D and 2-D case. This is also influenced by the different geometry mesh, the mesh itself has in all of the three simulations 1-D, 2-D and 3-D, the same mesh size 'fine'. However, in the 3-D case an extra dimension, and so an other mesh geometry.

The simulation time has also influence on the simulation results. Simulating with an other time period, causes other results. Also should be noted that the temperature of air and potatoes in the 1-D and 2-D case is more or less cooled down to 278.6 in the nearly the same time as in the 3-D case. Only to cool down homogeneously the last 0.05 to reach the desired temperature, the results are showing a slow convergence.

The temperature of 278.55 of the vertical line/plane at x=0 is causing a slight temperature difference in the horizontal direction. Due to the dominating forced ventilation the temperature does not penetrate too far in horizontal direction. Note that in the 2-D case only a temperature gradient in horizontal direction near x=0 is seen. In the 3-D case the gradient is also in the z-direction, and temperature diffuses a little bit more in horizontal direction.

Chapter 7

Conclusion and discussion

7-1 Storage concept

In literature the role of storage in a biobased economy, is part of a bigger concept: the logistic concept. Storages have to be placed on tactical places. The storages can have multiple tasks. Besides storage of (intermediate) products, also quality control and if possible some pre-processing for volume reduction can take place, to keep the transport cost low.

In general, a distinction between inside and outside storage facilities can be made. The products can be stored in boxes, sacks or in a bulk. For ventilation, a clear distinction between suction and blowing ventilation can be made. However, a clear distinction between the concepts from the produce quality point of view is not found in literature.

7-2 Modelling of potato storage

A reasonable amount of papers for the modelling of potatoes, in a storage facility is available. Investigations subjected to respiration, evaporation, heat and mass flows in single potatoes and within a potato stack is also available. From the literature we can state that from 1970 until now, potato storage models are still further developed. Through this period of time, lumped but also spatially distributed models were defined. Also, design of control systems for these systems was investigated. The related optimization of these systems with respect to economics, energy consumption and product quality via climate control were also published.

In most of the papers the model in- and outputs were restricted to the in- and outputs of the ventilation ducts. All of the models were applied in bulk storages. This gives relative easy geometries, as a homogeneous air distribution can be considered. Commonly, the model boundaries were defined by the potato bulk, the bulk with ventilation ducts and sometimes the whole storage facility when there was cooled with ambient air.

Summarizing, we can state that for modelling of potato storage, controller design, interaction of the storage with the environment, like weather forecasting or energy usage, a significant amount of knowledge is available. All this knowledge leads to new questions related to the potato storage. Some interesting related subjects, on which little to no investigation is done yet, are:

- Active control of the storage climate on the bases of the actual product quality. Until now almost all controllers use temperature and humidity for the storage of potato, as the storage climate directly affects the product quality. However, a good storage climate does not guarantee a good quality of the product.
- Study of the temperature and humidity profiles in the physical storage systems. It would be interesting to couple the inhomogeneous temperature and humidity contributions to the inhomogeneity of the stored product. This could lead to an optimization step, including sensor-actuator network design, on the control of specific physical storage systems, using today's available simulation techniques.

7-3 Discussion

From the inventory of storage facilities, a distinction between the in- and outdoor storage can be made. For the thesis part that follows, the indoor storage is most interesting, as in that case we have an climate that can be controlled. Two important modes should be distinguished when the models are implemented, namely, the forced and natural convective mode. Forced convection is the easiest one to implement. Natural convection can only occur if, without a external source, the pressure changes. As for instance due to change in air density or as a result of temperature changes. This mode is much more difficult to implement then the case with forced convection.

For the modelling of the agricultural storage facilities, Chapter 5 provides an overview of the states that are used in the models. None of the models is identical. It strongly depends on the objectives which model, or processes, should be implement. Since, none of the models are coupled to a real physical storage, these models are not often used in practice. However, with current software it is possible to couple the storage models particles to a specific geometry. One of the things that is not included in the models, is the presence of soil in the bulk. This can lead to a inaccurate model behaviour, especially in the drying and cooling process, immediately after the post-harvest process starts.

The implementation of the energy balance, in partial differential equations, gives a first impression of the simulation opportunities and limitations in COMSOL. For a spatially distributed system under the assumption of a homogeneous air distribution simulations have been done. Therefore, in later research, where a full model will be implemented, the critical points will be further highlighted. For a complete time simulation of the a storage period, it is wise to include also the processes that occur in the first period of post-harvest, such as wound heeling, drying and cooling of the potatoes. Especially, the evaporation and respiration rates are different in that state of storage. With this knowledge, optimization of the design of facilities, sensor-actuator network design and control strategies can be carried out...

Appendix A

Appendix A

A-1 Symbols

Table A-1: Used symbols

Symbol	Description	units
A	Area	[m^2]
c	Constant	[-]
C_p	Specific heat	[J/kg K]
d_p	Potato diameter	[m]
D	Diameter	[m]
$\mathbb{D}$	Diffusion coefficient	[m^2/s]
$\mathcal{D}_{ab}$	Binary diffusion coefficient	[m^2/s]
E	Energy	[J/kg]
F	Force	[N]
F_m	Specific surface of the mount	[m^2/m^3]
$\mathbb{F}$	Transfer factor	[Ja]
g	gravity constant	[m/s^2]
G	Surface	[m^2]
$\eth$	Mass transfer coefficient	[kg/m^2 s]
H	Vaporization constant	[J/kg]
h_c	Heat transfer coefficient	[W/m^2 K]
h_{fg}	Enthalpy of vaporization	[J/kg]
i	Cartesian coordinates	[m]
k	Thermal conductivity	[W/kg K]
L	Length	[m]
m	Mass	[kg]
Nu	Nusselt number	

p	pressure	[Pa]
Pr	Prandtl number	[-]
Q	Thermal energy	[J]
$\dot{Q}$	Energy flow	[W]
r	Production term	[J/s]
R	Respiration rate	[J/kg s]
Re	Reynolds number	[-]
t	time	[sec.]
T	Temperature	[K]
Sh	Sherwood number	[-]
u	Velocity	[m/s]
v	Velocity in certain direction	[m/s]
$\vec{v}$	Velocity vector	[m/s]
V	Volume	[m^3]
X	Certain amount of something	[-]
X	Mass	[kg]
α_c	Heat transfer coefficient	[W/m^2 K]
ϵ	Porosity	[-]
ε	emissivity	[m^2/s]
λ	Thermal conductivity	[W/m K]
ν	Kinetic viscosity	[m^2/s]
ξ	heat transfer coefficient	[W/m^2 K]
ρ	Density	[kg/m^3]
σ	Stefan-Boltzmann constant	[W/m^2 K^4]
ϕ	Flow in- or out of the system	[m$^3/s$]

Table A-2: Used subscripts

Symbol	Description	unit
1	Species index	
a	Air	
ap	Combination of air and produce	
c	Convection	
fil	filtration	
g	Gas phase	
i	Cartesian coordinates	
in	Injection	
m	A medium, or mean (if related to radiation), or mass fraction (if related to convection)	
n	Cartesian coordinates	
p	Produce	
r	Radiation	
s	Surface	
x	x direction	

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