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Modelling and simulation of rot in potato storage facilities

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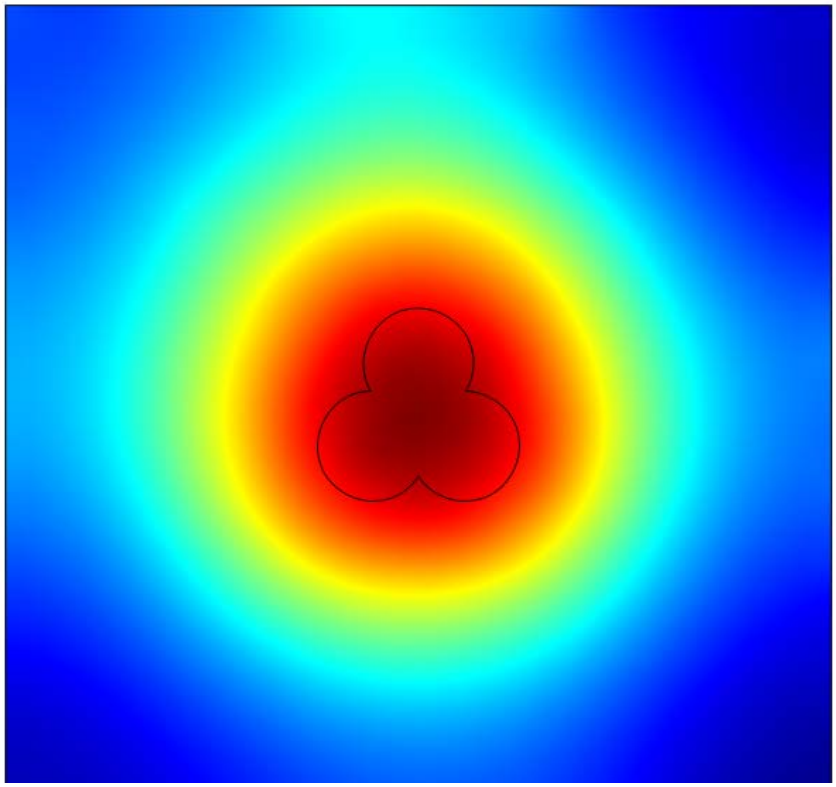

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Modelling and simulation of rot in potato storage facilities

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Abstract

Storage of potatoes is necessary for a continue supply of this product. To maintain the product quality, the climate in modern storage facilities is kept at a certain level. However, climate factors are not the only dependent variable for potato quality. During harvesting and storage the potato tubers are susceptible to pests and diseases. These diseases have a significant influence on the quality of the stored crop. In the first part of the thesis, the influence of post-harvest diseases, such as potato Late blight, *Erwinia carotovora* soft rot and freezing injuries on the storage climate and vice versa, were reviewed. This provided more insight of the progress of rot in potato bulk store facilities and thereby a spatially distributed physical model for freezing rot could be developed. Furthermore in this research, an already existing physically-based potato quality model is adjusted so it also accounts to rotten potatoes. The model includes parameters that influence the storage climate, which are temperature, relative humidity of the air, carbon dioxide and oxygen levels, respectively. One state is supplemented to the model to make it apply to rotten potatoes, namely: the surface of rot.
The model parameters affected by the percentage of rot in the bulk are calibrated and validated on the base of experimental data. To obtain experimental data for the calibration and validation of the model parameters, an experiment was set-up. The carbon dioxide levels, relative humidity and temperature are measured on a small scale storage facility. The calibration and validation of the model parameters will be done with COMSOL 5.2 CFD software. In COMSOL a dynamic 2D CFD simulation of the surface expansion of rot caused by freezing injuries inside bulk storages is carried out.

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1. Introduction

This thesis report presents the outcome of my BSc thesis project. The aim of the BSc study is to analyse the rotting process of potatoes in storage facilities and eventually to expand an already existing physically-based potato quality model, so it also accounts to rotten potatoes. Also a spatially distributed physical model for the spread of rot in the bulk has to be developed. In order to adjust the existing model, deviating properties of rotten potatoes compared to healthy potatoes are investigated and modeled. This chapter provides some background information with additional problem statement, objectives, research questions and the approach that will be used.

1.1. Background

Postharvest storage is imperative since potatoes are a perishable commodity and tubers undergo active metabolisms when they are stored for a period. A continues supply of potatoes over the year is made possible by storage. During cultivation and storage periods, the potato crop is susceptible to various pests and diseases which induce crop losses affect active tuber metabolisms and threaten the tuber quality and value as product. U.S. potato losses during storage have averaged about 7.5% over the past several years according to *(Olsen et al., 2006*). Individual losses could be far more severe, up to total crop loss. These crop losses result from physiological, physical and pathological causes or combination of all causes. Physical losses mainly consist of mechanical injuries. These damaged potatoes should not make it to the storage. However sometimes these damaged potatoes are overlooked and end up in the storage. This entails a serious risk, as wounded potato tubers are the very vulnerable for pathogen invasion which makes it the leading cause of soft rots, dry rots and other post-harvest diseases. Also some storage conditions like; a high RH (>95%) and low (freezing) temperatures, predispose the potato tubers to pathological invasions. Physiological disorders of potato tubers are often described as: non-pathogenic or non-infectious diseases. These so called disorders are caused by: unfavourable environmental factors like freezing temperatures, excessive use of fertilizer or other physiological factors that affect the development and growth of potato tubers (*Navarre and Pavek, 2014*) The pathological cause of losses occurs primarily in combination with physical and physiological phenomena. Wounds make the potato tubers susceptible for pathological attacks from for example: Fungi, bacteria, insects, nematodes, viruses and viroid's, which presumable cause the most gross severe post-harvest losses. The development of rot affects the condition of healthy potatoes by direct contact and the surrounding environment. The rotten potatoes generate more temperature, moisture and carbon dioxide than healthy potatoes which changes the air properties inside the bulk (*Fennir, 2002*). These results in a decrease in quality of healthy potatoes as they, for example, start to respire more due to the higher temperatures. Nowadays facilities use climate-based control to preserve the quality of the air on a certain level. However, a good climate does not necessarily prevent rot in storage facilities.

1.2. Problem formulation

The optimal storage scenario is to end up with the retained quality of the produce at the beginning of the storage period. The environmental climate of the potato piles in bulk storage is a critical factor to prevent quality losses. Storage diseases resulting into rot, induce quality losses and affect the storage climate. Recently, Grubben (2013) developed a spatially distributed physical model that gives full insight between the potato quality, in terms of temperature and moisture content and flow conditions. Climate factors such as temperature, relative humidity and carbon dioxide/oxygen concentrations have a major influence on the potato tuber quality. Rotting processes affect these climate factors and influence the potato quality, so are critical to be considered in the model. Not only to get insight in the spread and dynamics of rot, but also on the degree of influence of rot on the climate parameters and eventually on the potato quality.

1.3. Research goal

The goal of this research is to develop a dynamic 2D simulation model of the spread of rots inside bulk storages in terms of parameters that influence the storage climate. The parameters are temperature, relative humidity of the air, carbon dioxide and oxygen levels, respectively. The resulting model could be used to evaluate the spread of the rot and production of the additional compounds that affect the storage environment. In order to reach the goal stepwise the following research questions are defined:

How to develop a spatially distributed physical model for the spread of rot in the bulk?

- *What are the typical rotting processes that influence the potato quality in storage?*
- *What are the typical model parameters that are influenced by the rotting process and the other way around?*
- *What are typical periods and which storage conditions significantly affect the rotting process?*

How to set up an experiment to calibrate and validate the unknown model parameters?

How can the calibration and validation be performed in COMSOL?

1.4. Approach

First, a literature study on different types of rot, the corresponding physical changes and infection diffusion in the bulk will be performed. From this study a spatially distributed physical model that gives full insight between the potato quality, in terms of temperature and moisture content and flow conditions will result. This model has to be expanded so it also accounts to rotten potatoes, including basic physics affected by the rotting process like: temperature, relative humidity and carbon dioxide/ oxygen concentrations. Furthermore a spatially distributed physical model for the spread of rot in the bulk should be developed. If the basic physics are captured in the model, a calibration and validation of the model should be performed on real data. An experiment will be set up to obtain data to calibrate and validate the parameters found by the literature study. Eventually the calibration and validation will be performed in COMSOL, using CFD simulations.

1.5. Outline thesis

In chapter 2, a literature review concerning storage rots is presented. The several phases in of storage processes are described. Furthermore physical processes of tubers in storage will be discussed; these are the typical model parameters that are influenced by the rotting process. Also the post-harvest diseases and their prevention and control will be discussed.
To measure the model parameters an experimental set up was developed. With this set up, four different experiments were carried out. The materials and methods for the experiment will be discussed in chapter 3. Subsequently the experimental outcomes will be described and discussed in chapter 4. In chapter 5, the physical model will be explained and the implementation of the rot surface model will be performed. The validation and calibration of the results by implementing the dynamics in the software COMSOL Multiphysics 5.2 is presented in chapter 6.
Finally the conclusion of this research by answering the research questions is presented in chapter 7 and some future challenges and recommendations concerning the experiment are mentioned in chapter 8.

2. Theory

To retain the quality and quantity of the stored potato tubers, rots which can cause excessive crop loss, should be prevented from spreading. There are many different types of rot, which can occur in various periods of storage. In order to set up a model, it is important that the several types of rot and the phases they occur in, can be described. Also the degree in which the climate factors (or model parameters) such as temperature, relative humidity and carbon dioxide/oxygen concentrations are affected by rotting is important to be known. This has to be investigated in order to determine the measurement range of the experiment. Furthermore the spread of rot and the speed in which it happens is of importance for the duration of treatments to control rot in storage facilities. On the basis of this information the duration of the experiment can be determined.

This chapter first describes the processes taking place during a storage period in terms of conditioning, followed by the physical processes of the potato tubers during storage. Furthermore post-harvest diseases will be discussed. And this chapter ends with the description of different methods to control diseases.

2.1. Storage processes

Potato tubers are most susceptible to diseases at the beginning of the storage period, as the skin layer is in early development, hence is very thin. As time progresses, the potatoes gain maturity, hence the skin becomes thicker. Hereby potatoes become less susceptible to diseases in later storage periods (*Fennir, 2002*). At the begin of each storage period the remaining dust and soil should be removed from the storage facility as it is likely to contain pathogens that can pollute the crop about to be harvested, so the store should be properly cleaned and disinfected. This will minimize the risk of diseases being carried over from the stored crop to the newly harvest tubers, and it is particularly important if diseases came to expression previous season.

In storage of potato tubers we can distinguish the processes among the following phases that take place after loading the produce into the bulk storage. These phases take place in order to prevent quality losses and possible disease spread (*van't Ooster, 1999*):

- *Rot and surface drying of wet produce*
- *Suberization or wound healing (curing)*
- *Slowly cooling down to storage temperature*
- *Long-term storage of holding period*

Rot and surface drying of wet produce

Harvested tubers are covered with wet soil, which prevents air exchange. This reduced air exchange results in anaerobic respiration and increased pathogen growth. The ventilation should be running immediately when the tubers start to enter the storage, to dry the produce and to prevent the possible rot from spreading. When rot is present, it may take up to 6 weeks of extensive ventilation treatments to dry the rotting potato tubers and to prevent the spread of the infection causing sequential rotting (*Pringle et al., 2009*). Also the temperature has to be maintained between 12 and 20 °C so that it tracks the crops temperature in the ground. This minimizes temperature differences and the possibility of consequential convection currents forming, which can cause subsurface and produce surface condensation. This condensation makes potatoes more vulnerable to soft rots. If exceeding 20 °C, sprout growth and oxygen deficits in the tubers can occur. Once the skins of the potato tubers are dry, the continuous ventilation treatment could be replaced by pause-pulse ventilation preventing the tubers from drying out and to remove respirational heat and to ensure a homogenous temperature of the crop throughout (*van't Ooster, 1999*).

Suberization or wound healing

Potato tubers are exposed to physical damages due to harvesting, handling and transportation operations. The damages consist of wounds, bruises and the removal of skin. Injured potatoes have an increased respiration and evaporation. It is possible that the injured potatoes eventual will rot. The degree of quality losses is depending on the storage conditions but will always be higher in damaged and diseased tubers than in healthy looking tubers (*Booth and Shaw, 1981*). An open skin can even result in a 50% increasing respiration rate *(Fennir, 2002*). To prevent rot and inhibit quality losses the

suberization process, which is development of the potato skin, is aimed at wound healing and forming skin maturity. Damages in form of cuts and bruises are cured by development of a periderm layer, which is a rough corky skin layer on the damaged surfaces, to inhibit losses and exclude pathogens from entering the tuber through the damages. Suberization is achieved by keeping the tubers for 10 to 14 days at a high RH (92-97%) and between temperatures of 13.0 to 15.5 °C combined by a minimum ventilation flow rate *(Wijekoon et al., 2015*). Wound healing is not present under anaerobic conditions, which means that is does not occur under levels of oxygen below 3% to 5%. The forming of the periderm is also inhibited at carbon-dioxide concentration from 5% to 15% and sprout-inhibitor applications, so the use of these chemical or biological agents should be delayed. When the oxygen concentrations are about 21%, the relative humidity in-between 80 and 95% and the level of CO_2 is under 5%, the suberization process can be determined by the number of degree days.(van't Ooster, 1999) states a standard number of 150 degree day's duration of the wound healing process, which are expressed as:

$$\sum_{i=1}^{n}(T_{potato} - 5) \geq 150 \qquad [1]$$

With T_{potato} as the average tuber temperature inside the bulk. Temperatures extending the 20 °C limit have to be prevented. If violent damage occurs, the required number of days could be increased.

Slowly cooling down to storage temperature

After suberization is achieved and the crop is dry, the tubers have to be slowly cooled. Cooling helps to maintain dormancy and slows down the growth rate of any established diseases. But before cooling the produce down to storage temperature, there should be noted that the cooling rate depends on several influences. First the availability of cool air, where ambient air is used as cooling air. Also on the standard forced convection dilution rate, this is 100 m3/h air per m3 potatoes in practice. This airflow should also be homogenous when passing through the crop. When there is made use of a refrigeration system, the cooling capacity should be considered. Furthermore ice building up on cooling coils should be prevented (*Pringle et al., 2009*).

The tubers must be cooled to storage temperature; the rate of cooling can be influenced to an extent. The stored heat, suberization heat and respiration heat in the pile has to be removed. To realise a quick decrease in storage temperature, it is needed to use maximum cooling capacity, although there are some restrictions that have to be made; the cooling can be limited to a maximum of 0.5 °C per day to minimize temperature differences in and outside the pile (*Pringle et al., 2009*). Also when ambient air is used for cooling, it should not overtake the natural cooling of the atmosphere when winter is approaching.

Cooling is a heat and mass transfer process, whereby air gains heat and moisture from potato tubers through convection. In bulk storage, the ventilation air gains large amounts of heat and moisture, because of the large stored volumes. During cooling in bulk storages, the stack can be illustrated as various layers of produce. The first layer on top of the grid floor comes directly in contact with the ventilation air stream that picks up a considerable amount of moisture and heat. As the same air stream rises in the bulk, it will take up less heat and moisture as compared to previous layers, until it reaches the top. Consequently a lag in cooling time occurs, which results in cooling variations inside the stack, which should be avoided (*Fennir, 2002*).

Cooling time affects the produce quality, as it enhances a continuous breakdown of carbohydrates to provide energy to the tubers. This is not desirable for the end product, as it results in darkened frying colours. Cooling also results in weight loss, which can be minimized by (Pringle et al., 2009):

- Minimizing leakage of warm ambient air into the store.
- Prevent temperature differences by setting the product/duct differential to a maximum of 4 °C, whereby the differentials do not extend 0.5 °C.
- Usage of humidifiers when recirculating of the ventilating air occurs.

Long-term storage of holding period

After the crop is cooled down to desired storage holding temperature, it is critical to control and maintain this temperature and also to control the relative humidity and gas composition; the oxygen and carbon

dioxide levels. These storage conditions must be controlled because they may have excessive affection on the product quality when varying.

2.2. Physical processes of tubers in storage.

During a storage period the potato tubers undergo various active metabolisms. The quality of the tubers depends on influences from the ambient environment and the incidence of pests and diseases. There are many factors and relationships that play a part in the modelling of dynamic systems. The standard basic physical relations that narrate the dynamic behaviour of potatoes and air in a storage facility use laws of conservation of mass, energy in form of heat and momentum (*Grubben, 2013)*. The corresponding constitutive laws influenced by respiration, evaporation and losses of heat are affected by rotting processes. In this chapter these influences will be discussed in order of:

- Respiration
- Evaporation
- Heat loss

These phenomena are included in a mathematical representation of potatoes in a bulk (*Grubben, 2013*). The energy / temperature balance including heat generated from evaporation and respiration for healthy potatoes in a bulk is described by:

$$\frac{\partial T_p}{\partial t} - \nabla\left(\frac{\lambda_p}{\rho_p C_{pp}}\nabla \mathrm{T_p}\right) = -\frac{\alpha_c F_m}{\rho_p C_{pp}\epsilon_p}\left(T_p - T_a\right) + \frac{R}{C_{pp}\epsilon_p} - h_{fg}K_{evap}\frac{F_m}{\rho_p C_{pp}\epsilon_p}\left(X_s - X_a\right) \quad \text{on } (0,T] \times \Omega_p \quad [2]$$

$$\frac{\partial T_{ap}}{\partial t} - \nabla\left(\frac{\lambda_a}{\rho_a C_{pa}}\nabla \mathrm{T_{ap}}\right) + \frac{1}{\epsilon_a} v * \nabla \mathrm{T_{ap}} = \frac{\alpha_c F_m}{\rho_a C_{pa}\epsilon_a}\left(T_p - T_{ap}\right) \quad \text{on } (0,T] \times \Omega_p \quad [3]$$

Where $T_{ap} := T_{ap}(i,j)$, $T_p := T_p(i,j)$, $\nabla := [\frac{\partial}{\partial x}, \frac{\partial}{\partial y}]$ and $v := [v_x\ v_y]^T$

The moisture content, the ratio of kilogram water per kilogram produce in the bulk is described by:

$$\frac{\partial X_p}{\partial t} - \nabla\left(\mathbb{D}_p \nabla X_p\right) = -E_{resp}\frac{R}{\epsilon_p} - K_{evap}\frac{F_m}{\rho_p \epsilon_p}\left(X_s - X_a\right) \quad \text{on } (0,T] \times \Omega_p \quad [4]$$

$$\frac{\partial X_{ap}}{\partial t} - \nabla\left(\mathbb{D}_a \nabla X_{ap}\right) + \frac{1}{\epsilon_a} v * \nabla X_{ap} = K_{evap}\frac{F_m}{\rho_a \epsilon_a}\left(X_s - X_{ap}\right) \quad \text{on } (0,T] \times \Omega_p \quad [5]$$

Where $X_{ap} := X_{ap}(i,j)$, $X_p := X_p(i,j)$ and with constant ρ_p. There you also see a coupling between the equations as moisture produced by respiration is also included in the equation. (*Grubben and Keesman, 2015*) stated that more quality aspects should be included in the model, such as ethylene and carbon dioxide. As the rotting processes generate additional carbon dioxide by strengthening the respiration process, a carbon dioxide balance should be included. The carbon dioxide balance for potatoes makes it possible to control the product quality on the basis of actual data by the following equation:

$$\frac{\partial CO_{2,p}}{\partial t} + \frac{1}{\epsilon_a} * \nabla CO_{2,p} - \nabla\left(\mathbb{D}_{CO_{2,p}} \nabla CO_{2,p}\right) = E_{CO_2} R \quad [6]$$

With $CO_{2,p} := CO_{2,p}(i,j)$ and with constant $\mathbb{D}_{CO_{2,p}}$ [$1{,}5 * 10^{-5}$ m^2/s].

2.2.1. Respiration

Respiration is a major metabolic phenomenon occurring in all living cells, by which plants obtain energy through oxidation of organic matter accompanied by a release of carbon dioxide, water and heat. As a living organism, tubers continue to respire in storage. To obtain energy, sugars produced during starch hydrolysis, are used to form adenosine triphosphate that can be converted into energy:

$$C_6H_{12}O_6 + 6O_2 \xrightarrow[yields]{} 6CO_2 + 6H_2O + ATP + Heat \quad [7]$$

The starch hydrolysis process causes a loss of dry mater, resulting in tuber weight loss.
However, from a plant physiology point of view, the respiration process involves complex biochemical reactions and is much more than a simple sugar oxidation reaction. The respiration rate is influenced by temperature and hence will vary depending on storage conditions that are influenced by the end use of the potatoes. The respiration rate can be determined by means of CO_2 produced, O_2 consumed or heat released. This means the carbon dioxide balance is mainly determined by the respiration process due to CO_2 production. The respiration rate is minimal at about 5 °C and is gradually increasing up to approximately 15 °C, above which it severely increases. An increases in temperature due to rot will subsequently increase the respiration rates of the potatoes (*Fennir, 2002*). Consequently more heat will be produced which will lead to an even higher respiration rate and more favourable conditions for the pathogens (*Fennir, 2002*). Disease infestation can even lead to a significant 4- fold increase of the respiration rate (*Fennir, 2002*). Reducing the temperature to 3 °C also results in a sharp increase in respiration, because of the high level of reducing sugars constituted by the oxidation of organic matter hence the breakdown of starch. The respiration rates at 0 °C and 20 °C are equal to each other (*Pinhero et al., 2009*). Stable temperatures are a key element to maintain stable respiration rates (*Schippers, 1977*). Many researches have determined respiration rates for healthy potatoes for several units. (Fennir, 2002)determined a respiration rate of 1.44 -1.89 [ml CO2/kg/h] and 5.5 – 7.5 [ml CO2/kg/h] for rot, whereas (Keesman et al., 2003) showed a respiration rate of 195 [KJ/m^3/h], (Grähs et al., 1978) found a value of [29 KJ/ton/h] for a temperature of 7 °C, while (van't Ooster, 1999) stated a value of [112 KJ/ton/h] at a temperature of 20 °C and [72 KJ/ton/h] for 7 °C. This indicates that the variation of the respiration rate can be very large and dependent on that the respirational losses will differ within a large range. In the first month, the dry matter losses defined by the respiration rate is nearly 1-2% of the fresh weight, about 0.8% for the second month but rises to approximately 1.5% per month when sprouts are well developed (*Booth and Shaw, 1981*). The accompanied heat produced from respiration, during storage increases the storage temperature. In case of rot this heat production is even higher (*Fennir, 2002*). To maintain the desired storage conditions, the heat generated by the tubers due to the respiration process has to be discharged by cooling down the produce. It is not only important to lose this heat but also to provide the oxygen that is required for respiration and the removal of carbon dioxide released during respiration. Tuber respiration results in CO_2 levels of 0.1% to 4–6% in commercial storage. Accumulation of Carbon dioxide as high as 4% may cause black heart, and result in rotting tubers, which eventually result in quality losses at processing stored potatoes by affecting frying colour of chips and fries and an increased respiration rate (Pinhero et al., 2009). Especially carbon dioxide concentrations of 10 – 15% increase the start of rotting, also low carbon dioxide concentration and low oxygen concentrations give an increase of potato tuber rotting (Khanbari and Thompson, 1994). Accumulation of CO_2 up to 3% in well-sealed stores, results into an unacceptable fry colour. Tuber glucose and fructose content may also increase if CO_2 is maintained at 3–4%; however, CO_2-induced sweetening is reversible and variety-dependent. Whereas the CO_2 concentration outdoors is often 360–380 ppm, it often ranges from 1200 to 1500 ppm in well-maintained potato storage (Pinhero et al., 2009). When carbon dioxide levels stay above 5000 ppm, it may be a sign for rot pockets in the bulk or inadequate are exchange. Therefore, regular ventilation of stores for 2–4 h/day is recommended, with a standard ventilation rate: 100 m^3 air/ m^3 potatoes/ hour *(Gottschalk and Ezekiel, 2006); (Grubben, 2013)*.

Although temperature and carbon dioxide levels are important factors, the respiration rate is affected by several more factors. Most of the factors have something to do with the physiological phase of development the potato tubers are located in, such as maturity and wound healing. This kind of factors diversify depending on the crop, storage duration, season/year, storage facility, injuries to the tubers etc., hence are hard to measure (*Lukasse et al., 2007*). Even volatile gasses like ethylene cause a rapid rise in respiration rate (*Day et al., 1978*). The respiratory quotient (RQ), which is: the ratio of O_2 volume absorbed [h^{-1}] to the volume of CO_2 released [h^{-1}]. When the O_2 supply is not restricted, the RQ ratio

should be 1 in the most favourable conditions. The use of substrates other than glucose, make the RQ not valid.

$$RQ = \frac{CO_2\ produced}{O_2 consumed} \quad [8]$$

It has been reported that value of the CO_2-to-O_2 ratio is about 0.8 at the early storage phase, in the range of 0.9 to 1.0 at later stages of holding and 1.3 when the sprouting process starts *(Isherwood and Burton, 1974; Schippers, 1977; Gottschalk and Ezekiel, 2006)* found a correlation between the CO_2-to-O_2 ratio and the temperature of respiring potato tubers. Exhaustion of oxygen and a high rate of accumulation of carbon dioxide are associated with bacterial soft rots.
The respiratory coefficient R, used in the energy, moisture and carbon dioxide balances has a great influence on the losses of the potatoes. The respiration rate for healthy potato tubers is given by:

$$R_g = c_1 - c_2(T_p - 273.15) + c_3(T_p - 273.15)^2 \quad [9]$$

with; c_1 = 0.01075, c_2 = 0.00156 and c_3 = 0.00017, see (*Lukasse et al., 2007*). For a T_p of 24 °C, equation 8 gives a value for the respiration rate of healthy potatoes of Rg = 256.428 [J (kg produce)$^{-1}$ (h^{-1})]. The respiration rate for rotten potatoes is higher as more carbon dioxide is produced due to increased respiration (*Fennir, 2002*).

2.2.2. Evaporation

(Burton et al., 1992) stated that 98% of the moisture leaving a potato tuber during storage, is lost through the skin by evaporation. Only 2.4% leaves tubers by natural openings as lenticels and stomata, along with the carbon dioxide produced by the respiration process, as shown in Figure 1. Together with respiration, moisture losses are resulting in significant quality losses and eventually to nonmarketable produce, hence is unacceptable (*van't Ooster, 1999*). Moisture losses during a period of storage is depending on internal heat production, the potato temperature, physiological phase of development of the potato(skin), cultivar, sprout growth, relative humidity (RH), the duration of ventilation and also on damages. (*Booth and Shaw, 1981*) observed that about 0.14% to 0.17% of the potato tuber mass per mbar vapour pressure deficit per week is the average loss of water from mature healthy potato tubers, which increases to 0.5% to 0.8% for damaged tubers. Diseased tubers induce increasing temperatures and relative humidity which result into higher moisture losses.

Evaporation is the transformation of a liquid into vapour. The evaporation of water at a surface of agricultural produce is discussed in this report. In this case, evaporation is a consequence of a difference in vapour concentration at the surface area and the ambient air. The evaporation is induced by the released energy from motion of molecules which collide in to each other. If the moisture content in the adjacent air is lower as in the produce, the water in the produce is evaporated by the released energy. Thus, the evaporation rate depends on temperature, pressure and the relative humidity of the produce and surrounding environment (*Grubben, 2013*). When rot occurs, free surface moisture is oozing out of the potato tubers via the lesions caused by the pathogens. This means that the moisture can be evaporated more easily, as it is not retained by the potato and the vapour concentration of the ambient air is lower than free surface water (Pinhero et al., 2009) During storage the rate of moisture loss from the produce is proportional to the difference in water vapour pressure (WVP) within the cells of the skin and the WVP of the air in the voids inside the bulk. The difference between these two is often called the water vapour pressure deficit (WVPD). The lower the RH of the ventilating air, the greater the WVPD, which results in greater moisture loss through evaporation. In addition, the colder the temperature of the ventilating air compared with the potatoes, the greater the WVPD. This means: Ventilation of the storage produce with air cooler than the produce itself will always result in moisture loss through evaporation, no matter how humid. When there is no difference in pressure within the cells of the potato skin and the pressure of the air in the voids, no evaporation will take place if the RH inside the bulk is 97.8% or higher (*Pringle et al., 2009*).
Different equations for evaporation can be found, because there are different driving forces that could describe mass transport. (*Grubben, 2013*) uses a general notation for the evaporative or latent heat flux, which is based on mass transfer, by multiplying the convective mass transfer equation with the enthalpy of vaporization. In the moisture balance K_{evap} stands for the mass transfer coefficient for evaporation [(kg air) (m^{-2} produce) h^{-1}], influenced by the equilibrium of moisture content in air that is dependent on

the temperature and relative humidity, see (*Lukasse et al., 2007*). *(Grubben, 2013)* found a value for K_{evap} of 0.0002 [kg/m^2/s] for healthy potatoes, while in literature this parameter value was found in range of 0.000388 (*Lukasse et al., 2007)* and 0.0007848 [kg/m^2/s] by (*Kondrashov, 2007)*. This makes the evaporation coefficient a very sensitive parameter. As diseased tubers increase moisture losses and temperature, K_{evap} will become a different from the value for healthy potato tubers. As the potato tubers lose more moisture when rotten, the evaporation coefficient will increase. Increased evaporation affects the model on three different states:

- Water loss = Weight loss, each gram of water from the potato tuber is converted to a gram of water vapour in the surrounding air.
- Hence, the evaporative losses humidify the surrounding air.
- The evaporation process consumes sensible heat. The heat consumption of evaporation is equal to the latent heat of evaporation h_{fg}. In other words, the sensible heat is converted into latent heat.

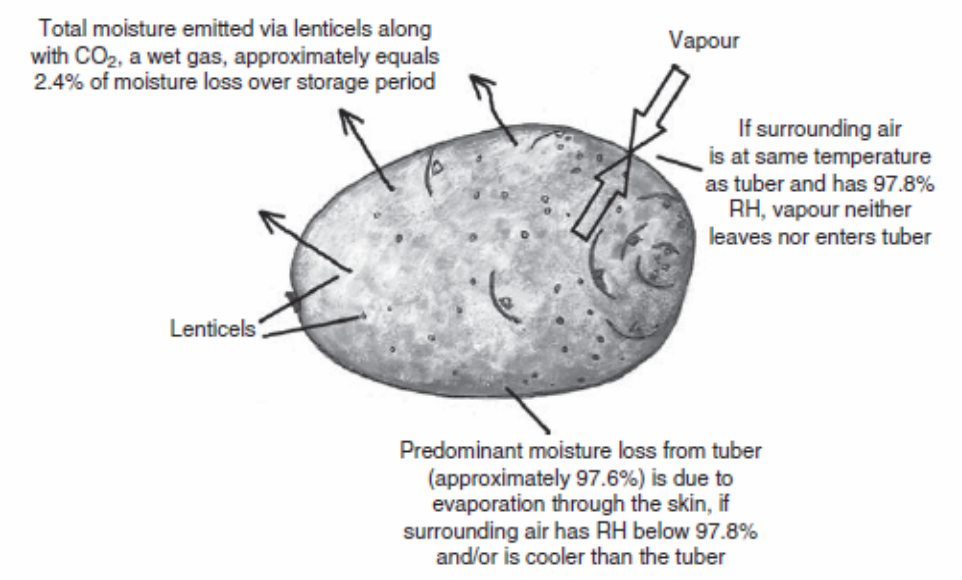

Figure 1 Water losses of potato tubers.

2.2.3. Heat loss

The metabolic rate of harvested products like potatoes is strongly influenced by the product temperature. As stated in earlier parts in this report, an increased temperature results in increased respiration rates, moisture loss and subsequently higher relative humidity, sprouting, changing chemical composition and the development of storages diseases. The total effect of temperatures on the metabolic rates is represented by the change in metabolic rates to the change in temperature. For storage it is critical to maintain the quality of the potato tubers throughout of a long-term storage or holding period, therefore it is required to minimize the metabolic processes. This can be realised by low storage temperatures, but provided that no cold damages occur.

The temperature balance includes three terms of heat generation by several processes. The first term: $\frac{\alpha_c F_m}{\rho_p C_{pp} \epsilon_p} \left(T_p - T_a\right)$, is a description of general heat transfer from the potatoes to the ambient air if they differ from each other in temperature. The transfer of heat is due to:

- Conduction
- Convection
- Radiation

The mathematical description of these phenomena can be found in (*Grubben, 2013*).

The second term: $\frac{R}{C_{pp}\epsilon_p}$, is the respirational heat. Stable temperatures are a key element to maintain stable respiration rates (*Schippers, 1977*). When the temperature increases, which will happen when rot occurs, the respiration rates will become higher than for healthy tubers (*Fennir, 2002*). So more temperature will be produced and transferred to the ambient air.

The third term: $h_{fg}K_{evap}\frac{F_m}{\rho_p C_{pp}\epsilon_p}(X_s - X_a)$, is the heat loss by the evaporation process. The evaporation process consumes sensible heat. The heat consumption of evaporation is equal to the latent heat of evaporation h_{fg}. Thus when surface water on the tuber is evaporated, heat is transferred to the colder ambient air that contains more water vapour than the potato tubers. This is an exothermic process; hence energy from the potato tuber is needed to change water into water vapour. When rotting occurs more surface moisture will be released, hence the temperature losses by evaporation will increase.

2.3. Potato post-harvest Diseases

During cultivation and storage periods, the potato crop is susceptible to various pests and diseases which induce crop losses, hence reducing quantities and threaten the potato tuber quality and value as product. Both quantity and quality losses result from physiological, physical and pathological causes or combination of all causes. The reasonable storage live of potatoes depends on wilting, sprouting and diseases or damages that cause rotting, depending on the physical conditions of the potato tubers. Many forms of these losses appear at different phases in the entire production; from the pre-harvest stage through harvesting, storage handling and operations, and even exposure in the market. Mechanical injuries are one of those losses. These damaged potatoes should not make it to the storage. Furthermore mechanical injuries are the leading cause of soft rots, dry rots and other post-harvest diseases *(Pinhero et al., 2009)*. The pathological cause of losses occurs primarily in combination with physical and physiological phenomena. Wounds make the potato tubers susceptible for pathological attacks which presumable cause the most gross severe post-harvest losses. Pathological problems consist of: Fungi, bacteria, insects, nematodes, viruses and viroid's. In this chapter the three most common diseases occurring in storage will be discussed. These diseases include:

- Blackleg and Bacterial soft rot
- Late Blight
- Cold temperature injury (deficit)

The characteristics of the diseases that will be discussed are: Importance, Causal Agent, Epidemiology and Symptomatology respectively.

2.3.1. Blackleg and Bacterial soft rot

Bacterial soft rot is a frequent occurring disease in many vegetables and fruits like: Potatoes, carrots and unions. Bacterial soft rots and Blackleg are considered the most serious and destructive of all potato storage diseases, found all over the world. Every cultivar is susceptible for bacterial soft rot. The disease is caused by different bacteria of the genera Pectobacterium and Dickeya, which can be found in Table 2. The principal pathogenic agents for potato tubers are: *Erwinia carotovora ssp. Carotovora* (Ecc), *E. carotovora ssp. Atroseptica* (Eca) and *E. chrysanthemi* (Ech) *(Hauben et al., 1998)*.

Table 1 Soft rot Erwinia species that can infect potatoes.

Bacteria	Disease symptoms	Host range
E. carotovora		
spp. Carotovora	Soft rot	Wide
spp. Atroseptica	Blackleg, soft rot	Potato
E. chrysanthemi	Soft rot, wilt	Wide

Bacteria are primarily wound parasites that enter through mechanical injuries in plant tissues due to for example harvest proceedings or insects, but they frequently enter uninjured healthy plants and tubers through natural openings such as stomata and lenticels (*Pringle et al., 2009*). Bacteria thrive on nutritious media containing sugars and starch. Thus tubers are an excellent medium to grow on. Also

warm, moist conditions are favourable for bacterial growth. Under favourable conditions like high temperature (with an optimal of 25 °C), high humidity and poor ventilation, the pathogen initiated at lenticels or in wounds, can liquefy a tuber in a few days *(Gardan et al., 2003)*. The ooze from this tubers spread bacteria to the surrounding tubers, which can eventually result in hot spots, as can be seen in Figure 3 (Pringle et al., 2009). In general, soft rot Erwinia agents are facultative anaerobes. Pathogenically growth Erwinia soft rot is in general most comprehensive under anaerobic conditions or on the other hand when O_2 concentration exceeds 30% (*Nielsen, 1968*). Hence the sensitivity of tubers to soft rot is increased at a combination of lower oxygen concentrations with high RH. Frequent occurrence of soft rot in potato storage under anaerobic instead of aerobic conditions could be due to suppression by lower oxygen levels on the resistance response of the potato tuber (*Mount, 2012*). There are many ways by which the bacteria can contaminate surrounding tubers. Air born sources can be a cause of infection spread (*Czajkowski et al., 2011*). Also surface water may be a source of bacterial contamination even as mechanical failing and handling operations (*Pérombelon and Salmond, 1995*).
Erwinia bacteria do not overwinter in the fields. (*Pérombelon and Salmond, 1995*) stated that the main source for infection are the tubers. According to (*Czajkowski et al., 2011*) soft rot Erwinia located in the soil can also colonize potato tuber roots and via transport through the vascular system they can reach to offspring tubers. Once they are established in the roots, they can survive in latent form without necessarily causing an infection.

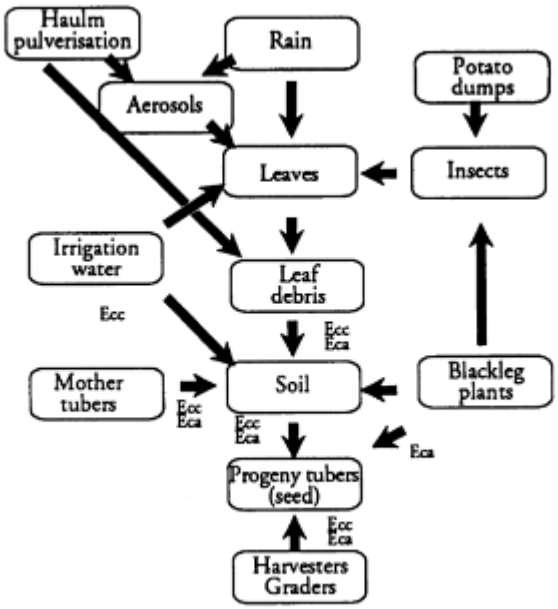

Figure 2 Sources and pathways of infection by soft rot Erwinias of potatoes.

The most characteristic symptoms of soft rot, usually developed during transit or storage, on potatoes caused by Pectobacterium and Dickeya species are watery, viscous, black/yellow rot lesion and an obnoxious odor when invaded by secondary pathogens. Predisposing factors are: low (freezing) temperatures, bruises, maturity of the tuber and insects that make wounds and transmit the bacteria from one tuber to another (*Rich, 2013*). The lesions caused by soft rot can spread to the whole tuber and thence to adjoining tubers as liquid from the infected tubers percolates onto others, frequently leading to massive rotting pockets in the stored tuber lot if no measurements were taken *(Pérombelon, 2002*). These pockets of blight and/or rot can start hotspots which can result in the breakdown of the pile, shown in Figure 3. When this rot is present, it may take up to 6 weeks of extensive ventilation treatments to dry the rotting potato tubers and to prevent the spread of the infection causing sequential rotting. Piles of tubers that contain more than 1% of soft rot are not or very difficult storable *(Veerman and Wustman, 2005)*. Other types of bacterial diseases that occur in potato fields and storages are:

- *Brown Rot (Bacterial wilt)*
- *Common Scab*
- *Pink Eye*
- *Ring rot*
- *Miscellaneous Bacterial Diseases*

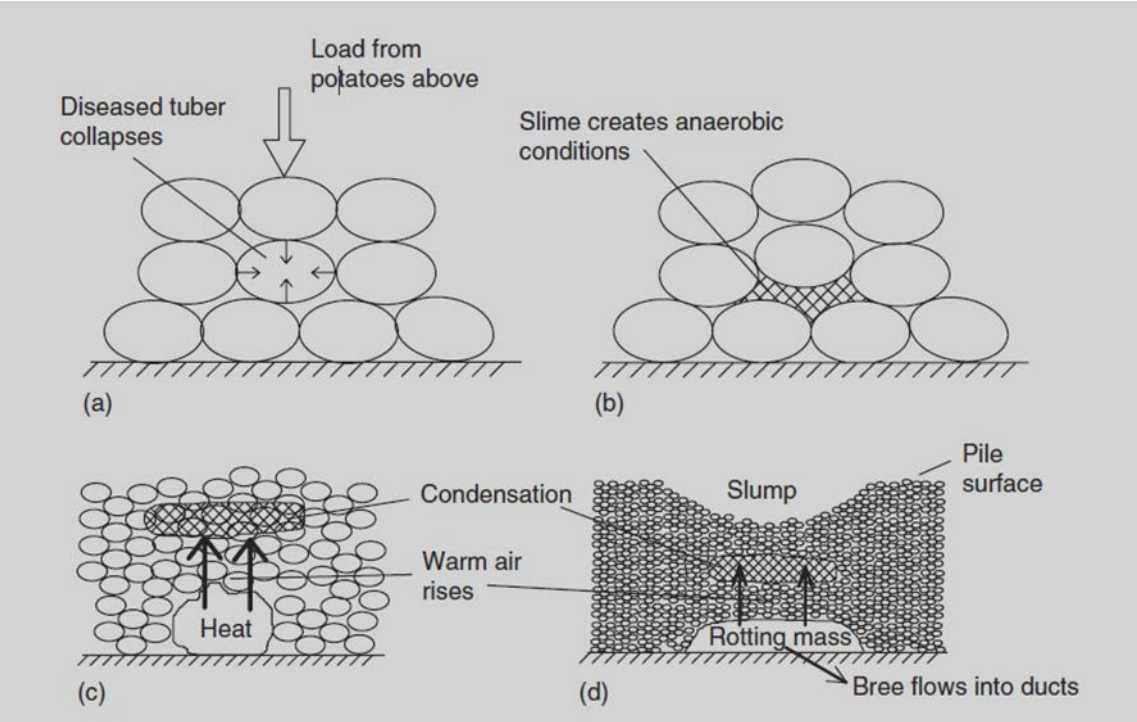

Figure 3 Sequential development of a hot spot in a bulk pile; (a) tuber rots turning into slime; (b) the slime contaminates surrounding tubers; (c) heat from rots causes warm air to rise and condense on parent tubers; (d) collapsing tubers cause breakdown, from (Pringle et al., 2009).

2.3.2. Late Blight

Potato Late Blight is considered as one of the most devastating potato diseases, in many cases causing a wide extension of agricultural disruption. Every year the disease is found in many production areas all over the world and can result in total yield loss. The disease is caused by the oomycete (water fungi): Phytophthora infestans. The name Phytophthora comes from the Greek language and literally means: 'Plant Destruction' *(Lees et al., 2008*). Fungi are primarily saprophytes or parasitic on higher plants including potatoes. Unlike bacteria many fungi reproduce by means of spores. These spores can be sexual, asexual or both, causing leaf, tuber or diseases on both plants and tubers. Under favourable conditions like cool temperatures and high relative humidity (>90%), spore production and germination is stimulated. Subsequently, when established in storage, spore production is stimulated due to favourable storage conditions (*Smart and Fry, 2001)*.The fungi can survive between seasons by remaining dust and dirt in storages, infected tubers that are used as seed potatoes, exiled potatoes, often in dump stacks or overwintering tubers remaining in the soil after harvest (*Smart and Fry, 2001)*. On short distances migration and epidemics are especially caused by sporangia transport through water and airborne sporangia, hence via ooze from lesions and through air in the bulk (*Lees et al., 2008*) . infestans populations gained more and more diversity in the last decennia. (*Drenth et al., 1995*) observed that new genotypes were formed with sexual reproduction as driving force, which induces new variations of the disease. Isolates of the recently established *P. infestans* population in the Netherlands have the special ability to infect potato tubers at temperatures in range of 3 to 27 °C, while for older populations the range was 8 to 23 °C *(Lebecka et al., 2006*). These adaptions of populations can cause severe danger for tubers in storage, as they favour development of *P. infestans* on a wider temperature range. The establishment of the infection generally takes place in the field but can also occur in storage under dry conditions, where it often causes serious tuber rot (Grinberger et al., 1995). Storage of potatoes for processing purposes are usually held at 10 °C (*Burton et al., 1992*). Long storage periods at this temperature can favour tissue infection instead of sporulation caused by Phytophthora infestans. Hence colonization of potato tuber tissue is potentially more important than secondary spread by sporulation (*Grinberger et al., 1995*). The initial infection is not visible, and the rot becomes apparent after minimal one week *(Bonde and Schultz, 1945*).
Eventually when the pathogen is established it causes lesions with brown/purple colour on the surface of the potato tubers. The fungal infection per se is odourless, but often secondary invaders, mainly bacteria, cause an obnoxious smell making observations of symptoms difficult (*Lees et al., 2008*).

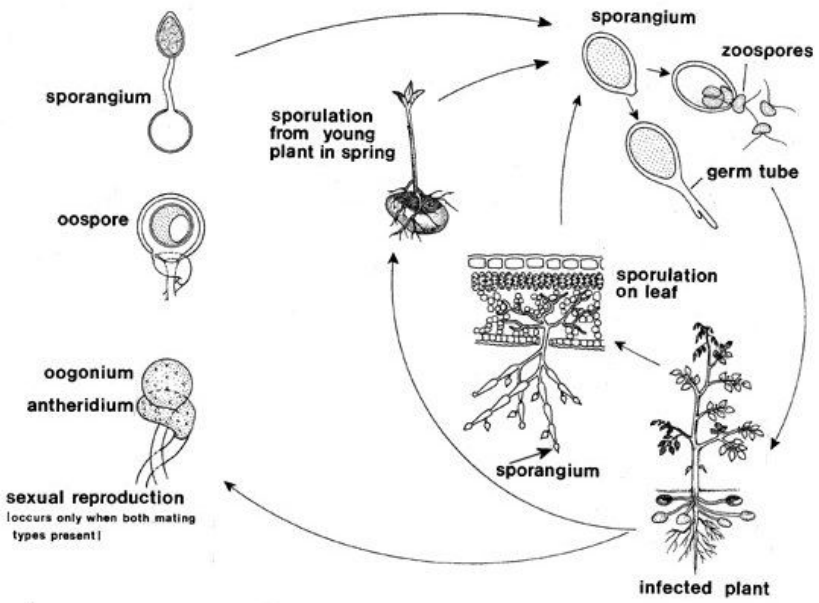

Figure 4 Simplified disease cycle for potato late blight.

Other types of fungal diseases that occur in potato fields and storages are:

- *Early Blight*
- *Fusarium dry rot*
- *Black Dot*
- *Pink Rot*
- *Silver scabies*
- *Rhizoctinia*

2.3.3. Cold Temperature Injury

Injuries due to low temperatures occur in different range from completely frozen which kills the potato tuber to lower degrees of chilling injuries due to prolonged exposure to freezing temperatures in the field or low storage temperatures slightly above freezing. Below -1.7 °C potato tubers start to freeze, which results into the formation of ice crystals in the potato tissue making it unable to perform the ordinary metabolic processes. Prolonged chilling stress is followed by injuries like surface lesions, oozing and soaking of the tissue, discoloration and eventually a rapid death of the tuber. Chilling injuries potentially result into tuber death, but will anyway expose the tuber to secondary pathogenically invaders. When still stored under low temperatures, the symptoms often remain concealed. But when thawed, the symptoms will become evident within short time *(Wang and Wallace, 2004)*.
As stated earlier potatoes are very susceptible to chilling damage, but research have shown that potato tubers after a short time of freezing temperatures of about –5.5 °C and thereafter carefully warmed, did not show any chilling injuries or symptoms *(Hruschka, 1961)*. However, storage life of recovered potato tubers often is reduced and are more sensitive to microbial attacks *(Wang and Wallace, 2004)*.
There are multiple potential causes of the freezing of potatoes in storage: This could be due to falling freezing air from on products from the evaporator coils of through contact between the freezing walls and the produce. Also the way the pile is built up can be a cause of freezing injury, especially when stacked high near the evaporator coils and when not stacked tight enough it may result in static freezing air spots in the bulk (*Chourasia and Goswami, 2009*).

2.4. Prevention of diseases

Prevention is the best form of control. When no rot/diseases occur, you do not have to control it. Storage diseases are not curable, so it is important to practise active prevention management, to prevent diseased tubers from entering storage. Sanitation is very imperative for the control of diseases that cause rot. Storage facilities should be cleaned and disinfected with a good quality disinfectant such as copper sulphate or formaldehyde. Priority is to carry out the best cultural practices, to preclude pathogens from enter the potato tuber through mechanically caused damages. Avoiding physical damages is very important and effective against diseases; this can be done by careful harvesting and handling. But also the period of harvesting is important in terms of the timing with a view to the current weather and soil conditions and crop maturity. Fungicide programmes to manage diseases and disease-free seed also reduce the quantity of infected potato tubers being stored. *(Pérombelon and Salmond, 1995)* suggest that, even in the absence of disease, significant yield losses of up to 20% can occur in crops grown from latently infected seed tubers.
The first step to be made before storage of the bulk is taking care of the sanitation in the storage facilities, making sure that the store is clean, hygienic and free of last year's waste before loading the tubers. Secondly, effective drying and curing including cooling of the tubers is necessary, which is important for an effective wound healing process. Also controlling the storage conditions, to minimize losses as much as possible to try maintaining the quality of the tuber entering the storage and also to inhibit disease activity is a must. It is critical to stay vigilant in surveillance throughout the storage period for potential problems and appropriate management strategies to limit pathogen spread and disease development should be implemented *(Bishop et al., 2012).*

2.5. Disease detection methods

In storage facilities, detection of disease is a critical consideration. Before you can control diseases, they firstly have to be identified. Several techniques are used to identify early outbreaks of rot and to prevent enormous yield losses. These methods are discussed in the next paragraphs.

Manager's inspection

The first and most obvious method of disease detection is the manager's inspection. Conventional detection methods depend on sensing and visual signs for disease identification. There should be checks of the facility on a daily basis. The storage managers have collected some practical experience over the years and can use their sense of smell, which plays an important role as rotten tubers release a very unpleasant odor, that progressively increase as the disease advances. They can also use their visual focus on the physical sings in the pile. Diseased tubers slowly dissolve and the tissues become creamy and start to ooze, which infect the surrounding potatoes.
Besides the smelling conditions, free moisture is carried away when ventilating the air, which results in condensation on the top of the pile and store ceiling. In advanced stages even wet spots become visible, giving the indication of a diseased pocket within the potato pile. After some time these pockets become weak, leading to spatial collapsing of the pile. Although frequent inspections confirm existence of infections, it is not easy to quantify its severity, giving the managers little time to make decisions on which measures should be taken.

Temperature sensing

Inside the bulk, diseased tuber pockets are biologically metabolic spots which have higher respiration rates, and hence generate more heat. Additionally, heat is produced by the pathogen activities and the break-down of potato tissue, resulting in much higher heat generation rates as in healthy potato tubers. Theoretically local hotspots and heat changes within the pile could be detected with temperature sensing applications like temperature transducers or infrared detection instruments. However these instruments are not yet used in real life storage because of several technical limitations and high costs for commercial storages.

Volatile monitoring and electronic sensing

The potato flavour consists of beyond 100 volatile compounds including aldehydes, alcohols, ketones, acids, esters, hydrocarbons, amines, furans and sulphur compounds (*Lui et al., 2005*). Microorganisms like fungi, bacteria, viruses, nematodes and protozoa can modify the volatile pattern transmitted from potato tubers and produce markers of the pest. Several studies have been carried out on the practice of volatile monitoring as an early detection method. These methods are based on the concept of identifying certain volatiles which are an indicator for specific diseases. Chromatography-Mass Spectrometry (GC-

MS) was used for the practice of these methods by analysing gas samples obtained from a closed space with infected tubers *(Lui et al., 2005)*, (*Lyew et al., 1999*), (*Lyew et al., 2001*), (*Ouellette et al., 1990*). In principle all analytical methods rely on analysing gas samples from an enclosure which obtain infected tubers and identifying the appearance of the specific volatile biomarkers for the studied disease. The volatile biomarkers discussed in this report are; Acetone,ethanol,2-butanone and 3-hydroxy-2-butanone that were recognized as markers of soft rot (caused by Pecto bacterium carotovorum ssp. carotovorum) in stored potato tubers. And; Ethoxy-ethene,2-methyl-l-butanol, 2-butanone, 2-methyl-2-butanamine, 2-2-propenyl-1,3-dioxolane and 3,5-heptadiyn-2-one are disease markers for fungi in stored potato tubers (*Laothawornkitkul et al., 2010*), (*Varns and Glynn, 1979*). (Rutolo et al., 2016) found a way to identify and monitor potato storage diseases by using metal-oxide based gas sensors. For further information see his research.

2.6. Control of diseases

Even when good prevention management is implemented, the probability of occurrence of diseases is always present at all stages of production. Disease development consists of three components:
(i) The pathogen present; (ii) the host tuber; and (iii) the surrounding micro-environment. The 'disease triangle' of (Plank, 1963) helps us to visualize the contributions to the development of diseases and how to restrict this development by various control strategies. In potato storage the host is the tuber; the pathogen a range of fungi and bacteria etc.; and the environment consists of temperature, free surface moisture on the skin of the tuber, and the RH and carbon dioxide concentration of the void air in the bulk. The store manager could interfere and affect the amount of disease that develops.

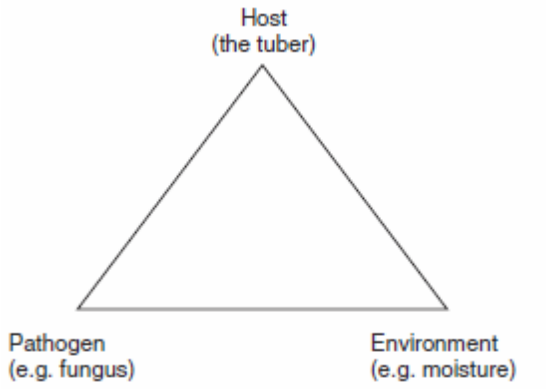

Figure 5 The disease triangle.

Unfortunately there are restrictions to the intervention possibilities that could be taken to limit the disease development:

- In a storage facility with a single airspace, the whole stored mass of tubers has to be kept at a single compromise optimum temperature. Storage under different temperatures for various diseases cannot be realised when there is a single airspace.
- The potato tubers primarily influence the RH in air in the voids through evaporation. This gives the store manager limited control over RH.
- Even in when there is refrigeration available in the facility, it will take 30 days to cool a crop by 15 °C. Rapidly cooling of a crop to minimize disease development is therefore not always possible.
- Sections of tubers that were harvested wet, or have become wet during condensation, could be dried by directing air towards specific wet areas or by ventilating the whole stored mass. When rot occurs the ventilation can be taken a stage further, by using prolonged ventilation to desiccate rots and prevent pectolytic oozing from digesting the skins of neighbour tubers.

Many pathogens slow their development, enter a static resting stage or will even die if their environment becomes hostile. Their life cycle therefore fails. Environmental conditions that induce life cycle failure of pathogens can mostly be influenced, such as storage temperature and surface moisture on the tuber. A key contribution to the shape (and size) of a disease triangle comes from the application of fungicides that kill or prevent further development of a proportion of the pathogenic organisms present. In theory, a disease triangle will collapse if any one of the three components meets criteria where disease development is impossible. When a crop variety expresses complete immunity to a given pathogen, then there is no adjustment of environment needed, also removing the pathogen would be irrelevant for disease control. Similarly, if a pathogen is completely absent from a growing region, changing crop or storage conditions adaption has no influence on disease development. However, it is difficult to reach these absolute conditions for a given disease hence, it is important to understand that modifying one point in the triangle will simultaneously influence the others (*Pringle et al., 2009*).

Also the stage of disease development influences the way it can be combated. The transition from latent to active infection is affected by several different factors which may interact with each other, for example: surface moisture. (*Pringle et al., 2009*) used stocks inoculated with antibiotic-resistant strains of *E. carotovora* to measure the effects of surface moisture on the development of bacterial populations throughout storage periods. By preventing condensation during curing of the tubers they achieved a 50% decrease in bacterial levels compared with crops where condensation had not been prevented.
Thus moisture is clearly a main factor in bacterial growth. Also temperature is a major factor; the rate of multiplication is more rapid under cooler conditions (*Pringle et al., 2009*). As the temperature of storage for crops destined for fresh use tends to be lower than for crops destined for processing, tuber surface moisture is a more significant risk in the latter. The presence of free moisture, which creates anaerobic conditions, will increase the development of bacteria like *Erwinia carotovora* causing soft rotting. Careful removal of surface moisture, through either windrowing in the field or ventilating the crop (during wound healing), is important to reduce the risk of rot. It is important for storage managers to ensure wounds are healed more rapidly than pathogens can gain entry. Also tuber surface moisture should be removed by drying and condensation due to respiration heat or exposure to wet circumstances should be avoided by ventilation and finally there the crop can be cooled when all wounds are healed, where there has to be paid attention to temperature differentials within the mass which may not exceed 0.5 °C or condensation and secondly possible bacterial development is likely to occur (*Pringle et al., 2009*).
When the storage temperature decreases, the metabolic rate of bacteria and consequently their ability to grow and multiply will also decrease. Most of the diseases are partially of entirely inhibited by storage temperatures below 7.2 °C (*Wijekoon et al., 2015*). These cold temperatures also extend the dormancy period, and thus postpone sprouting. For most bacterial pathogens, the optimum temperature for growth and development lays usually higher than the normal storage conditions. For Erwinia species the optima lie around 30 °C. With this knowledge the assumption of cooling the crop immediately after harvesting is easily made. But such cooling would be very slow with a maximum of 0.5 °C/day also the wound healing process would slow down and the rate of periderm, the primary defence to disease entry, would be reduced. It can also lead to conversion of starch to sugar which may result in dark fry colour.
Furthermore, cooling would result in condensation forming due to temperature differences between the new stored and the already stored crop. The need for cooling ventilation is minimized by a well-insulated storage facility, so heat entering the storage is limited. In addition of temperature, low oxygen concentration is necessary. Rotting of tubers is more rapid under low oxygen concentrations than in air, as the bacteria grow more rapidly under aerobic than anaerobic conditions (*Pinhero et al., 2009)*.
Anaerobic conditions lead to affection of the potato cell membrane integrity, which result in cell contents leaking out into intercellular spaces thereby providing a favourable and nutritional environment for bacterial growth. The relationship between the extent of rotting and low oxygen concentrations could be described in terms of an inhibitory effect on the low oxygen conditions on the resistance response of the tubers to infection. So it is critical to keep the oxygen concentrations on a normal level to realise aerobic conditions *(Pérombelon and Salmond, 1995*).

Most fungal pathogens incubate tubers at relatively high temperatures, 15-20 °C and at high RH. But fungi can occur even at low storage temperatures. Rapid suberization right after tubers are placed in storage is desirable. High humidity [95%], an optimum temperature of 10–12 °C, and good ventilation [100 m^3 air/ m^3 potatoes / hour] to avoid condensation, can minimize *Fusarium, Pythium*, and *Phytophthora infestations*. If there is a significant amount of pink rot or leak in tubers going to storage, fans should be operated continuously to increase air movement, and the storage temperature should be dropped below 10 °C, with outside air used as needed to cool the crop as quickly as possible (*Lees et al., 2008*). At higher storage temperatures for example 15-18 °C, the wound healing ability allows formation of a barrier before pathogens can enter the tuber flesh. In practice skin spot tends to develop most rapidly on tubers in store at 3–5°C, where the rate of wound healing is slow, while the fungus can still grow rapidly enough to access the flesh of the tuber.

2.6.1. Ventilation and drying mechanisms

Even when good prevention management is implemented, the probability of occurrence of diseases in storage is always present. When rot is established in the pile there it is necessary to prevent the rot from expanding. Critical is to identify what kind of rot you have to deal with, so the right measures can be taken. It is important to be conscious that adaptations of storage conditions also affect the quality attributes of healthy tubers, such as sugar concentrations when cooling the produce and drying out of the crop when using extensive ventilation. Three basic storage management mechanisms are:

- Temperature
- Humidity
- Air movement

Finding a balance between these three is the key to implement good potato disease management. As the first two items are already discussed in previous chapters, leads it to discussing Airflow.

Air movement includes both through-the-pile and over-the-pile ventilation (= recirculation) strategies. Ventilating through the pile is critical for cooling and drying of the tubers and as supply for fresh air and removal of CO_2, volatiles and excessive heat and moisture. The recirculation air contributes to uniform temperature in the storage facility and removes condensation from walls and ceiling. Normal ventilation rates are about [20 cfm/ton = 3.75 * 10^{-2} kg Air / kg produce per hour]. However higher rates of ventilation [40-50 cfm/ton] are needed when frosted or diseased tubers occur, providing rapid cooling and drying to avoid condense forming on the tuber's skin. This adjustment can minimize diseases like Pythium leak, bacterial soft rots and Phytophthora (*Pinhero et al., 2009*). The rate of moisture loss from the tubers stays stable at ventilation rates slightly above [20 cfm/ton], whereas the drying rate is rising. Hence, the drying of tubers with high ventilation capacity is much quicker and with less overall shrinkage *(Wijekoon et al., 2015)*.

How often and whether to use over or through-the-pile ventilation is dependent on the conditions of the tubers and the end use. During cooling and wound healing different strategies should be performed compared to the holding period. When the pile is stabilized at the desired storage temperature, the ventilation rate should be minimal. To maintain a stabilized differential, which should not be higher than 0.5 °C per 2 meter pile depth, the ventilation rate is dependent on the temperature of holding *(Wijekoon et al., 2015*). When diseased tubers occur in the pile, the ventilation rate naturally should be strongly increased. Continuous fan operation to perform high draught airflow ventilation is critical to dry out the wet, diseased tubers *(Elphinstone, 1987)*. The percentage rot in storage determines the rate and duration of additional drying ventilation with reduced-humidity air (*Olsen et al., 2006*). This may however, result in shrinkage of the rest of the pile and may also delay wound healing.

Table 2 Viability of pathogens (%) on Potato Tuber Surface when ventilated for a certain period (*Olsen et al., 2006*)

	Time 0	0.5 hour of ventilation	1 hour of ventilation	2 hours of ventilation
Late Blight	100%	100%	95%	60%
Soft Rot	100%	30%	10%	0%
Dry Rot	100%	100%	100%	100%
Silver scurf	100%	100%	100%	100%

2.7. Biological defence mechanism against pathogenically infections

In nature, plants constantly have to defend themselves against pathological attacks. The performed physical barriers like cuticle, plant cell wand and other periderm tissues are effective against pathogen attacks, the unbroken skin being impenetrable to fungi or bacteria. Besides that, plants have just like human developed an congenital immune system to identify microbial invasion through natural openings like the lenticels, stomata, etc. or mechanical wounds, and to launch effective biological static and dynamic defence mechanism to combat the pathological attacks. This makes plants generally resistant to the major pathogens with the assumption that the skin stays intact, so if no wounds occur. The susceptibility to pathogens like fungi, bacteria and viruses generally depends on the ability of the plant to identify the pathogen in the early infection process. When the pathogens are recognized, rapid tissue necrosis in the ambient region of the infection will arise to prevent the diffusion of the infection, this is also known as the hypersensitive response (HR), also known as programmed cell death (PCD). The HR divests the nutrients from the pathogen and/or releases toxic molecules, to confine the growth medium for the infection. This means a much more limited number of pathogen can enter the host without arousing tuber tissue necrosis at all or only after serious delay. If the plant exposes accessibility and the pathogens successfully enter the host, they can cause a severe amount of damage (*Mehdy, 1994*).
The recognition of molecular signatures of pathogens plays a key role in innate immunity. Certain races of fungal or bacterial pathogens are recognized by certain cultivars resulting in the HR triggering. The cultivar's ability to keep recognizing several pathogenic varieties keeps evolving, while the pathogen remains to adapt itself and keeps evolving to avoid recognition by a resistant host. Plant pattern-triggered immunity (PTI) corresponds to the perception of pathogens and is initiated upon present evidence that states that observing the danger signals could appear in three different kinds of signals; through the recognition of: PAMPs, MAMPs and DAMPs. PAMPs, MAMPs and DAMPs also known as *Pathogen-Microbe-Damage associated molecular patterns*, are different kind of plant defence response triggering molecules from microbes. These molecules can be saccharides, proteins, peptides. These danger signals whether emanating from different pathogens such as: viruses, bacteria, fungi, or oomycete, can trigger a range of general inducible defence mechanisms that contribute to overall resistance of the host. Although equal in terms of quality, these defence mechanisms may have various expressions in terms of kinetics and quantity considered the specific danger signals involved *(Wu and Chen, 2014*). The perception of PAMPs, MAMPs and DAMPs takes place in the direct surroundings of wounds. Microbial attacks can trigger defence responses systemically due to perception of MAMPs or other danger signals of the local invasion, also called system acquired resistance (SAR), which has gained more and more attention last years *(Boller and Felix, 2009).* A part of the regulation of the plant immune system activity in plants or surrounding plants is done by signalling hormones like: Ethylene, Salicylic and Jasmonic acid (There can be substantial cross-talk among these pathways) *(Moore et al., 2011)*. To generate SAR, ethylene is required in infected potato tissue, also perception of different PAMPs cause production of ethylene in infected tubers.
Recent studies has identified Ca^{2+} signalling as a pivotal modulator of transcription kinetics (Bigeard et al., 2015)*, (Boller and Felix, 2009)*. Numerous studies have observed clear momentary fluxes in accumulation of Ca^{2+} when plant immune responses were activated, but so far, the channels of Ca^{2+} and the sensing and transducing of the Ca^{2+} signals on pathogenic attacks still yet remain mostly unknown (Moore et al., 2011). A physical response induced by these signals is: Reactive oxygen species (ROS) production also known as the oxidative burst. The oxidative burst combined with pathogen identification has been well established for most of the plant-pathogen interactions. The first perceptions of ROS during plant-pathogen interactions were made in research of infected potato tubers with late blight (*Phytophthora infestans*) (*Doke et al., 1996b*). The ROS response to pathogen attacks are toxic intermediates (Superoxide (O_2^-), hydrogen peroxide (H_2O_2) and hydroxyl radical (OH)) that result from successive one electron steps in the reduction of molecular O_2. These compounds induce lipid peroxidation which causes lipid damage resulting into affection of the cellular membrane functions. The oxidative burst is highly correlated with the hypersensitive response in many plant-pathogen interactions and is consequently a significant aspect contributing to disease resistance (*Mehdy, 1994*), (*Lamb et al., 1989*). Several studies indicate that the oxygen burst directly reduce pathogen viability. It has also been shown that micro molar concentrations of hydrogen peroxide (H_2O_2) inhibit spore germination for a significant amount of fungal pathogens *(Peng and Kuc, 1992).*
For more review, see: *(Lamb et al., 1989) (Mur et al., 2008) (Albert, 2013) (Boller and Felix, 2009) (Wu and Chen, 2014) (Moore et al., 2011) (Schreck and Baeuerle, 1991) (Doke et al., 1996b) (Peng and Kuc, 1992) (Doke et al., 1996a) (Doke, 1983) (Bigeard et al., 2015) (Lannoo and Van Damme) (Macho and Zipfel, 2014) (Coll et al., 2011).*

2.8. Modelling Disease spread

Crop infection can be defined as "Change of disease intensity in a host population over time and space". In most cases is the change an increase in diseases intensity. It is a dynamic process in which the fundamental depiction of an epidemic is the diseases progress curve (DPC). This is a plot of the disease proportion against the time. The DPC express the interaction of pathogen, suspect an environment over time. Quantification of disease progression is desirable for numerous reasons including:

- Predicting future levels of diseases
- Evaluating control strategies
- Verification of disease simulators and forecasters

(Plank, 1963), is a pioneer in quantification of disease progression, laid the foundation for the modern analysis of epidemics and since his publication several extensions to this field have been made. Two specific case models are obtained by his work; a Monomolecular and Logistic model, with model assumptions:

- Steady state Environment
- Constant Host
- Constant Pathogen virulence
- Spatially random

Monomolecular ("Simple interest" model)
This model also called: negative exponential model, has been used to describe monomolecular chemical reactions in the form of a first order derivative:

$$\frac{\partial A}{\partial t} = QR\,(1 - A) \qquad [10]$$

With: $x = QRt \;\; and \;\; x = \; x_0 e^{rt}$

A = proportion of infected plants or diseased tissue
(1-A) = proportion of healthy plants or tissue
Q = inoculum density
R = basic infection rate (0.1-1.0)

Tells you:

i. QR: inoculum (density and 'potential') and effects of environment combined.
ii. Increase in Q -> increase $\frac{\partial A}{\partial t}$ *(Pullman and DeVay, 1982)*
iii. Increase in R, due to more favourable environment leads to an increase of: $\frac{\partial A}{\partial t}$

Note: Disease increase is not dependant on the amount of disease present; only primary inoculum is effective because there are no secondary cycles, hence the rate of disease increase is proportional to inoculum density.

Logistic Model ("Compound interest" model) for polycyclic process.

$$\frac{\partial A}{\partial t} = rA\,(1 - A) \qquad [11]$$

With:

x = proportion of infected plants or tissue diseased
(1-x) = proportion of healthy plants or tissue
r = apparent infection rate

The absolute rate of disease increase is jointly proportional to the level of disease '(x)' and healthy tissue '(1-x)'. Although the rate of $\frac{\partial x}{\partial t}$ increases with few levels of y, it will finally decrease to zero. The inflection point of x=0.5, means that the maximum rate is obtained

For the spread of infection a basic theoretical model can be set up. It is providing a simplified notation of the real physical dynamics and attempts to summarise the main processes, to put forward hypotheses and to verify their coherence and consequences. It also represents an exploratory way to ascertain the minimal hypotheses which would allow minimal mathematical representation of the real processes. The following model is a general model, which is descriptive and also allows the prediction of the occurrence and the severity of the infection;

$$\nabla A = k_1 * A_1 (\Delta T) + k_2 * A_2 (\Delta T) \quad [12]$$

Where;

$$A_1 + A_2 = 1 \quad \Rightarrow \quad A_2 = (1 - A_1)$$

Which gives:

$$\nabla A = \left(k_1 * A_1 + k_2(1 - A_1)\right) * (\Delta T) \quad [13]$$

Where ∇A is the proportion of infected or diseased plant tissue over time, A_1 is the infected plant tissue and the healthy plant tissue is given by A_2. k_i defines a spread constant and ΔT represents the difference in temperature between the lesion surface of the potato and the ambient storage air.

3. Materials & Methods

When the basic physics are captured in a model, the calibration and validation of the model should be performed on real data. In this chapter the experimental setup to obtain data to calibrate and validate the parameters will be described. The obtained experimental data should allow the parameter values to be determined. So it is critical that the model parameters are measured in the right way and in the right range, to obtain significant data that can be used to analyze the system on base of practical data. Therefore the right measurement instruments should be selected and also environmental conditions should be considered. A research scale facility based on the model of an air-cooled storage system was constructed, simulating a bulk storage facility. To obtain a successful storage facility and to facilitate stable storage conditions, design and operational considerations were chosen carefully.

3.1. The storage facility

The storage facility was divided into four storage boxes with external dimensions of 700 x 450 x 150 [mm] and a board PC who collects data from the CO2, RH and temperature instruments. The dimensions of the boxes were chosen in order to form a 1-D configuration. The maximal length of the potatoes was chosen as depth of the chest. The dimensions were also chosen such that the experimental set up could be placed into a fume cupboard, this in order to prevent the smelly odour from spreading in the lab. (Figure 6, 7 and 8) show plan and section views of the experimental setup, respectively. For the collected data to include ways for comparison, to allow similar treatments and to facilitate future use for long term studies, four storage boxes were built to be identical in size and to simulate real storage conditions on a smaller scale. A trolley with the computer, Gas chromatograph (GC) and monitor for gas measurements is placed in front of the set-up. The heart of the storage facility was the four identical and independent storage boxes that are carried out in two different models with a storage capacity of ±0.03 m^3 potatoes, which are 49 potatoes. This number of potatoes is chosen, as the normal bulk piles heights in conventional bulk storages are between 4.5 and 5.5 m, and a height of 7 potatoes is about 0.45 m. This makes calculations easier, and realises the simulation of a small scale bulk pile. The two different models are: Model 1, which is a set-up with a compressed air flow and Model 2, which is a hermetically closed set-up.

Both models are designed with external dimensions of 700 x 450 x 150 mm to, as stated earlier, allow comparison of collected data and similar treatment. The front of all boxes is not removable and is made of Perspex, to make observation of the spread of the infection through the potato lot possible. The walls were made of 10(mm) thick treated plywood sheets. On the rear of each box there are placed three coupling nuts to connect the RH, carbon dioxide and temperature sensors in the box and lead them through the back without losses of air and gasses. All boxes could be closed by a lid at the top.

Model 1 has, in contrast to Model 2, a 1/8" socket for the connection with the gas chromatograph. Furthermore, it has a removable bottom, with permeability of 8 – 10 % carried out in plywood and a PVC connection for the supply for compressed air, whereby the ventilation treatment for rot in reality can be simulated.

Figure 6 Experimental set-up. From left to right: (1) Ventilated box with rot; (2) Closed box with rot; (3) Ventilated box with healthy potatoes; (4) Closed box with healthy potatoes

3.2. Instrumentation

The boxes were all equipped with the same instrumentation consisting of: RV (humidity) and carbon dioxide transmitter, and a thermocouple to measure the temperature, provided by Omnivent. Also the environmental conditions are measured with the same devices. All the instrument measurements are made available as analogue outputs (0-1/2.5/5V) and as a digital interface (E2-interface), so easy implementation and data processing are made possible.

Carbon dioxide – CO_2 transmitter (EE820).
Gas analysis was performed for the four boxes. The EE820 carbon dioxide transmitter is used to carry out the carbon dioxide measurement. The measured Carbon dioxide percentages were used to determine the respiration rates. It is designed for use in rigid, demanding applications. A multiple point carbon dioxide and temperature adjustment leads to high accuracy over the entire temperature working range, hence the EE820 is suitable for outdoor use. The incorporating of the E+E dual wavelength NDIR CO_2 sensor, which compensates for ageing effects and is highly insensitive to pollution, offers long term stability.

Relative Humidity – RH transmitter (EE08)
The relative humidity was measured at various locations in the system. Therefore the EE08 was used, which is an accurate humidity/temperature measurement device that has a wide working range, hence is a versatile and compact sensor. It has low power consumption and short start-up time support, efficient energy management for battery operated systems, hence an ideal device to perform the experimental measurements.

Temperature – Thermocouple (EE461) Pt100 wire sensor
The air temperatures were measured at various locations in the system, distributed as follows: One thermocouple in each box and one for the environmental temperature, hence the temperature of the potatoes and the surrounding air temperature was measured. Cable sensors are used to perform the temperature measurements. In general these sensors are used in heating, ventilation and air conditioning systems as well for process control. The thermocouple has a sensitivity of 3.850 x 10^{-3}/°C with an insulation resistance of > 100 MΩ at 20 °C. This device can operate by temperatures in range of -30 to 105 °C.

Flow rate – Flowmeter Brooks Instrument (Model #1355)
The flow meters used for air velocity measurement is a glass tube variable area flow meter with a scale length of 150 mm. The float material is stainless steel, which gives the meter a perfect fit in the range of the airflow used. The meters were placed right before the inlet of air into the boxes.

Camera – Windows LifeCam HD 3000
To record and observe the diffusion of the infection the Windows Lifecam HD 3000 was used. The camera makes use of COMs sensor technology and has an imaging rate up to 30 frames per second. It has a 16:9 widescreen and 24-bit colour depth with True colour technology that Automatic image adjustment with manual override.

Computer Hardware/Software
The program used to make snapshots with the Windows LifeCam HD-3000 is called Ispy, which is a free, open source video surveillance platform. This software facilitated full automation of the observation and data collection. Four captures were taken every day and saved by the program.
The control on the facility operations and data acquisition were performed using object oriented software obtained by OmniCuro. This software facilitated full automation of the facility conditions and data collection. Measured relative humidity, temperatures, and carbon dioxide were all saved on a daily basis and transferred from the control computer and used for the observation application online.

Gas chromatograph (GC)
The headspace gas was sampled and analysed using a portable GC system (Flash RGA, compact GC4.0), which allows analysis of permanent gases (including helium and hydrogen), hydrocarbons (C1-C5, C6+) and H2S, with a running time of 10 minutes. The gasses to be analysed for this report are: carbon dioxide, oxygen, ethylene, ethanol and other volatile biomarkers (described in '*Volatile monitoring and electronic sensing in Disease detection methods*'). The boxes were connected to the GC by a twofold of tubes and valves with a diameter of 1/8" (0.318 cm). The RGA was programmed to sample headspace

air for 30 s at the rate of 100 ml/min and 50 ml of the headspace air sampled was pre concentrated in a Carboxen trap (15 mg) which was heated to 220 °C to desorb volatiles. Helium (He) gas was used as carrier gas. The injection of the carrier gas was done under a pressure of 100 kPa at a flow rate of 1.0 ml/min and velocity of 123.3 cm/s under a temperature of 80 °C. A capillary column SPB-5 of 30 m with 0.32 mm internal diameter was used. The GC column temperature was held at 110 degrees Celsius for 4 min and then increased at the rate of 3 °C /min until it reached 220 °C. Mass ions were scanned at the rate of 0.8 spectra/second over a mass range of 46-300 m/z.

3.3. Experiments

There are 50 potatoes placed in each box, where for the experiment with the rot, the box contains a core of rot. As referential point, the experiment is carried out in the same model storage box with only healthy potatoes. The experiments will be executed for the two most common and major types of pathogens and one physical deficit that cause rot in potato storage (Table 3) namely:

1. Bacterial soft rot, caused by the *Erwinia carotovora bacteria*
2. Late Blight, caused by the *Phytophthora fungi*
3. Frozen potatoes (at -18 °C)

The potatoes used for the experiment were randomly selected from the potato storage. The only screening done in selecting the tubers was to not knowingly use potatoes that were already exhibiting visible rot or were grossly formed. The gross weight of the box and the potatoes were recorded as the potatoes were placed in the experimental set-up. The average gross weight of the boxes was: 11 kg and with potatoes 23.4 kg, with a range of 22.0 kg for the lightest to 25.4 kg for the heaviest sample. The tubers and boxes were weighted by a scale with a capacity of 100 kg and a resolution of 0.01 kg. The potatoes were stacked on top of each other in 1-Dimensional form of 7 rows and 7 columns, in order to realise a 1-D configuration. Shrinkage losses were determined by placing the potatoes of known weights in a grid pattern in the potato pile as the boxes were filled and then retrieving the bags and reweighing them when the boxes were unloaded. The spread of the infection is observed by 2 webcams. By taking photo's automatically, the spread will be captured in a sufficient time range. On the basis of these pictures the future diffusion coefficient of the rotting process will be determined. When carrying out the experiments, each day the lit was removed from the box to let the parameter values of temperature, relative humidity become equal to the surrounding conditions. After closing the chest again, it can be seen that the values will rise again. In this way, the production of moisture, temperature and carbon dioxide from the potatoes could be measured. This method applies to the hermitically closed boxes, where a difference should between rotten and healthy potatoes in time by which they reach the end of the range of the measurement instruments. In this way the parameter values of the respiration rate and the evaporation rate can be calculated, based on the data of the carbon dioxide and moisture production.

Table 3 Different types of rot used for the experiments

	Erwinia soft rot	Phytophthora infestans	Frozen potatoes
Experiment 1	X		
Experiment 2		X	
Experiment 3			X
Experiment 4			X

3.3.1. Differences between conventional bulk storage facilities and the experimental set up

A research scale bulk storage facility was constructed as accurate as possible. Stable storage conditions, design and operational considerations were chosen carefully, however some differences cannot be avoided. Firstly, the temperature in the experimental set up is much higher than in a conventional bulk storage facility as can be seen in Table 4. This choice is made because higher temperatures are more favourable for the spread of rot, as conventional storage temperatures (4-5 °C) inhibit the spread. Also implementation of a cooling system to maintain low and stable temperatures would be very expensive. The RH in the experimental set up should be 100% for the closed boxes, as the potato tubers produce moisture, while the boxes are hermetically closed so this would mean that the moisture would built up to a level of 100%. The value of the RH for the ventilated boxes is estimated as 50%, because due to the high flow, the produced moisture leaves the box and expected is that the RH transmitter cannot measure some of the moisture leaving. Furthermore the environmental RH is very low due to the fume cupboard, which means that most of the moisture will be suctioned out. Expected is that the carbon dioxide levels in the closed boxes will reach over 10.000 [ppm], but because of the measurement ceiling, higher concentrations cannot be measured. In conventional storages the carbon dioxide levels are 1200 – 1500 [ppm]. This difference is very big and it may have influence on the physical conditions of the potato tubers.

Table 4 Conventional bulk storage facilities vs Experimental set up

	Experimental closed boxes	Experimental ventilated boxes	Conventional bulk storage facility	Resource
Relative Humidity	100 %	±50%	95 -100% 90 – 100%	*(Fennir, 2002)* *(Grubben, 2013)* *(Rastovski and van Es, 1981)* *(Eltawil et al., 2006)* *(Pringle et al., 2009)* *(van't Ooster, 1999)*
Temperature	20 - 25°C	20 - 25°C	4-5 °C	*(Fennir, 2002)* *(Grubben, 2013)* *(Rastovski and van Es, 1981)* *(Eltawil et al., 2006)* *(Pinhero et al., 2009)* *(Pringle et al., 2009)* *(Veerman and Wustman, 2005)* *(van't Ooster, 1999)*
Carbon Dioxide levels	10.000 [ppm]	400 – 500 [ppm]	1200 –1500[ppm] 0.1 – 4.6% 0.25 -3%	*(Pinhero et al., 2009)* *(Veerman and Wustman, 2005)*

3.3.2. Ventilation treatment

The produce in box 1 and box 3 was cooled and dried using a floor type ventilation system. The air was distributed into the potatoes through a rectangular permeable plate with dimensions: 420 x 140 [mm] that was placed at the bottom beneath the potato pile, above the air inlet, as the boxes were filled with potatoes. The plate has a permeability of 8 to 10% as there were drilled 56 holes (4 x 14), with a diameter of 5 [mm] and 1 [cm] space in-between to realise a homogeneous air distribution. Prior to storage, the ducts were tested for air distribution uniformity and the flowmeters were also calibrated. Several assumptions were made: (1) heat gain and losses from the box by convection and radiation were neglected; (2) heat, carbon dioxide and moisture gained by the ventilation air was due to convection in one-dimensional flow; (3) air infiltration was entirely due to thermal forces (natural convection), the air temperature differs between the storage boxes and their surroundings. The applied flow is based on the standard forced convection dilution rate used in practice of 100 [m^3/h air per m^3 potatoes]. For bulk storage an average bulk height is four meters. This means that in a real storage facility a dilution rate of 400 [m^3/h air per m^3 potatoes] with an air velocity of ±0.33 [m/s] inside the bulk is used, obtained by a floor porosity of 8 to 10%. The average diameter of potatoes is ± 65 mm stacked seven rows high, so the volume of potatoes used: $0.45\,m * 0.45\,m * 0.15\,m = \pm 0.03\,m^3$ potatoes, which means the dilution

used for this experiment is:

$$0.030375\ m^3\ potatoes * 100 \frac{m^3}{h}\ air\ per\ m^3 potatoes = 3038\ l \frac{air}{h}$$

When calculating the corresponding air velocity inside the bulk a problem occurred. The air velocity can be calculated by: $\frac{1}{1-\epsilon} * \left(\frac{m^3 air}{s}\right)$

With ϵ = 0.64278 (Grubben, 2013), gives us an air velocity of 0.0024 [m*s^{-1}]. This is too small compared to the 0.33 [m/s] in conventional storages and cannot be realised. There are several options to solve this problem.

1. The dimensions of the chest must be adjusted. This would mean that the new dimensions have to be: 4000 x 1000 x 1000 [mm]. This option could not be realised because of exceeding costs. Also the 1-D configuration would be lost, which we cannot afford to happen.
2. Another option is raise of the ventilation rate to 10.000 [m^3/h air per m^3 potatoes] and adjust the height of the stacked potatoes to 0.63 [m], so increase the height of the chest. This would give:
$$\left(\frac{10000}{3600}\right) * (0.63 * 0.45 * 0.15) * \frac{1}{1-\epsilon} = 0.3307\ [\mathrm{m} * \mathrm{s}^{-1}]$$
This is not an ideal option either, because the flow would be too high and could dilute the gas concentration in such way that it would not be possible to measure the gas concentrations with the GC.
3. The third option would be lowering the permeability of the plate to a percentage of 0.5% for a height of 0.9 [m] potatoes or 0.25% for a height of 0.45 [m] potatoes.
$$\left(\frac{100}{3600}\right) * \frac{0.9 * 0.45 * 0.15}{0.005} = 0.3375 \frac{\mathrm{m}}{\mathrm{s}}$$
$$\left(\frac{100}{3600}\right) * \frac{0.45 * 0.45 * 0.15}{0.0025} = 0.3375 \frac{\mathrm{m}}{\mathrm{s}}$$
This would be the most ideal option but could not be realised by the executor of the chests as the pressure inside the chest would become too high.

Eventually option 2 is chosen to use in the experiment, because in practice the ventilation rate is increased when rots occur. There is still no directive for this, so excessive ventilation is used by storage managers to dry rots. The ventilation treatment will last for 24 hours a day, to find the extremes between no ventilation to completely ventilate and then finding the means. The relative humidity of the compressed air was determined by placing a RH meter right before the inlet of the box to measure the RH of the inlet air for 5 minutes, repeating the procedure 5 times. The average gives us a RH of ±25%, used to simulate the ventilation treatment against ±75% used in practice.

3.3.3. Experiment 1

The rot used in this experiment is bacterial soft rot, caused by the *Erwinia carotovora bacteria.* Soft rot bacteria (Erwinia carotovora subs. Carotovora) were obtained from the Laboratory of Phytopathology at the Department of Plant Sciences of Wageningen UR. The disease agent was grown on an agar nutrient base in a petri plate. The pathogens were pure and no contaminations were observed. The bacteria were contained at the time of transferring inoculum to the potato tuber. Apparently healthy cv. Agria potato tubers and uniform in size were selected (Medium size with: Diameter: ± 6 cm, ±15 cm length and mass ±250 g, the surface was sterilized with a 70% alcohol solution and rinsed with de-ionized water. Thereafter five holes were made with a potato peeler (±3 cm diameter x 5 mm deep). For each treatment about 15 mL of the bacterial solution was prepared. The solution was equally divided among three tubers. Then all tubers were placed in separate airtight bags and placed under the hood at about 20 °C. After a week of letting the rot establish itself, they were placed in the experimental setup. Not knowingly how long it will take for the rot to spread, the duration of the experiment would be determined

on observations. When after a period it takes more time than before, the optimal production is reached for a certain surface of rot. When this point is found, the experiment can be completed.

Figure 7 Filled storage boxes.

3.3.4. Experiment 2

The rot used in this experiment is Late Blight, caused by the *Phytophthora fungi.* Phytophthora was obtained from the Laboratory of Phytopathology at the Department of Plant Sciences of Wageningen UR. The fungi was grown on two potato plant leaves in a petri plate with a agar nutrient base, which was enough to make 10 to 20 mL of a 10.000 sporangia/mL suspension. The pathogen were pure and with no contaminations as well as the bacteria. The same potatoes were used in experiment 2 as in experiment 1. About 15 mL fungi suspension was prepared for each treatment and equally divided over the wounded and fumigated potato tubers. Then all potato tubers were placed in separate airtight bags and placed under the hood at about 20 °C. The inoculation of the tubers was done at the same time as the Erwinia soft rot. The tubers were placed in the experimental setup after finishing experiment 1. At first only one diseased potato was placed at the centre of the boxes. When there does not occur a spread of the infection, it is intended to enlarge the hot spot manually, to simulate the spread of rot. Thus after a period the centre will consist of three rotten potatoes, subsequently out of five.

3.3.5. Experiment 3

In this experiment frozen potatoes were used. Six cv. Ramos potatoes with incisions, to speed up the process of moisture oozing out of the potatoes on the surrounding potatoes, were placed in the freezer for 24 hours. This low temperature causes chilling injuries resulting into rot when unfreezing them. When removing the potatoes out of the freezer, they were immediately placed in the experimental set-up without letting them thaw, as a rotting core consisting of three potatoes. If the rot do spreads, the period of measuring is dependent on the measured values. If the surface of rot expands, it should take less time for the potatoes to reach the measurement ceiling. When after a period it takes more time than before, the optimal production is reached for a certain surface of rot. When this point is found, the experiment can be completed. When no rot spread occurs within a week, the core of rot would be enlarged manually as in experiment 2. In this way the spread is simulated and the moisture, temperature and carbon dioxide production could be determined for certain surfaces of rot.

Figure 8 (left) Potato frozen for four hours; (right) potato frozen for 24 hours

3.3.6. Experiment 4

Experiment 4 is a repetition of experiment 3 in order to collect validation data and to find out if the experiment is reproducible. To keep the execution of the experiment consistent, the same proceedings as in experiment 3 were performed to hopefully obtain the same data in range of experiment 3. So, in this experiment a rotting core consisting of three potatoes is used.

4. Experimental results

In this chapter, the obtained experimental data will be discussed on the base of the four different experiments that were carried out. Data of experiment 1 and 2 is rejected as due to several problems the data became invalid. The data of experiment 3 will be used to calibrate the model parameters and experiment 4 as validation data .

4.1. Experiment 1

While performing the first experiment, various problems occurred, whereby the data became invalid. Firstly, the spread of rot was inhibited. The inhibited spread of rot in the first performance of the experiment with the soft rot and Phytophthora could be due to different causes.

Before the rotten potatoes were added to the experimental, they were left out for a couple of days in order to ensure the bacteria and fungi were well-established. As discussed in 'Biological defence mechanism against pathogenically infections' certain races of fungal or bacterial pathogens are recognized by potato tubers, so after those days the hypersensitive response could already be initiated. In de gas analysis (Figure 13) a peak can be seen, where the ethylene concentrations should be indicated, which could warn the surrounding tubers to activate their defence mechanisms. This may be the confirmation of this presumption.

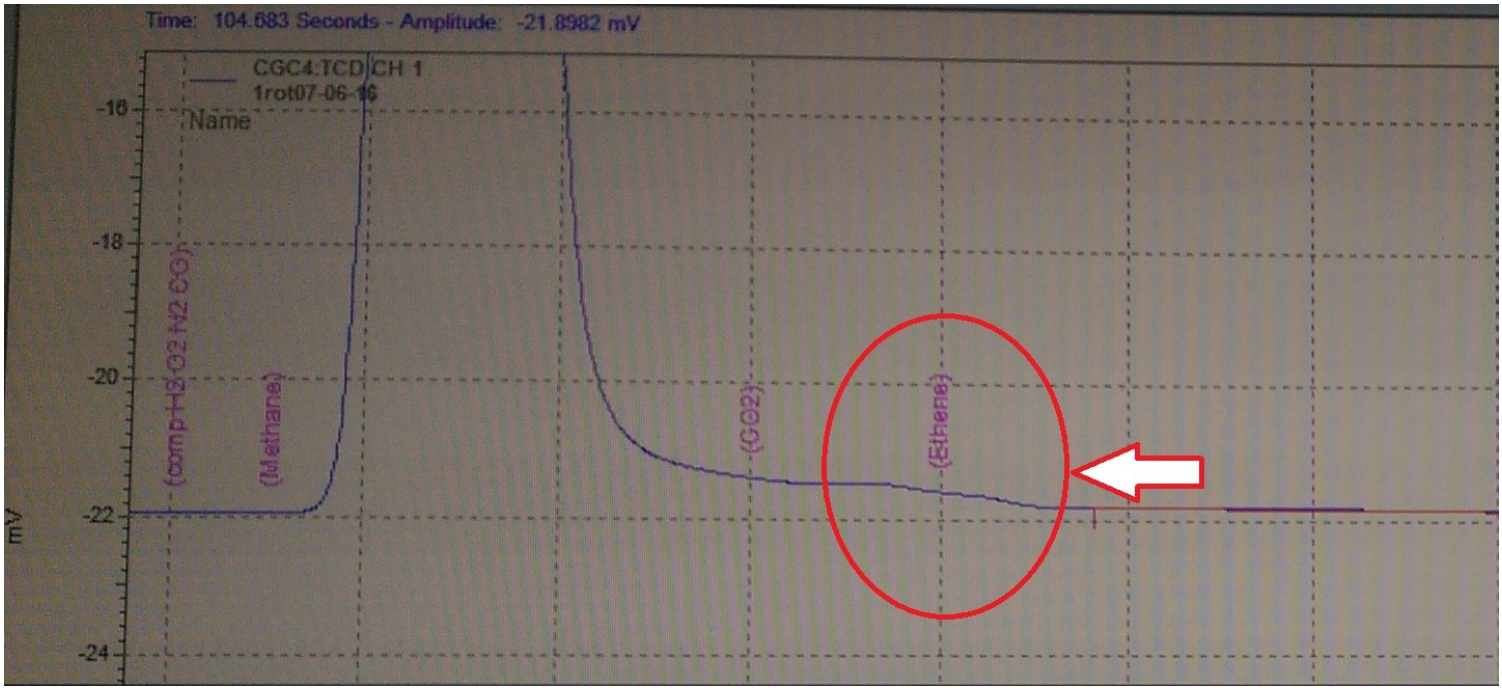

Figure 9 GC outcome of rot experiment 3 (chest 4), in order to indicate the Ethane peak

Another cause could be that the spores did not spread well, as there was no air circulation, hence the air was stagnant and the spores didn't have a medium to spread out over space. The type of cultivar may also have played an important role. The used type (Agria) is intermediate susceptible to Phytophthora (*Möller and Reents, 2007*). However the potato tubers used, were at the end of their holding period, this may have effect on the susceptibility, since the tubers are very mature and have formed a thick skin over the seven months. This may be a reason why the healthy potatoes were not affected by the rotting cores. Furthermore the inhibited spread may be caused by the potato tubers in the experimental set-up not stacked tightly enough, so there was not enough contact surfaces between the potatoes to distribute the disease. Also the sprouting occurring at one time can be a cause. The lenticels are either used as point for sprouts to grow but also as entrance for pathogens, so when sprouts start to grow the natural openings are no longer accessible to pathogens.

Secondly, the relative humidity in the boxes was too low. In practice the relative humidity in storage is 95 to 100%. Also the ventilation air used is 75 to 80%. This was not reachable in the experimental set-up. The air extraction in the fume cupboard induces dry conditions outside the boxes with a RH of ±50%. The boxes appeared to be not fully locked; otherwise the RH inside these boxes would be 100%. These dry conditions result in not precisely simulations of practice. Also the humidifier placed in the fume cupboard did not have enough capacity to change the RH in the experimental environment. The ventilation air used was compressed air. When this air passes through the compressor it loses moisture, since the air pressure is increased to 5 bars. Measurements revealed that the RH of the compressive air is 25% compared to 75-80% in reality. This declares the early dry out of the rot in ventilation boxes.

4.2. Experiment 2

At a certain point during the experiment, the surrounding healthy potatoes started to sprout. This made the measurements unusable, because we only look at the parameters influenced by disease development. Not knowingly when the process started, which can be long time before the sprouts become visible, confirmed better not to use the data. (*Fennir, 2002*) stated that respiration rates could increase by four to five folds, as sprouts grow. Additional to that, the suggestion made by *(Burton et al., 1992)* that an increase of 50% or more could occur due to an early stage of sprouting, made us decide to abandon the data from this experiment. Several reasons can be proposed for the starting of the process. Warm and dry conditions may be a cause of a shortened period of dormancy. The main reason of sprouts start to grow is the temperature. The temperature retained in the experimental set-up was far higher than the general storage temperature in practice. Sprout growth is slow below 5°C, whereas the optimal temperature for sprout growth is 20 °C (*Pinhero et al., 2009*). The experimental temperature was about 23 °C, so this could be a huge influence on the sprout growth. Also a high CO_2 concentration could be the cause of sprouting. Since the rotten potatoes produce more carbon dioxide and the potatoes are in a closed space, the CO_2 concentration will keep rising when there is oxygen to consume. The physiological phase of development of the potato tubers is depending for the oxygen content that is required for optimal sprout growth. In early storage phase, the optimal O_2 content in the storage atmosphere required for sprouting is 4 to 5% at a temperature of 10 to 20 °C, which increases between 17 to 20% after a couple of months (*Pinhero et al., 2009*). Furthermore, sprouting will affect the quality of stored potato tubers by converting storage compounds such as starch and protein and shrinking tubers resulting into loss of water (*Pringle et al., 2009*).Sprouting reduces the quality and value of the stored potatoes because of increased respiration and moisture losses (*Burton et al., 1955*). Briefly summarized, sprouting increases physical ageing and affects the outward appearance of the potato. Also too much direct light falling at the potatoes could induce sprout growth, however this is not scientific declared.

The GC measurements were not usable either. This was the first time someone used the GC, hence made the proceedings more difficult and mistakes could be made more easily. Probably the flow was too high and could dilute the gas concentration in such way that it would not be possible to measure the gas concentrations with the GC. Another cause could be that the potatoes were ventilated 24 hours. In this way the gases could not built up to measurable concentrations. Samples by hand did not give any usable information of the carbon dioxide concentrations, as the peaks were too small (Figure 9). Besides this practices, there is tried to make some samples with the photo spectrometer, but the peaks for carbon dioxide could be a few other particles, hence this measurements gave us no clarity.

4.3. Experiment 3

The experimental data is obtained from the Omnicuro program. This data will be used to calibrate the model parameters, as no further problems occurred. As stated earlier in Materials & Methods, the measured parameters are:

- Carbon dioxide
- Relative Humidity
- Temperature

Which are discussed in the order mentioned above, respectively.

Carbon dioxide measurements

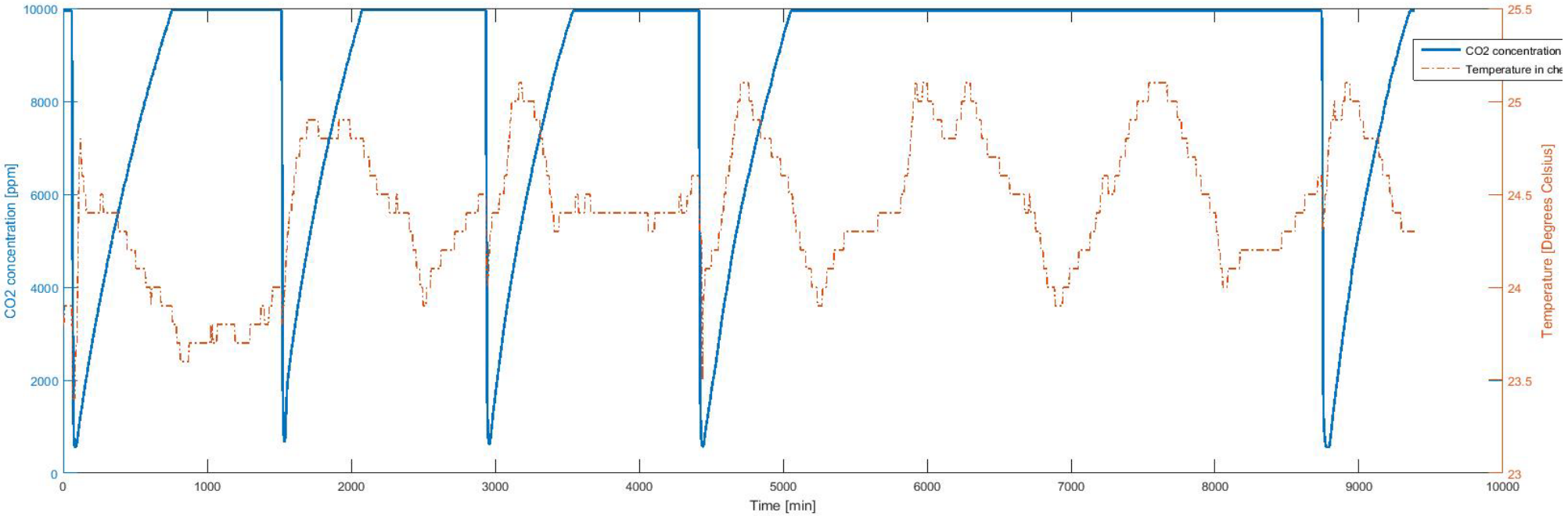

Figure 10 Carbon dioxide and Temperature data of experiment 3, during 7 seven days of measurements for healthy potatoes (box 4).

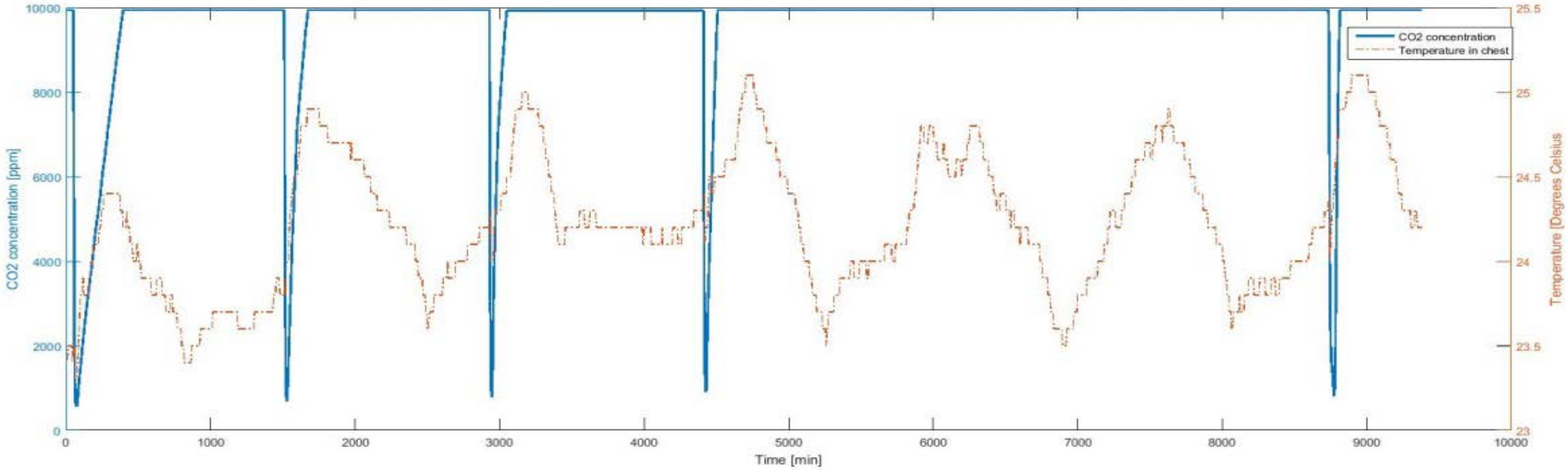

Figure 11 Carbon dioxide and Temperature data of experiment 3, during 7 seven days of measurements for rotten potatoes (box 2).

The total length of the storage period in experiment 3 is shown in Figure 10 and 11. The (blue) thick line presents the carbon dioxide levels, whereas the (red) dashed line presents the temperature inside the boxes. The drops in the carbon dioxide levels and temperature levels indicate the opening of the boxes to let the values become equal to their environment. The temperature data seems to follow the carbon dioxide levels quite well; however the differences between initial values and values of the increasing temperatures are very small in a range of 1 degree Celsius. Because of the limiting measurement range of the carbon dioxide transmitter, the levels of carbon dioxide only reach to 10.000 [ppm]; however in reality they reach much further than that. Furthermore it can be seen that the velocity of the increasing carbon dioxide levels is much higher for the rotten potatoes than for the healthy potatoes. From this we can conclude that the carbon dioxide production of rotten potatoes is higher than for healthy potatoes, except for day 1. At the first day of measurements t = [0] for figure 11, the rot is not fully established yet, this makes the increasing carbon dioxide level following the levels for healthy potatoes. When time proceeds you can see that the increasing carbon dioxide levels reach their ceiling faster. This means more carbon dioxide is produced at day 7 compared to day 1. From this we can conclude that when the surface of rot increases, the carbon dioxide production consequently increases. In other words: higher percentage of rot inside the bulk will induce higher respirational carbon dioxide production.

Relative humidity measurements

The increase of relative humidity is measured at the same time as the carbon dioxide levels.

Table 5 Increasing RH with additional temperature for healthy potatoes (box 4) experiment 3

Time [min]	RH day 2	T[°C]	RH day 3	T[°C]	RH day 4	T[°C]	RH day 7	T[°C]
0	*64*	*23.4*	*64*	*24.1*	*64*	*23.5*	*66*	*24.3*
5	*65*	*23.5*	*78*	*24.2*	*65*	*23.9*	*66*	*24.3*
10	*66*	*23.8*	*78*	*24.3*	*72*	*24.0*	*66*	*24.2*
15	*74*	*24.0*	*80*	*24.3*	*78*	*24.0*	*74*	*23.5*
20	*78*	*24.0*	*80*	*24.3*	*78*	*24.3*	*80*	*23.9*
25	*78*	*23.8*	*82*	*24.4*	*80*	*24.2*	*80*	*24.0*
30	*80*	*23.9*	*82*	*24.4*	*80*	*24.3*	*82*	*24.0*

Table 6 Increasing RH with additional temperature for rotten potatoes (box 2) experiment 3

Time [min]	RH day 2	T[°C]	RH day 3	T[°C]	RH day 4	T[°C]	RH day 7	T[°C]
0	*66*	*24.2*	*69*	*24.0*	*67*	*24.2*	*69*	*25.0*
5	*69*	*24.3*	*71*	*24.1*	*75*	*24.4*	*71*	*25.0*
10	*69*	*24.3*	*75*	*24.2*	*83*	*24.5*	*71*	*25.0*
15	*71*	*24.4*	*77*	*24.3*	*83*	*24.5*	*71*	*25.1*
20	*77*	*24.4*	*79*	*24.3*	*85*	*24.5*	*73*	*25.1*
25	*77*	*24.5*	*79*	*24.3*	*85*	*24.5*	*73*	*25.1*
30	*79*	*24.5*	*81*	*24.3*	*85*	*24.5*	*73*	*25.1*
35	*79*	*24.5*	*81*	*24.3*	*85*	*24.5*	*73*	*25.1*
40	*79*	*24.6*	*83*	*24.4*	*87*	*24.5*	*75*	*25.1*
45	*81*	*24.6*	*83*	*24.4*			*75*	*25.1*
50	*81*	*24.7*					*75*	*25.1*
55							*85*	*25.1*

It was expected that the rotten potatoes would generate significant more moisture than healthy tubers. However, in Table 5 and Table 6 it can be seen that the increasing moisture levels are quite similar to each other. This could be due to the low environmental RH, which is induced by the suction system in the fume cupboard. The maximal RH reached in the experiment is 87% while conventional storage systems in practice have their potatoes stored at 95 – 100% RH. This indicates leakage in the storage boxes, which should reach 100% when closed, if the potato tubers keep losing moisture. At day 7 you can

clearly see that reaching the measurement ceiling takes way more time than at day 4, from this we can conclude that the potatoes are starting to dry out after a week of losing moisture.

Temperature measurements

It was expected that the rotten potatoes would generate significant more heat than healthy potatoes. However, this was not the case when carrying out the experiment as can be seen in Table 7 and Table 8 . In these tables you can see that the temperature differences are negligible. The cause of this problem in all probability could be due to the relatively high environmental temperature. Hereby the temperature in the boxes will also be high, and from the experimental data can be seen that after opening the chest, the temperature inside the chest also increases a bit. This makes the temperature measurements a bit inaccurate. Therefore we are forced to take an average temperature to determine the respiration rates.

Table 7 Temperature values after closing the boxes at Wednesday 01-06 (day2)

Time	*T healthy tubers [°C]*	*T rotten tubers [°C]*	*T environment [°C]*
11:30	*23.9*	*24.0*	*24.1*
12:00	*24.3*	*24.4*	*24.4*
12:30	*24.5*	*24.5*	*24.5*
13:00	*24.7*	*24.8*	*24.5*
13:30	*24.8*	*24.8*	*24.3*
14:00	*24.8*	*24.9*	*24.4*

Table 8 Temperature values after closing the boxes at Monday 06-06 (day 7)

Time	*T healthy tubers [°C]*	*T rotten tubers [°C]*	*T environment [°C]*
12:00	*24.7*	*24.6*	*24.8*
12:30	*24.9*	*24.9*	*24.9*
13:00	*24.9*	*24.9*	*24.9*
13:30	*24.9*	*25.0*	*24.9*
14:00	*25.1*	*25.1*	*25.0*
14:30	*25.0*	*25.1*	*24.9*

Measurements ventilated chests

The measured values of the ventilated chests did not provide much usable data, as the rot in box 1 dried out in less than one day probably due to the high flow. The rot was placed on 30-05 at 12:00. After twenty minutes an increase of the carbon dioxide level can be seen in Table 9. However the increase stagnates very fast and subsequently starts to decrease after 10 to 15 minutes. This could be due immediately drying out of the potatoes, or the flow in the chest is too high, which makes it difficult for the transmitter to measure the carbon dioxide levels. The measured environmental carbon dioxide level is constant for a value of 462 [ppm]. This indicates that despite the high flow, the transmitter measured a bit of production. But this is questionable, while the level in chest one remains at 500 [ppm], the difference could be also due to inaccuracy of the measurement instrument.

Table 9 Carbon dioxide concentration rotten ventilated potatoes after placement (30-05)

Time	*CO2 rot ventilated [ppm]*
12:20	475
12:25	575
12:30	775
12:35	625
12:40	525
12:45	500

The values for the relative humidity at the first days can be seen in Table 10. In this table some unexpected values can be seen. The RH of the rotten potatoes seemed to follow the environmental RH. This is unexpected, since the RH for healthy potatoes is very low due to the high flow in the chest. This makes the accuracy of the RH transmitter in chest 1 questionable, as the same outcome should be seen as in the chest with healthy potatoes. It seems unlikely that the high RH levels of rotten potatoes are this high due to excessive moisture production of the rotten potatoes, as in the photos can be seen that the rot is already dried out after day 1.

Table 10 RH values ventilated chests

Date and Time	RH healthy ventilated potatoes [%]	RH rotten ventilated potatoes [%]	RH environment [%]
30-05 12:00	*58*	*58*	*58*
31-05 0:00	*20*	*62*	*62*
31-05 12:00	*16*	*54*	*54*
01-06 0:00	*16*	*52*	*52*
01-06 12:00	*16*	*62*	*62*
02-06 0:00	*14*	*60*	*60*
02-06 12:00	*14*	*56*	*56*
03-06 0:00	*14*	*54*	*54*

4.4. Experiment 4

Carbon dioxide measurements

The results of experiment 3 and 4 for healthy potatoes are quite similar, as can be seen in Figure 12 . Also after analysis and comparing the data retrieved from both experiments, it was found that the data is very consistent so consequently accurate. This proves that the experiment is reproducible. The same holds for the experiments for rotten potatoes as can be seen in Figure 13. In Figure 12 and 13, it can be seen that the velocity of the increasing carbon dioxide levels is much higher for the rotten potatoes than for the healthy potatoes. This proves our conclusion made in experiment 3, that the carbon dioxide production of rotten potatoes is indeed higher than for healthy potatoes. From this experiment you can also see that the rot is not fully established yet at day 1, as the increasing carbon dioxide level is almost linear and resembles that of the increasing levels of healthy potatoes.

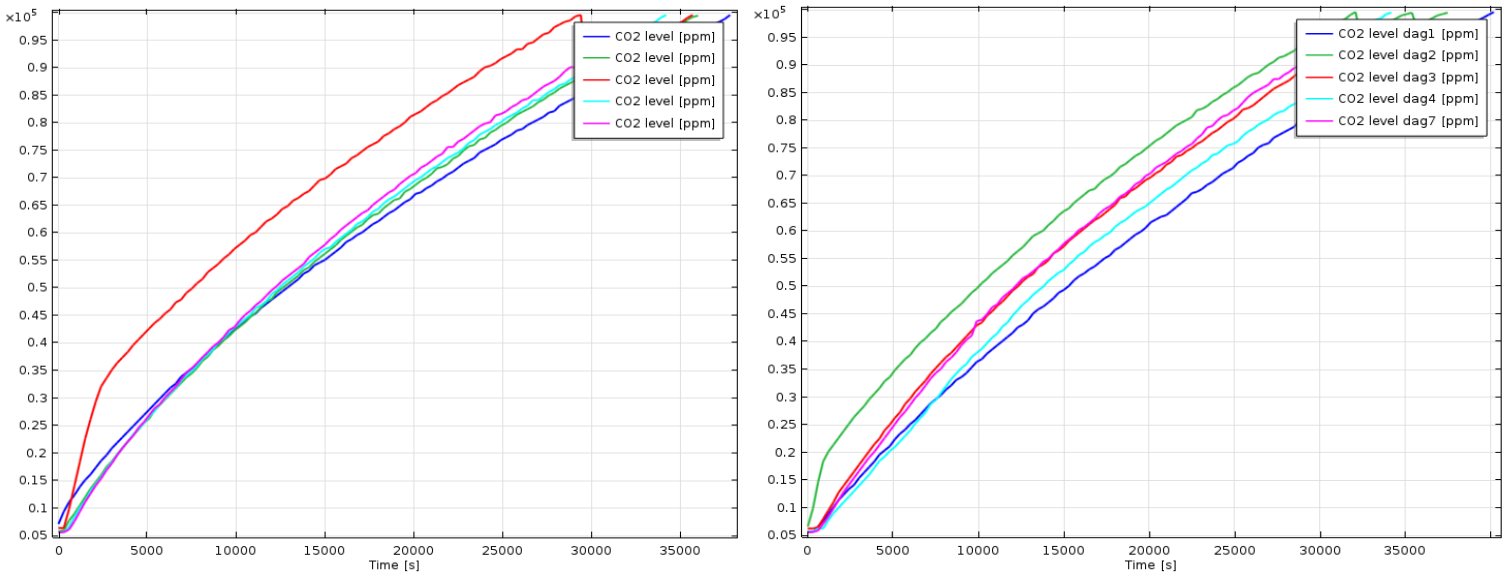

Figure 12 (left) Increase of CO2 concentration of healthy potatoes experiment 3, (right) Increase of CO2 concentration of healthy potatoes experiment 4.

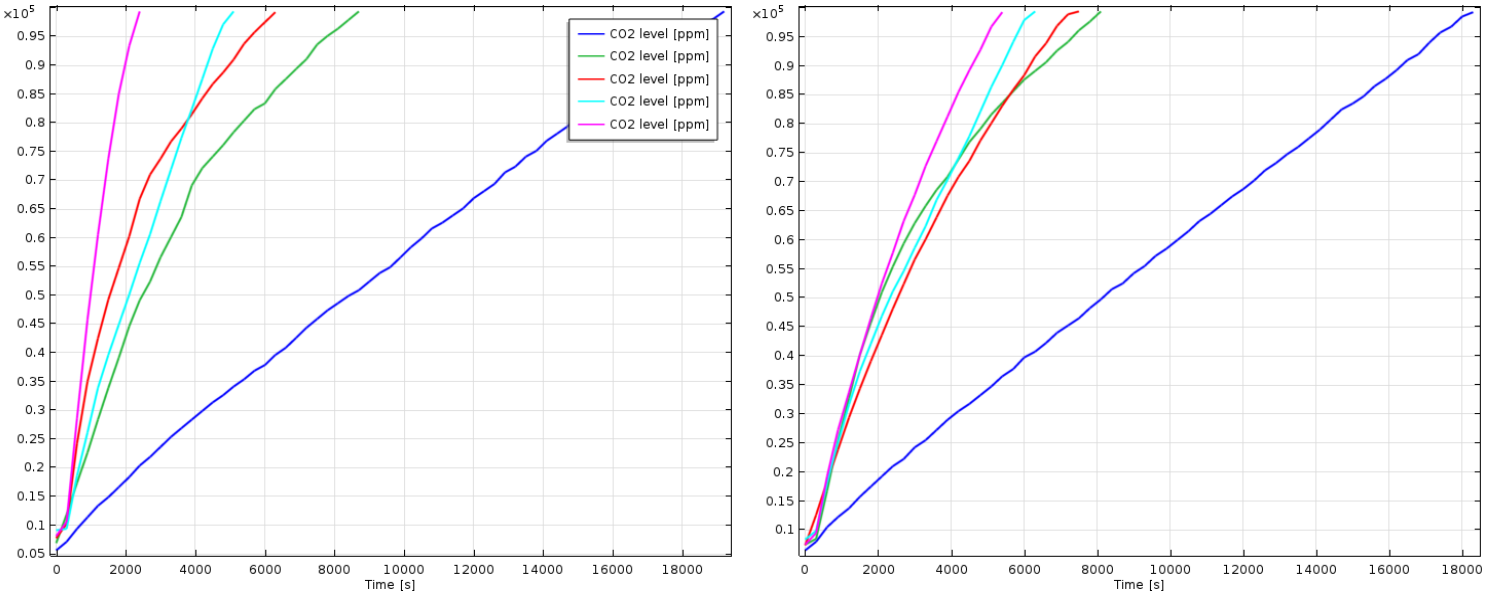

Figure 13 (left) Increase of CO2 concentration of rotten potatoes experiment 3, (right) Increase of CO2 concentration of rotten potatoes experiment 4.

Temperature measurements

It was expected to get the same temperature results as in experiment 3. Due to the high environmental temperatures, no significant differences between rotten and healthy potatoes could be found. In Table 10 and Table 12, you can see the negligible temperature differences, that suit the measured values from experiment 3.

Table 11 Temperature values after closing the boxes at Wednesday 22-06 (day2)

Time	T healthy tubers [°C]	T rotten tubers [°C]	T environment [°C]
11:45	*24.0*	*24.0*	*24.3*
12:15	*24.1*	*24.1*	*23.9*
12:45	*24.2*	*24.2*	*24.1*
13:15	*24.3*	*24.3*	*24.1*
13:45	*24.4*	*24.4*	*24.1*
14:15	*24.5*	*24.5*	*24.2*

Table 12 Temperature values after closing the boxes at Monday 27-06 (day7)

Time	T healthy tubers [°C]	T rotten tubers [°C]	T environment [°C]
11:25	*22.7*	*22.7*	*22.8*
11:55	*23.0*	*23.0*	*23.0*
12:25	*23.2*	*23.1*	*23.0*
12:55	*23.3*	*23.3*	*23.1*
13:25	*23.4*	*23.4*	*22.9*
13:55	*23.4*	*23.4*	*23.1*

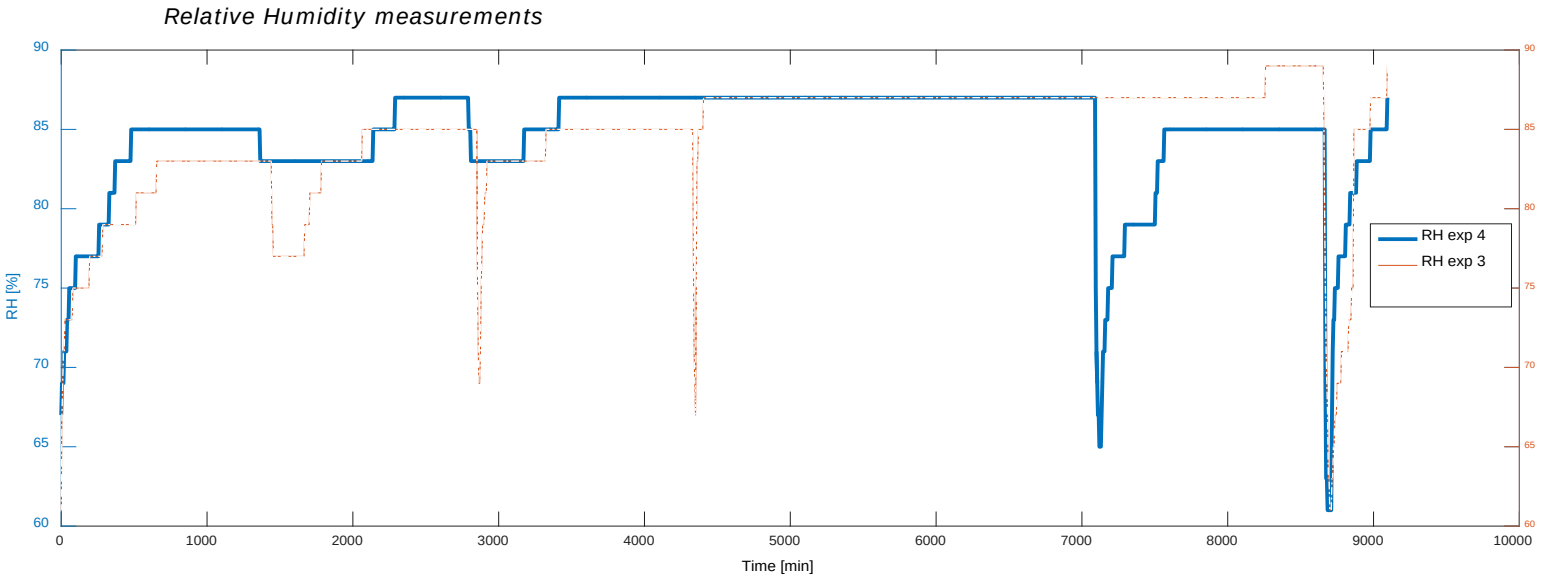

Figure 14 RH rotten potatoes experiment 3 vs. RH rotten potatoes experiment 4 over the whole storage period of 7 days

The (blue) thick line represents the RH of the rotten potatoes in experiment 4, as the (red) dashed line shows the RH of rotten potatoes in experiment 3. As you can see in Figure 14, it takes a significant more time for the RH in experiment 4 to reach the measurement ceiling than in experiment 3. This could indicate that there is more moisture produced by the potatoes in experiment 3, as in experiment four. This could be either due to a greater expansion of the surface of rot or due overall warmer conditions at experiment 3, as water losses will increase in that case. However, at t = 1000 and t = 3000, it can be seen that the drop of the RH after opening the chest in experiment 4 is much lower than in experiment 3, while the opening time for both experiments is the same. This could be due to more moisture production from the potatoes in experiment 4 compared to experiment 3, or the leakage from the chest is significantly lower than in experiment 3. Overall the RH measurements of both experiments do not fit very well to each other, except for day 1 and day 7. This makes it not very reliable to use the RH from experiment 4 as validation data.

5. Physical Modelling

In this chapter the spatially distributed storage model concerning temperature, moisture and carbon dioxide transfer for healthy potatoes will be defined. After that the implementation of states for rot will be done.

In a recent study, (*Grubben, 2013*) presented a spatially distributed physical model that gives full insight between the potato quality, in terms of temperature and moisture content and also flow conditions. The physics of transport phenomena in a bulk can be covered by mass, energy, momentum and continuity balances. The mass and energy balances are applied to transport of energy and mass inside the bulk and in the air. The motion of the air is covered by the momentum and continuity balances. He performed CFD-simulations of the 'healthy' product and air that were validated with measurements. This makes Grubben's study the starting point to implement disease spread. In his study and in this research the simulation software COMSOL is used. Firstly the geometry of the system has to be defined. This can be divided into several computational domains. Secondly a proper mesh of the geometry has to be created, such that the computational domains are covered by a finite number of elements and since too coarse mashes will result in inaccurate or even unsolvable solutions. The density of this mesh depends on the physics and geometry of the system. As rule of thumb, the mesh size should be at maximum one third of the smallest dimension of the corresponding domain. After those two stages, the physical transport phenomena can be defined in from of partial differential equations (PDE's) with accompanying fluid properties. Finally all boundary conditions and initial conditions of each domain of the system have to be specified. COMSOL couples the PDE's to the geometry and provides the solution by solving the set of equations with the finite element method (FEM).

Model Assumptions

All relevant physics for a simulation model of a potato bulk are taken into account. Several assumptions are made for the transport phenomena related to the mathematical model:

1. Steady state region of storage period
   - Storage operations such as: drying, wound healing and cooling are not taken into account. Therefore the changes in the parameter values related to the change of the potato (skin) are negligible.

2. Homogenous distribution of moisture and temperature content in the bulk of uniform spherical potatoes
   - Homogenous distribution of uniform shaped potatoes makes that processes in the bulk are only temperature and moisture content dependant.

3. The Diffusion coefficient is the same for the interior and skin of the potato.
   - A nominal diffusion rate at the edge/skin of the potato is taken.

4. The individual potatoes are completely surrounded by air.
   - Since the contact surfaces between potatoes in the bulk is very small, the interacting process between tubers (conduction) and radiation is neglected.

5. No Condensation
   - Condensation on the product or on surfaces of the storage facility is neglected, since the drying process is not taken into account and temperature/humidity changes in time are relatively small.

The goal is to implement a complete 2-D bulk model in COMSOL. This is realised by taking the following steps:

1. Take static air (so no air movement) and fixed air density
2. Implement the temperature (energy) balance
3. Implement the moisture content (Rutolo et al.) balance
4. Implement the carbon dioxide balance

By following steps described above, a simulation of relevant physics of porous medium and air domain can be accomplished. In this section, first the geometry of the 2D set-up will be presented. Thereafter the physics and boundary conditions related to all domains are described.

Geometry
The geometry used for the simulation study represented in Figure 15.

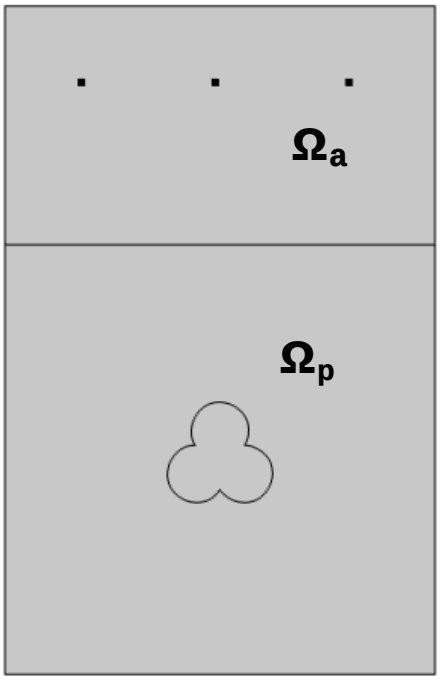

Figure 15 Schematic representation of the storage box.

The rectangular shape visualises a schematic representation of the storage box (model 2, hermetically closed) used in the experiment. The bounding line separates the potato bulk domain and the air domain above with three points representing the measurement instruments. In the middle of the potato bulk domain a figure of three potatoes triangular stacked. This figure depicts the initial core of rot when starting the experiment. As the simulations are progressing, the core will expand to a certain level, influencing the physics of the system.

Physics
In order to simulate the storage box, the configuration as showed in Figure 15 is separated into various domains. For each domain a set of PDE's is defined that cover the temperature, moisture and carbon dioxide balances. These PDE's are presented by (Grubben and Keesman, 2015) and all model parameters are equal to his study, except for the ones that are affected by the rotting process. Also an additional carbon dioxide PDE for all domains is added, obtained from (Lukasse et al., 2007).

Domains
Potato domain
The potato bulk domain (Ω_p) is considered as porous media. The potatoes are considered a solid fraction with corresponding energy balance, including temperature and moisture content for healthy potatoes in a bulk described by:

$$\frac{\partial T_p}{\partial t} - \nabla\left(\frac{\lambda_p}{\rho_p C_{pp}}\nabla \mathrm{T_p}\right) = -\frac{\alpha_c F_m}{\rho_p C_{pp}\epsilon_p}\left(T_p - T_{ap}\right) + \frac{R}{C_{pp}\epsilon_p} - h_{fg}K_{evap}\frac{F_m}{\rho_p C_{pp}\epsilon_p}\left(X_s - X_{ap}\right) \quad \text{on } (0,T] \times \Omega_p \qquad [14]$$

Where $T_{ap} := T_{ap}(i,j)$, $T_p := T_p(i,j)$, $\nabla := [\frac{\partial}{\partial x}, \frac{\partial}{\partial y}]$ and $v := [v_x\ v_y]^T$

The moisture content for the potato:

$$\frac{\partial X_p}{\partial t} - \nabla\left(\mathbb{D}_{\mathrm{p}} \nabla \mathrm{X}_p\right) = -E_{resp}\frac{R}{\epsilon_p} - K_{evap}\frac{F_m}{\rho_p \epsilon_p}\left(X_s - X_a\right) \quad \text{on } (0,T] \times \Omega_p \quad [15]$$

Where $X_p := X_p(i,j)$ and with constant ρ_p

The air in the bulk, hence the air between the stacked potatoes has a different description:

$$\frac{\partial T_{ap}}{\partial t} - \nabla\left(\frac{\lambda_a}{\rho_a C_{pa}} \nabla \mathrm{T}_{\mathrm{ap}}\right) + \frac{1}{\epsilon_a} v * \nabla \mathrm{T}_{\mathrm{ap}} = \frac{\alpha_c F_m}{\rho_a C_{pa} \epsilon_a}\left(T_p - T_{ap}\right) \quad \text{on } (0,T] \times \Omega_p \quad [16]$$

$$\frac{\partial X_{ap}}{\partial t} - \nabla\left(\mathbb{D}_{\mathrm{a}} \nabla \mathrm{X}_{\mathrm{ap}}\right) + \frac{1}{\epsilon_a} v * \nabla \mathrm{X}_{\mathrm{ap}} = K_{evap}\frac{F_m}{\rho_a \epsilon_a}\left(X_s - X_{ap}\right) \quad \text{on } (0,T] \times \Omega_p \quad [17]$$

The carbon dioxide balance for the potato bulk air is described by:

$$\frac{\partial CO_{2,p}}{\partial t} - \nabla\left(\mathbb{D}_{CO_{2,p}} \nabla CO_{2,p}\right) + \frac{1}{\epsilon_a} * \nabla CO_{2,p} = E_{CO_2} R \quad \text{on } (0,T] \times \Omega_p \quad [18]$$

Where $CO_{2,p} := CO_{2,p}(i,j)$ and with constant E_{CO2} race specific determined and constant $\mathbb{D}_{CO_{2,p}}$ (= $1.5*10^{-5}$). In this equation a convection term ($\frac{1}{\epsilon_a} * \nabla CO_{2,p}$) is included. However in the simulations the second model which is hermetically closed is used. This means that the air inside the box is static; hence no convection is taking place. As the measurement instruments in the top of box measure carbon dioxide concentrations, there has to be some kind of phenomenon taking place that induces the spread of concentration. So, therefore the convection term is included in the model, even as for the boxes where ventilation treatment is used.

Air domain

The air domain ($\Omega_{a)}$ equations for the air bare almost similar to the porous medium equations. The equations for temperature, moisture and carbon dioxide level can be mathematically described by:

$$\frac{\partial T_a}{\partial t} - \nabla\left(\frac{\lambda_a}{\rho_a C_{pa}} \nabla \mathrm{T}_{\mathrm{a}}\right) + \frac{1}{\epsilon_a} v * \nabla \mathrm{T}_{\mathrm{a}} = 0 \quad \text{on } (0,T] \times \Omega_a \quad [19]$$

$$\frac{\partial X_a}{\partial t} - \nabla(\mathbb{D}_{\mathrm{a}} \nabla \mathrm{X}_{\mathrm{a}}) + \frac{1}{\epsilon_a} v = 0 \quad \text{on } (0,T] \times \Omega_a \quad [20]$$

$$\frac{\partial CO_{2,a}}{\partial t} - \nabla\left(\mathbb{D}_{CO_{2,a}} \nabla CO_{2,a}\right) + v * \nabla CO_{2,a} = 0 \quad \text{on } (0,T] \times \Omega_a \quad [21]$$

Boundary conditions

To make simulation studies possible, it is necessary that all the contiguous domains are coupled to each other. Therefore boundary conditions are applied for temperature, moisture and carbon dioxide concentration. The next boundary conditions are described:

- Zero flux boundary conditions
- Dirichlet boundary conditions

Zero flux boundary conditions
Zero flux boundary conditions are considered as closed conditions, hence there is no exchange of physics. In this case no exchange of temperature, moisture and carbon dioxide. The zero flux boundaries apply to the outer layers of the storage box. The mathematical description of these boundary conditions (on (0, T]) :

$$\frac{\partial Ta}{\partial n} = \frac{\partial Tap}{\partial n} = \frac{\partial Tp}{\partial n} = 0 \quad [22]$$

$$\frac{\partial Xa}{\partial n} = \frac{\partial Xap}{\partial n} = \frac{\partial Xp}{\partial n} = 0 \quad [23]$$

$$\frac{\partial CO_{2,a}}{\partial n} = \frac{\partial CO_{2,p}}{\partial n} = 0 \quad [24]$$

With n as the corresponding direction to the related boundary condition.

Dirichlet boundary conditions for coupling domains
To realise the coupling between the porous medium and the air domain, the following boundary conditions are applied to the bounding line between the air domain and porous medium domain (on (0,T]):

$$P_{\Omega a} = P_{\Omega p} \quad [25]$$

$$T_{\Omega a} = T_{\Omega p} \quad [26]$$

$$X_{\Omega a} = X_{\Omega p} \quad [27]$$

$$CO_{2,\Omega a} = CO_{2,\Omega p} \quad [28]$$

5.1. Model Adjustments

The spread of the diseases is considered as gas diffusion in this report, because the spread of pathogens is mainly through air, and to simplify the model, so it is widely applicable. Therefore it is assumed that the diffusion coefficient is the same for the interior and skin of the potato, hence a nominal diffusion rate at the edge/skin of the potato is taken. Fick's second law, in other words the diffusion equation for a gas is a linear equation which considers the concentration of diffusive components as dependent variable. The diffusion of each component is described independently, which makes the transport easy to simulate numerically. The equation is described by:

$$\frac{\partial c_i}{\partial t} = \mathbb{D}_i * \nabla^2 c_i \qquad [29]$$

Where the species concentration is described as c_i and with the assumption that $\mathbb{D}_i$ is constant for dilute gasses in air. The diffusion coefficient is explained as parameterizing the area of a spherical surface, in this case the potato tuber, circumscribed as the surface of root-mean-square shifting of components diffusing away from an infinitesimal point where mass is originally concentrated. Whereas the statistics of diffusion induce this area to grow linearly in time, the diffusion coefficient is described as quantity by area per time. Gas exchange between a potato tuber and its ambient air, hence the gas diffusion through a barrier of tissue and its environment follows Fick's first law of diffusion *(Dehkordi et al., 2010)*. Fick's law states that the flux gas diffusion through a barrier of tissue is proportional to the concentration gradient over this barrier (Bird, 2002). So, if the area available for diffusion increases, the flux should also increase. A partial differential equation in order to determine the rot concentration profiles in form of the surface of diseased potato tissue are given by a One-Dimensional unsteady state diffusion phenomenon for cylindrical geometry in r direction, Fick's second law (the diffusion equation) rewritten *(Dehkordi et al., 2010)*:

$$\frac{\partial A_{rot}}{\partial t} = \mathbb{D}_{rot}\left(\frac{1}{r}\frac{\partial}{\partial r}\left(r\,\frac{\partial A_{rot}}{\partial r}\right)\right) \qquad [30]$$

Where x = 0 at the centre and x = ±1 at the surfaces. The initial condition is: at t=0; c_i=0 for all x. $\mathbb{D}_{rot}$ is the diffusion coefficient of the infection that can be determined by experimental values (The pictures for the infection spread over time).

Boundary conditions:
at t = 0: A_{rot} = 0; for all r, at t = 0: $\frac{\partial A_{rot}}{\partial r}$ = 0; for all r, at r = R: A_{rot}=$A_{rot,\infty}$; for all t

Two-dimensional unsteady state diffusion in x and r directions are given by:

$$\frac{\partial A_{rot}}{\partial t} = \mathbb{D}_{rot}\left(\frac{\partial^2 A_{rot}}{\partial x^2} + \frac{1}{r}\frac{\partial}{\partial r}\left(r\,\frac{\partial A_{rot}}{\partial r}\right)\right) \qquad [31]$$

Boundary Conditions:

at t = 0: A_{rot} = 0; for all x and r, at t = 0: $\frac{\partial A_{rot}}{\partial r}$ = 0; for all x and r, at x = ±l: A_{rot}=$A_{rot,\infty}$; for all t
at r = 0: $\frac{\partial A_{rot}}{\partial r}$ = 0; for all t and x, at r = R: A_{rot}=$A_{rot,\infty}$; for all t and x

This model does not apply to the storage boxes with forced ventilation treatment. The model requires a convection term in order to make it suitable for the ventilation treatment, which gives the following equation:

$$\frac{\partial A_{rot}}{\partial t} = \mathbb{D}_{rot}\left(\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial A_{rot}}{\partial r}\right)\right) - u * \frac{\partial A_{rot}}{\partial r} \qquad [32]$$

With the velocity of the gas described as: u.

To implemented the disease spread model, certain parameters in the PDE's has to be made dependent on the surface of rot. The parameter Fm is the specific surface of the bulk and defined as follows (Grubben, 2013):

$$F_m = \frac{\pi d_p^2}{\left(\frac{1}{6}\right)\pi d_p^3}\,\epsilon_p \qquad [33]$$

The specific surface F_m can be substituted and separated into a percentage of healthy (A_1) and rot (A_2) surface area of the bulk with respect to the time. This can be written as:

$$\nabla A_2 = \mathbb{D}_{\mathrm{rot}}\,(1 - A_1)$$

Where ∇A_2 is the rotten plant tissue over time, $(1 - A_1)$ is the infected plant tissue. The respiratory coefficient R, used in the energy, moisture and carbon dioxide balances has a great influence on the losses of the potatoes. To include the rotting process in the equations, which even induce increased respirational, evaporative and heat losses, the respiration coefficient can be divided in a healthy and infected surface area in order to behold the dynamics:

$$R_d = R_g * A_1 + R_r * (1 - A_2) \qquad [34]$$

The respiration rate for healthy potato tubers is given by:

$$R_g = c_1 - c_2\left(T_p - 273.15\right) + c_3\left(T_p - 273.15\right)^2 \qquad [35]$$

With; c1, c2 and c3 fitted for this model. And the respiration rate for the infected tuber tubers follows from experimental values:

And the respiration rate for the infected tuber tubers follows from experimental values:

$$R_r = c_4 - c_5(T_{p,rot} - 273.15) + c_6\left(T_{p,rot} - 273.15\right)^2 \qquad [36]$$

This adjusted respiration coefficients also apply to the respiration coefficient used in the carbon dioxide balance. Not only in the form of R but also in de production of CO_2 over time.

$$\nabla A_p = \nabla A_r + \nabla A_g$$

This means the balances for the potatoes in the bulk are adapted in the following way:

$$\frac{\partial T_p}{\partial t} - \nabla\left(\frac{\lambda_p}{\rho_p C_{pp}}\,\nabla \mathrm{T_p}\right) = -\frac{\alpha_c \nabla A_p}{\rho_p C_{pp}\epsilon_p}\left(T_p - T_a\right) + \frac{R_d}{C_{pp}\epsilon_p} - h_{fg}K_{evap}\frac{\nabla A_p}{\rho_p C_{pp}\epsilon_p}\left(X_s - X_a\right) \qquad \text{on } (0,T] \times \Omega_p \qquad [37]$$

$$\frac{\partial X_p}{\partial t} - \nabla\left(\mathbb{D}_{\mathrm{p}}\nabla \mathrm{X}_p\right) = -E_{resp}\frac{R_d}{\epsilon_p} - K_{evap}\frac{\nabla \mathrm{A_p}}{\rho_p \epsilon_p}\left(X_s - X_a\right) \qquad \text{on } (0,T] \times \Omega_p \qquad [38]$$

$$\frac{\partial CO_{2,p}}{\partial t} + \frac{1}{\epsilon_a} * \nabla CO_{2,p} - \nabla\left(\mathbb{D}_{CO_{2,p}}\nabla CO_{2,p}\right) = E_{CO_2}R_g A_1 + E_{CO_2}R_r(1 - A_2) \qquad \text{on } (0,T] \times \Omega_p \qquad [39]$$

6. Calibration & Validation

(Grubben, 2013) presented a already calibrated and validated spatially distributed 2D model for healthy bulk potatoes. In this report, similar parameter values where used to describe the physics of potatoes in bulk. Hereby it is assumed that the parameter values are correct, except for the respiration coefficient and evaporation coefficient. These two parameters will be calibrated and validated along with the 'rot surface model'. The calibration and validation of the parameters will be done by data obtained from the experiments. The states related to healthy potatoes and thereafter, the states related to rotten potatoes will be calibrated and validated against experimental data even as for the rot spread model.

6.1 Calibration

For the calibration of the model parameters dataset were used from measurements from experiment 3.

6.1.1. Calibration of the respiration rates

Experiment three is chosen as starting position. The respiration rate for healthy potatoes dependant on the temperature of the potatoes, can be found by fitting the experimental data on the (Lukasse et al., 2007) expression of the respiration rate for healthy potatoes and the carbon dioxide balance. The carbon dioxide balance can be simplified into a three-term equation:

$$\rightarrow \ Respiratory\ CO_2\ production\ [\% * h^{-1}] = E_{CO_2} * R \qquad [40]$$

Where the respiratory CO_2 production is obtained from the carbon dioxide measurements during the experiments. Following (*Lukasse et al., 2007*) E_{CO_2} is given by:

$$E_{CO_2} = \frac{RQM_{CO_2}\ 6\rho_{bulk}}{E_R \rho_{CO_2} \varepsilon 10} = 9.3 * 10^{-3}\ [g * J^{-1}] \qquad [41]$$

With E_{CO_2}, as the oxidation energy from

To determine the respiration rate for healthy potatoes, a couple assumptions should be made. Firstly, it is assumed that E_{CO_2} holds for this type of crop and is the same for rotten potatoes as for healthy ones. This means that it is assumed that the respiration coefficient (RQ) is equal for rotten potatoes and healthy potatoes. Thus, the carbon dioxide production and oxygen consumption would be the same for rotten potatoes as for healthy potatoes. Furthermore it is assumed that the value of E_{CO_2} from (*Lukasse et al., 2007)* holds for the used crop in this research. Thirdly it is assumed that the temperature difference between rotten potatoes and healthy potatoes can be neglected, as can be seen in Table 3 and Table 4. These assumptions give us the opportunity to determine the respiration rate R for the healthy potatoes in both experiments. Firstly the respiration rate dependant on the surrounding temperature from Lukasse was determined for our circumstances, which means for a T_p of 24 °C.

$$Rg = 256.428\ [J\ (kg\ produce)^{-1}(h^{-1})]$$

Which means when filling in the equation for respiratory carbon dioxide production, that the production over ten hours, is equal to 0.2347 [%/10h]. The range of 10 hours is taken because that is the time it takes for the healthy potatoes on the first day to reach the measurement ceiling. The calculated values for experiment two can be seen in Table 13:

Table 13 Respiration rates healthy potatoes from experiment 3 for an average temperature of 24 [°C]

	CO2 production [%/10h]	Respiration rate (Rg) [J (kg produce)$^{-1}$h^{-1}]
Day 2, 22-06	0.9375	1008.06
Day 3, 23-06	0.9324	1002.58
Day 4, 24-06	0.9400	1010.75
Day 7, 28-06	0.9400	1010.75
		Rg average = 1008.04 for Tp = 24.78 °C

The calculated respiration rate for healthy potatoes is about four times the value found in *(Lukasse et al., 2007)*, which seems to give a good fit to the data. A polynomial fit function in Matlab is used for tuning the parameters c1, c2, c3 (equation [*35*]). Very small values for c2 and c2 were found. Modifying the model by stating that c2 = c3 = 0 and thereafter fitting the parameter value of c1 to the data, resulted in an improved model fit. This gives us:

C1 = 466.3446 C2 = -0.9011 C3 = 0.0005

The constants C1 and C2 seems to be in the range of the constants fit by (*Lukasse et al., 2007*), however constant C3 falls out of this range. Overall it seems not to be a very reliable fit. Therefore there should be done more temperature measurements at other conditions, so that there will be greater and more temperature differences. These measurements will give a more reliable polynomial fit, hence results in a higher R^2.

Besides the assumptions made for healthy potatoes, a few other delimitations have to be made to determine the respiration rate for rotten potatoes. Note that day 1 of opening the boxes can be neglected as the rot is not established yet, so the production is almost equal to the box with healthy potatoes. Also an adjustment to the model should be made, as the percentage rotten potatoes should be included in the model. This is done by taking the amount of rotten potatoes from the total number of potatoes determined by observation of the potatoes by hand after the experiment and the pictures that were taken every day, which results in the following equation:

$$\rightarrow Respiratory\ CO_2\ production\ rotten\ potatoes\ [\% * h^{-1}] = E_{CO_2} * R_g * A_{healthy} + E_{CO_2} * R_r * A_{rot} \quad [42]$$

Table 14 Respiration rates from experiment 3 for an average temperature of 24 [°C]

	Respiration rate (Rg) [J (kg produce)$^{-1}$h^{-1}] (healthy potatoes)	Surface healthy potatoes (A)	Surface rotten potatoes (1-A)	Respiration rate (R_r) [J (kg produce)$^{-1}$h^{-1}] (rotten potatoes)
Day 2, 22-06	1008.06	44/50	6/50	26909
Day 3, 23-06	1002.58	42/50	8/50	29849
Day 4, 24-06	1010.75	38/50	12/50	25381
Day 7, 28-06	1010.75	32/50	18/50	39092
	Rg average = 1008.04			**R_r average** = 30300 for Tp = 24.54 °C

Although only one respiration rate for rot was expected to be found, the calculations resulted in a different value per day. This is very beneficial for the model fit as the production per day seems not only to be dependent on the surface A, but also on the environmental conditions. Besides that the assumption that: E_{CO_2} holds for this type of crop and is the same for rotten potatoes as for healthy ones, could be incorrect. This means that there are different values for E_{CO_2}. From Table 14 can be seen that the respiration rates for rotten potatoes significantly higher than the respiration rates for healthy potatoes. Also RQ which is: the ratio of O_2 volume absorbed [h^{-1}] to the volume of CO_2 released [h^{-1}] is taken as a constant. This could lead to inaccuracy of the calculated respiration rates as this parameter will vary at higher respiration rates, because more carbon dioxide will be produced. However following *(Fennir, 2002*) the RQ showed no significant difference among healthy and rotten potatoes.

A polynomial fit function in Matlab is used for tuning the parameters c4, c5, c6 (equation [*36*]). Resulting into a more proper and reliable fit than found for the respiration rates for healthy potatoes.

C4 = 1.3912 C5 = -0.1131 C6 = 0.0023

6.1.2. Calibration of the evaporation coefficients

Changes in potato temperature and moisture are related to a very sensitive parameter, namely the evaporation coefficient (Kevap). In literature there are many different evaporation coefficients described for healthy potatoes. (*Grubben, 2013*) found a value of 0.0002 [kg/m^2/s], while in literature this parameter value was found in range of 0.000388 (*Lukasse et al., 2007*) and 0.0007848 [kg/m^2/s] by (*Kondrashov, 2007*). The sensitivity of the parameter will give us a reasson to calibrate this parameter. The calibration is carried out by varying the evaporation coefficient with the use of a parametric sweep in COMSOL. Hereby an very imporatant assumption is made: the air space of the experimental setup can be neglected. This because the calculation are made only for the porous medium. As the relative humidity transmitter can measure the RH in the box, it is assumed that the moisture in the box is devided equally. The calibration of the evaporation rate is carried out in the same way as for the respiration rates, but with the use of COMSOL. But first some calulations have to be made in order to compare the data to the simulations. The measured relative humidity is in percentages. In order to convert this percentages to absolute moisture content in air for the RH at the start of closing the boxes and the RH until it becomes stable, an online calculation programme is used. When knowing the difference between these values is equal to the moisture produced by the potatoes, as can be seen in Table 15.

Table 15 Calculations for produced moisture by healthy potatoes

Day	RHstart	Moisture content air [g/kg]	RHend	Moisture content air [g/kg]	Moisture produced [g/kg]	Time [min]
2	64% at 23.4°C	11.52	80% at 23.9°C	14.92	3.40	30
3	64% at 24.1°C	12.03	82% at 24.4°C	15.78	3.75	25
4	64% at 23.5°C	11.59	80% at 24.2°C	15.20	3.61	25
7	66% at 24.3°C	12.56	82% at 24.0°C	15.40	2.84	30

As reference, the average moisture production for the four days is taken. This is 3.40 [g/kg] after half an hour, respectively. The simulated production with the smallest error at 1800 seconds is 3.02 [g/kg] for Kevap = 0.00095 as you can see in (Figure 16). The production for the same evaporation rate but at t=2160 seconds is somewhat closer to the actual experimental production: 3.63 [g/kg], but fits perfect in the range of day 3 and 4.

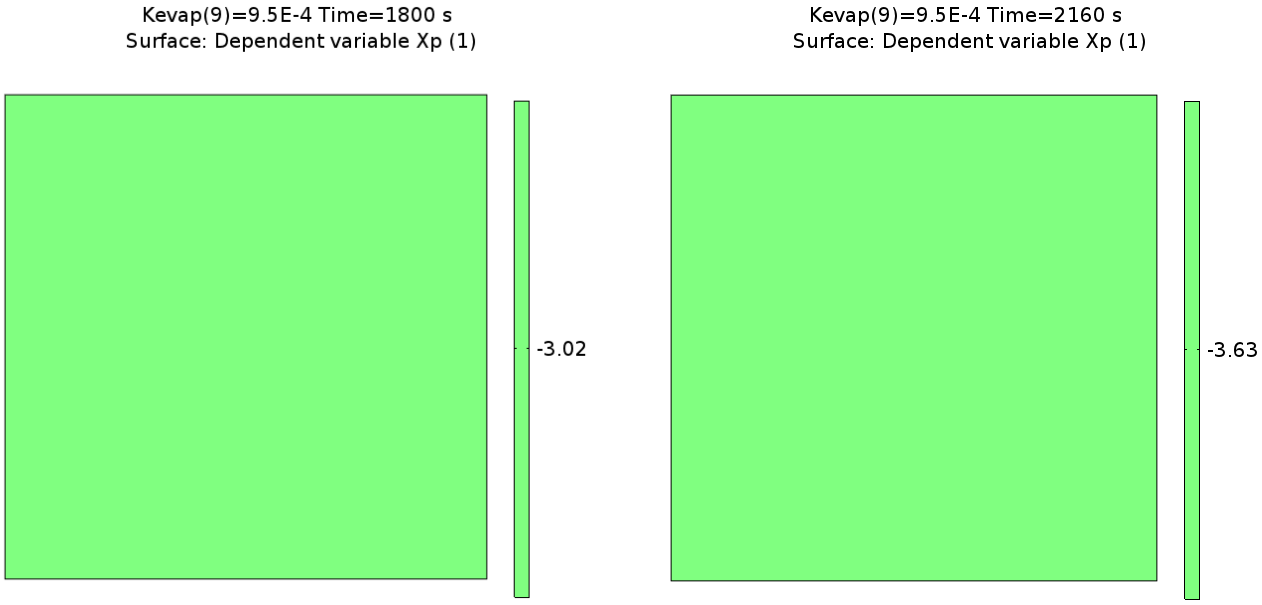

Figure 16 Moisture production healthy potatoes [g/kg]

For the calibration of the evaporation coefficient for rotten potatoes, the same method is used as for healthy potatoes.

Table 16 Calculations for produced moisture by rotten potatoes

Day	RHstart	Moisture content air [g/kg]	RHend	Moisture content air [g/kg]	Moisture produced [g/kg]	Time [min]
2	66% at 24.2°C	12.49	81% at 24.7°C	15.88	3.39	50
3	69% at 24.0°C	12.91	83% at 24.4°C	15.98	3.07	45
4	67% at 24.2°C	12.67	87% at 24.5°C	16.88	4.21	40
7	69% at 25.0°C	13.72	85% at 25.1°C	17.10	3.38	55

As reference, the moisture production of day 4 is taken from Table 16. This is the most absolute point of comparison, because the rot is established well and it takes the shortest time for the potatoes to produce the moisture. Also the RH of 87% lays closest the practical storage RH, but is still not high enough. Furthermore a clear difference in production to the healthy potatoes can be seen. This is 4.21 [g/kg] after 40 minutes, respectively. The simulated production with the smallest error at 2520 seconds, which is 42 minutes, is 4.25 [g/kg] for Kevap = 0.00099, as you can see in Figure 16.

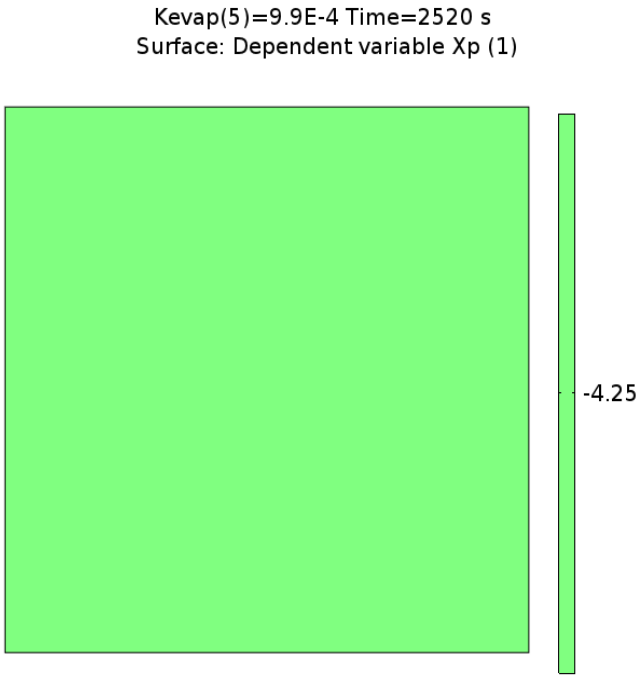

Figure 17 Moisture production rotten potatoes + surrounding healthy potatoes [g/kg] at 42 [min] for an evaporation coefficient of 0.00099

6.1.3. Calibration of the rot spread model

The rot spread model (equation *[30]*) is dependent on the diffusion coefficient of the rot spread: $\mathbb{D}_{\mathrm{rot}}$. This parameter can be defined as a quantity of area per time. The 1-Dimensional equation used can be calibrated by determining the diffusion coefficient of rot. This is done by estimating the spread on the base of the pictures that were taken. Out of the pictures in A- 2 and A- 3 the percentage rot per day is determined. When looking at the initial and final percentages a simple calculation can be made up for the diffusion coefficient of experiment 3:

$$\mathbb{D}_{\mathrm{rot,exp3}} = \frac{\frac{18}{3}}{3600 * 24 * 7} = 9.92 * 10^{-6}$$

6.2. Validation

Experiment 4 was carried out as a repetition of experiment 3 in order to collect validation data and to find out if the experiment is reproducible. To keep the execution of the experiment consistent, the same proceedings as in experiment 3 were used. To investigate, whether the model parameters are valid and in realistic range, the parameter values will be cross-validated against the dataset obtained from experiment 4.

6.2.1. Validation of the respiration rates

The respiration rates for healthy potatoes are calculated from the dataset of experiment 4 and compared to the respiration rates of experiment 3. Furthermore the carbon dioxide production of the actual measured data from both experiments is compared to each other.

Table 17 Respiration rates and carbon dioxide production for experiment 3 and 4

Day	Rg experiment 3	Rg experiment 4	CO2 production experiment 3 [% / 10h]	CO2 production experiment 4 [% / 10h]
2	1008.06	1000	0.9375	0.9300
3	1002.58	1002.7	0.9325	0.9325
4	1010.75	1002.7	0.9400	0.9325
7	1010.75	1009.5	0.9400	0.9388
	Average = 1008.035	Average = 1003.725		

As you can see in Table 17, the data for both experiments are very close to each other, with an estimated error of: 0.00405. The error is very small from which we can conclude that the calculated respiration rates for experiment 3 are valid.

Validation respiration rates rotten potatoes

For the validation of the respiration rate for rotten potatoes, the dataset of experiment 4 is used, looking at day 2 and day 5. Do determine if the estimated values of the respiration rates based on the dataset of experiment two are correct for the data of experiment three, they have to fill in in equation 43.

$$\rightarrow Respiratory\ CO_2\ production\ rotten\ potatoes\ [\% * h^{-1}] = E_{CO_2} * R_g * A_{healthy} + E_{CO_2} * R_r * A_{rot} \quad [43]$$

Where R_g = 998.902 and the surface of rot is determined out of the pictures made during experiment 4.

Table 18 Validation data of the respiration rate on day 2 for Rr = 26976 + respiration of healthy potatoes, with an overall error of 0.059075

Time [h]	Estimated CO2 production [%/h]	CO2 production experimental [%/h]	Error
0	0.0462	0.0750	0.0288
0.25	0.2021	0.2550	0.0529
0.5	0.4042	0.4575	0.0533
0.75	0.6063	0.5938	0.008
1	0.8083	0.6862	0.1221
1.25	1.0104	0.7688	0.2416
1.5	1.2125	0.8362	0.3763
1.75	1.4146	0.8912	0.5234
2	1.6167	0.9412	0.6755
2.25	2.0208	0.9938	1.027

Table 19 Validation data of the respiration rate on day 7 for Rr= 39108+ respiration of healthy potatoes with, an overall error of 0.0636

Time [h]	Estimated CO2 production [%/h]	CO2 production experimental [%/h]	Error
0	0.0462	0.0750	0.0288
0.25	0.1859	0.2725	0.0866
0.5	0.3718	0.4650	0.0932
0.75	0.5577	0.6325	0.0748
1	0.7437	0.7700	0.0263
1.25	0.9296	0.8925	0.0371
1.5	1.1155	0.9925	0.1230

Table 18 and Table 19, give the calculated validation data for the respiration rate of rot. An increase of the error can be noted as time progresses. This can be due to a couple of causes. Firstly the range of the measurement instrument. The carbon dioxide transmitter used has a measurement range up to 10.000 [ppm], which means 1 [%/h] carbon dioxide can be measured. After 1.25 hours the simulated production exceeds the 1 [%/h] what is beyond the measuring range. Also the initial carbon dioxide production in the boxes will never reach the 462 ppm when opening them because of the continu production of the potato tubers. This errors can be ignored. Furthermore, it can be noticed that after 0.75 hour the simulation reaches above the experimental production for the first time, whereafter the difference will increase by time. This can be explained by the CO_2 accumulation inside the box, creating more and more anaerobic conditions, which suffocate the potatoes so to speak. This means the production slowly starts to stagnate. The experimental production on day 7 fit the estimated production a bit better, as can be seen in Table 17.

In the following simulation images can be seen how the CO_2 produced by the healthy potatoes is spread over the boxes at t=0h and t=10h. Just as you can see in the tables, the spread starts at a very low concentration but strongly increases as time progresses. The spread throughout the box has to be induced by some kind of natural convection as carbon dioxide is an heavier gas than oxygen, so theoretically the carbon dioxide concentration should be shinking to the bottom of the box. However this is not the case, as the carbon dioxide transmitter can measure the concentration in the air. But as you can see the upper concentration in the box is subsequently lower than the concentration underneath.

Because there is no build-in resistance, the simulation could be go on forever, so the values of the carbon dioxide production can become infinite. However in practice, as discussed earlier, the production will start to stagnate when oxygen levels are exploited, until the point is reached that all oxygen present is turned into carbon dioxide.

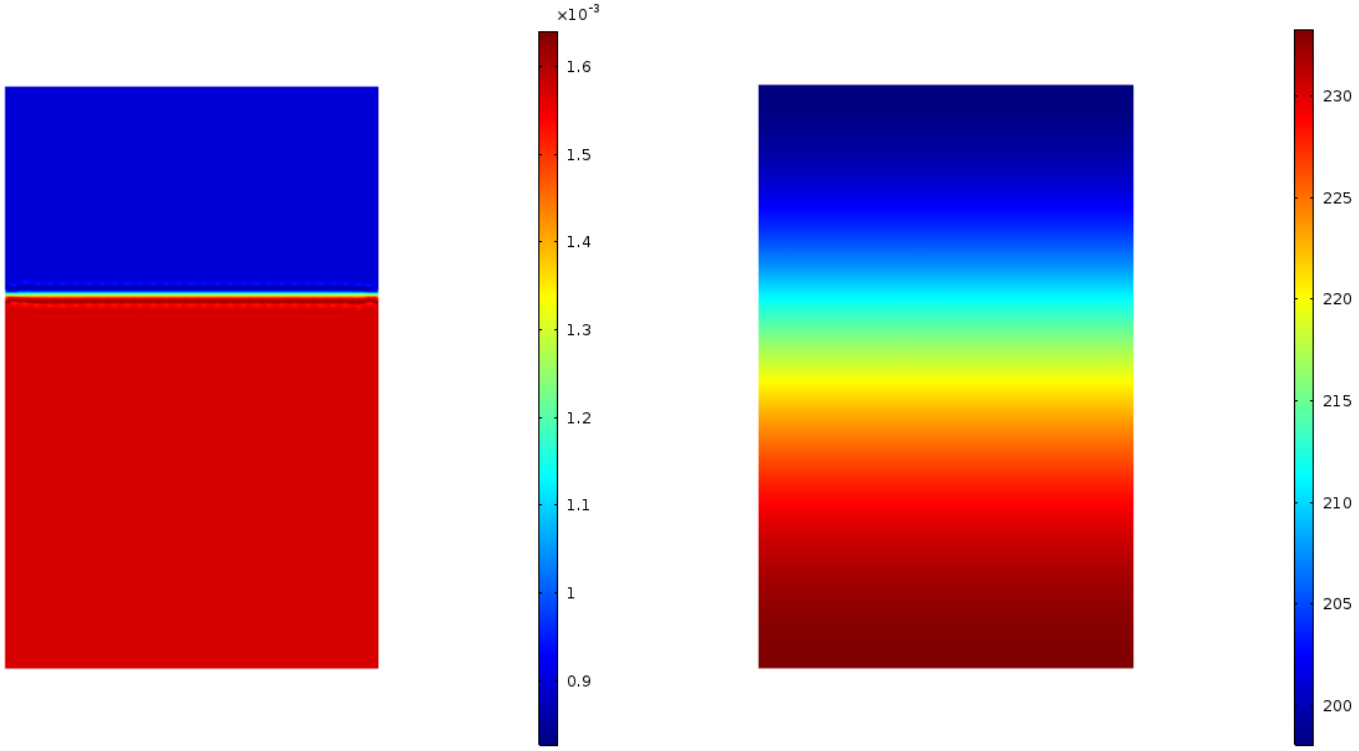

Figure 18 Simulation CO2 production [g/kg air] for Rg = 1010; at t=0[h] (left), and for t=10[h] (right)

6.2.2. Validation of the evaporation rates

In literature there are many different evaporation coefficients described for healthy potatoes. (*Grubben, 2013)* found a value of 0.0002 [kg/m^2/s], while in literature this parameter value was found in range of 0.000388 (*Lukasse et al., 2007*) and 0.0007848 [kg/m^2/s] by (*Kondrashov, 2007*).

The evaporation rates of 0.00095 [kg/m^2/s] for healthy potatoes and 0.00099[kg/m^2/s] for rotten potatoes fit in the range of the evaporation rate found by (*Kondrashov, 2007*)**.** This gives an indication of the practical range they should at least fit in, as the estimated error has a value of: 0.00405 for the healthy evaporation rate compared to the value of (*Kondrashov, 2007)*. The evaporation rate of rotten potatoes is slightly higher than the evaporation rate for healthy potatoes, as expected.

6.2.3. Validation of the rot spread model

The rot spread model is dependent on the diffusion coefficient of the rot spread: $\mathbb{D}_{\mathrm{rot}}$. This coefficient is determined out of the pictures made during experiment 3. To validate the diffusion coefficient from experiment 3, similar pictures were taken when carrying out experiment 4. From these pictures as well as for experiment 3, the percentage rot can be determined and the diffusion coefficient could be calculated:

$$\mathbb{D}_{\mathrm{rot,exp4}} = \frac{\frac{16}{3}}{3600 * 24 * 7} = 8.82 * 10^{-6}$$

The value of the diffusion coefficient for experiment 3 was: $9.92 * 10^{-6}$. The diffusion coefficients do not differ much from eachother. This results in a model error of: $1.10 * 10^{-6}$ which is very small. This gives an indication that the diffusion coefficient for the rot spread model is in the correct range.

6.2.4. Model validation simulation

In Comsol simulations are done to calibrate the total model that contains the energy and mass balances. These include the temperature balance of the potatoes, the moisture balance of the potatoes, the carbon dioxide balance of the potatoes and the surface of rot balance. These balances are implemented using the PDE interface. The validated states are used, as described in the previous sections of this chapter. Firstly the spread of the rot is showed in Figure 19. At day 1, which is the initial state, the core of 3 rotten potatoes is placed. After four days the core is already expanded to 13 rotten potatoes and after a week 23 potatoes are rotten. Compared to the pictures this seems a pretty good indication of how the rot would spread in the experimental setup. As after day 4 in practice, there were 12 rotten potatoes in experiment 3 and 14 rotten potatoes in experiment 4. And after a week there were 18 and 16 rotten potatoes.

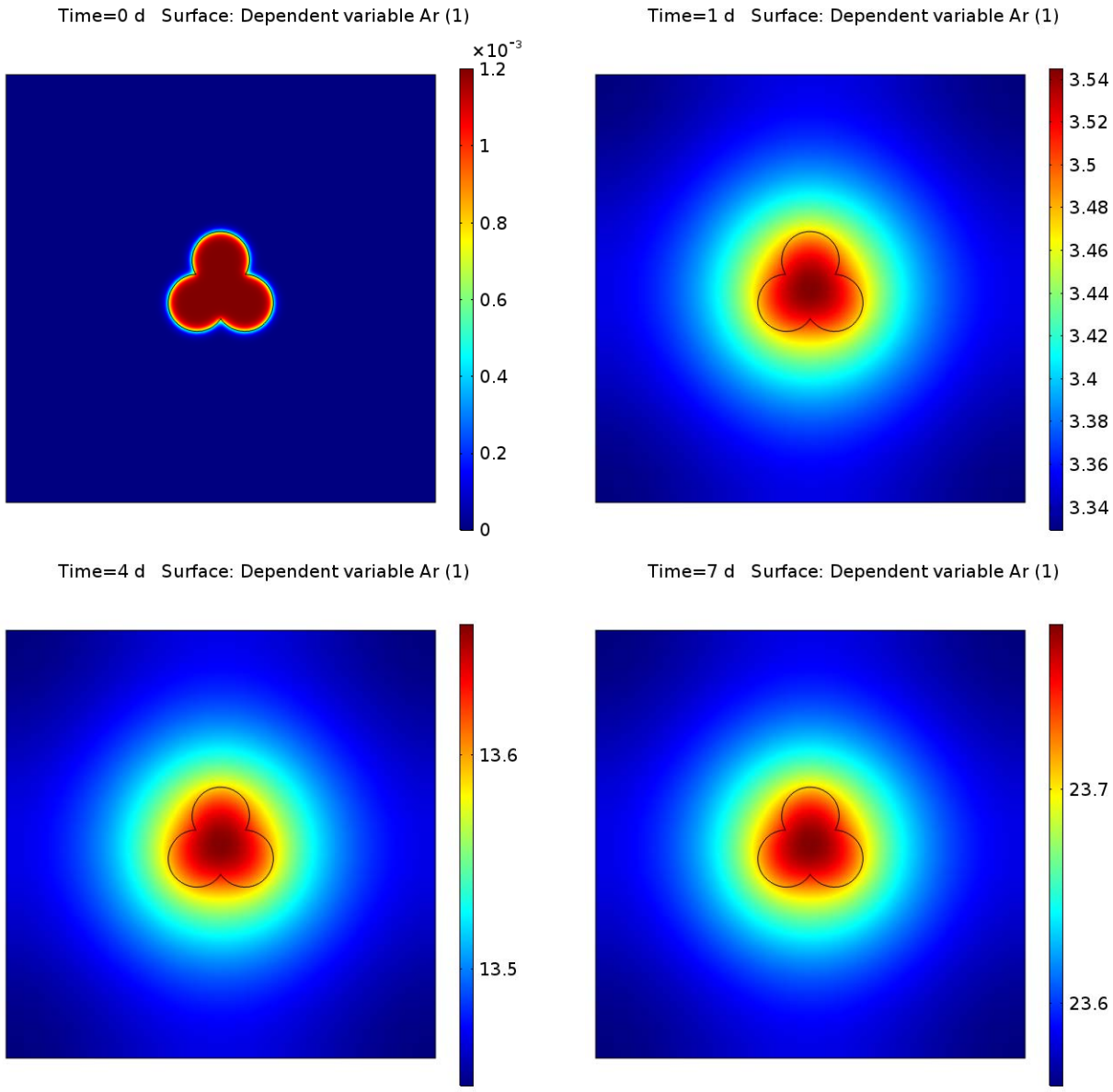

Figure 19 Increasing surface of rot in amount of potatoes from day 0 until day 7

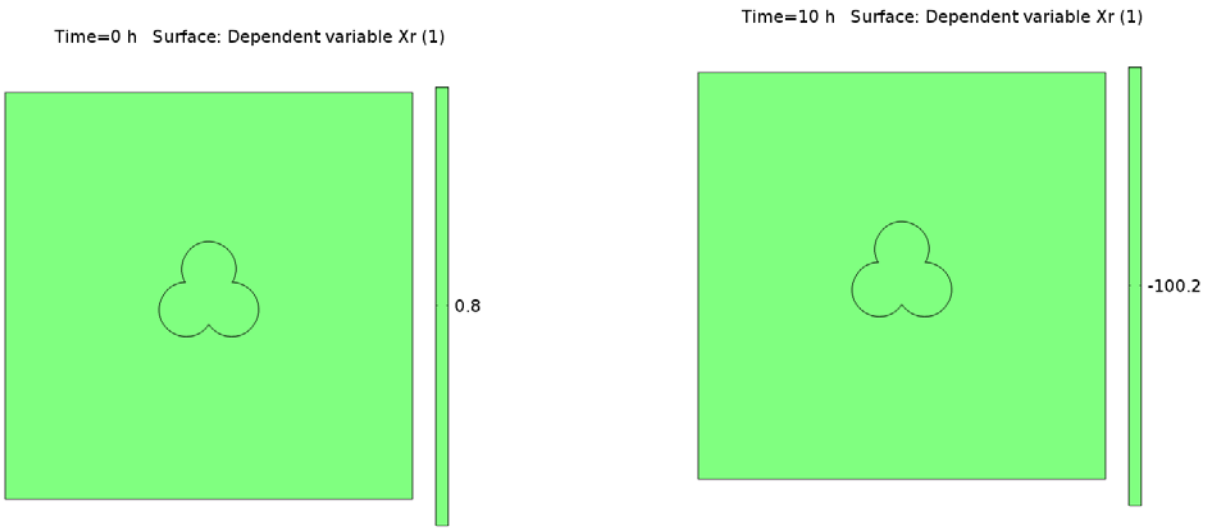

Figure 21 Moisture production [g/kg] of rotten potatoes at t=1h and t=10h

Figure 20 shows the moisture production of rotten potatoes. During the calibration of the evaporation rate a value of 4.25 [g/kg] moisture produced after 42 minutes was found. When including the moisture production for healthy potatoes a production of 100.2 [g/kg] after 10 hour seems not unlikely. This

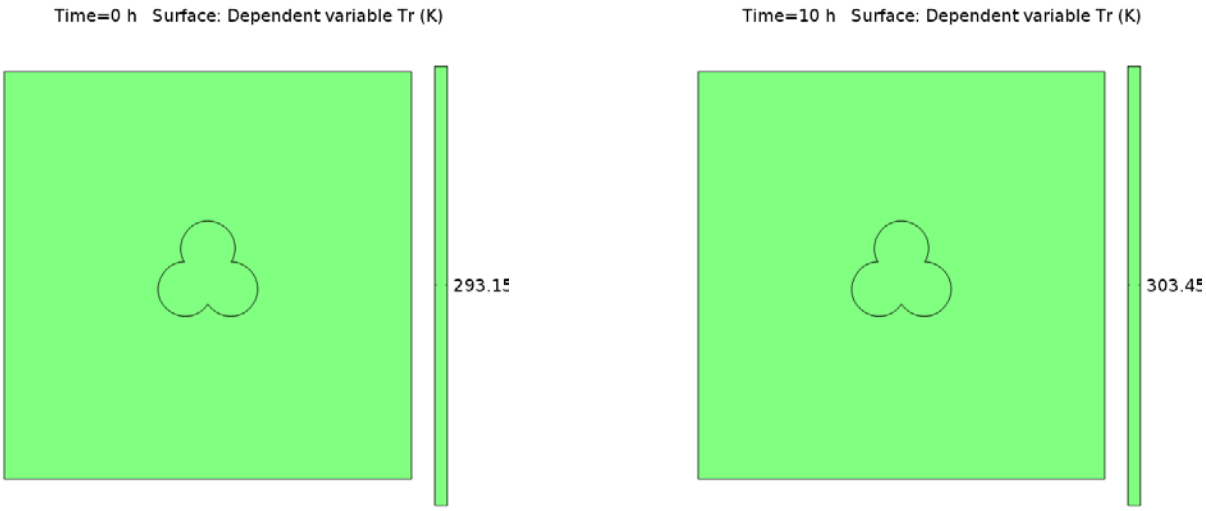

Figure 20 Heat production [K] of rotten potatoes at t=1h and t=10h

means that after 10 hour each potato has produced 2 grams of moisture. At a temperature of 24 °C, this is possible.

Figure 21 shows the heat production of rotten potatoes at initial time and after 10 hours. From this figure you can see that over 10 hours the overall temperature increases with 10.3 °C. Compared to the experiments this increase in temperature cannot be seen, and seems a bit high. However, when potatoes are stored at cooler conditions instead of 24 °C, there should be a rise in temperature inside the bulk. Besides that the environmental temperature outside the boxes is not considered in this model simulation. However, from the experimental results can be concluded that the ambient temperature certainly affects the temperature inside the storage boxes.

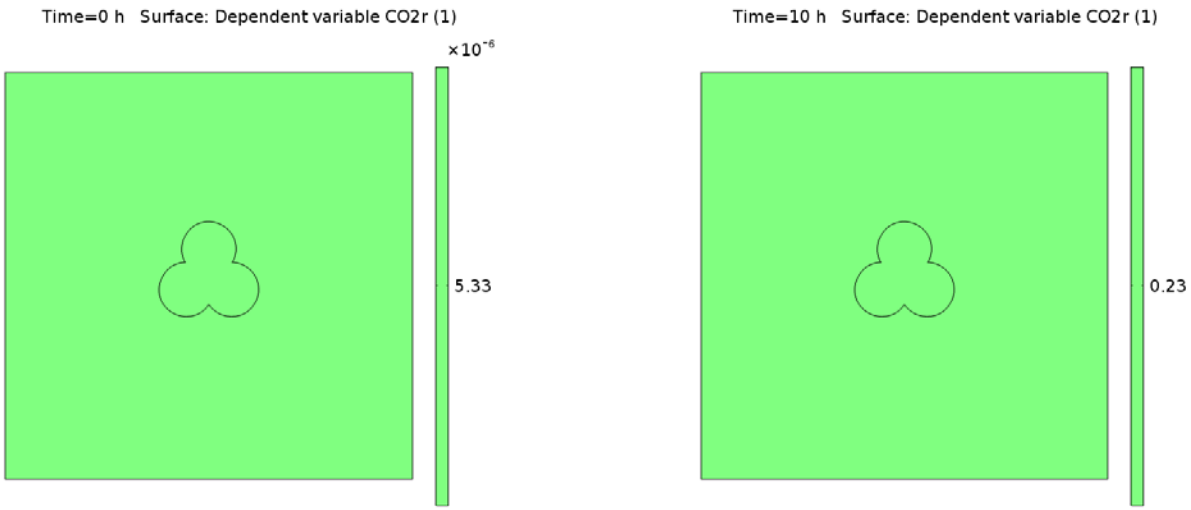

Figure 22 Carbon dioxide production [kg/kg] of rotten potatoes at t=1h and t=10h

Figure 22 represents the carbon dioxide production at 0 and 10 hours. This means that 0.23 kg carbon dioxide per kg produce is produced after ten hours. Overall this seems to be quite in range with the measured values. This means a valid, validated model is obtained.

7. Conclusion

(Grubben, 2013) presented a already calibrated and validated spatially distributed 2D model for healthy bulk potatoes in terms of temperature and moisture content and flow conditions. However, not all processes are taken into account. The rotting processes that influence potato quality and affect the storage conditions were not present. By adding a rot dependent parameter and determine the degree in which the already present model parameters are affected by rot, the model also accounts to rotten potatoes. Also a spatially distributed physical model for the spread of rot is set up, to give insight in the spread of rot inside the bulk. In order to investigate the effect on climate factors, dynamics and identification of rotting processes several research questions were defined and can be answered at this time. The following main research questions were defined:

How to develop a spatially distributed physical model for the spread of rot in the bulk?

To develop a model for the spread of rot in the bulk, it is important to identify the causes of rot and the influence on the potato quality in storage. These are mainly: *Phytophthora infestans*, bacterial soft rots and cold temperature injuries. The quality of the potato tubers depends on influences from the ambient environment and the incidence of pests and diseases.
Based on the gas diffusion equation, to simplify the model so it is widely applicable, the spatially distributed physical model for the spread of rot is developed. To implement the spread of rot in the potato bulk model, the surface of rot in the bulk is defined as quantity. The already present specific bulk surface parameter is divided into a quantity healthy bulk surface and a quantity rotten surface and implemented in the potato quality model.
The most relevant physical relations that narrate the dynamic behaviour of potatoes and air in a storage facility use laws of conservation of mass, energy in form of heat and momentum influenced by respiration, evaporation and losses of heat. From the experimental results we can conclude that the quantity of rot surface affected these constitutive laws by inducing increased respiration, evaporation and increased CO_2 production/oxygen consumption. The physical potato quality model for rot should be based on these increased losses; hence the respiration rate and evaporation rate were determined for rot. Following this approach the existing potato quality model was expanded, so it also accounts to rot.

How to set up an experiment to calibrate and validate the unknown model parameters?

To set up an experiment it was important that the obtained experimental data should allow the parameter values that contribute to the model to be determined and compared. So it was critical that the model parameters were measured in the right way and in the right range, to obtain significant data that can be used to analyze the system on base of practical data. Therefore the right measurement instruments were selected and also environmental conditions were considered. The geometry of the experimental set up was chosen carefully to simulate the real storage facility as accurate as possible. Additional to that the geometry had to be considered in such way that eventually simulations can be performed, Hereby was chosen for a 1-D configuration. Also the conditions inside the experimental setup were considered on base of real storage conditions, to realize an as accurate possible simulation of the storage facilities in practice. In this way the outcomes were more reliable.

How can the calibration and validation be performed in COMSOL?

Several computations were made to calibrate the respiration rates. Firstly the respiration rates for healthy potatoes per day were computed and subsequently the respiration rates for rot could be determined. Calibrating the evaporation coefficients was done by simulation of varying evaporation rates to find the most precise model estimation compared to the experimental data. Hence the evaporation rate was determined on the basis of the smallest error. After estimating both parameters, they were validated by a dataset of a similar experiment to make sure the experiment is reproducible and the found parameters are reliable. For the validation the same procedures were carried out. To calibrate the rot spread model, the dependent parameter $\mathbb{D}_{\mathrm{rot}}$, was determined out of pictures that were taken during the experiment and validated with the diffusion coefficient determined out of similar pictures of the validation experiment. The model errors were very small, which indicates that the parameters are reliable.
Eventually an overall model validation simulation was performed, to confirm there was obtained a valid, validated model.

8. Recommendations

Several challenges occurred during performance of the experiments. In this chapter, recommendations are given, to provide some important information for sequel experiments.

The experiments, mainly experiment 1 and experiment 2, worked out differently than expected. Firstly the inhibited rot spread. In the first two experiments the rot could not establish itself in the surrounding healthy potatoes. The thick skin formed over seven months of storage, seemed impermeable to the pathogens. It is recommended to carry out the experiments at the beginning of the storage season, when the potato skin is still thin and easier to access and affect for the pathogens. From this it can be concluded that: *Phytophthora* infections mainly take place at the beginning of the storage season and in the field.

Furthermore the low environmental RH resulted in the drying out of the potatoes. In practice the relative humidity in storage is 95 to 100%. Also the ventilation air used is 75 to 80%.
This was not reachable in the experimental set-up. So for sequel experiment, I strongly recommend to simulate the humidity values more precise, because it has great influence on the physical condition of the potatoes. This could be done by placing the experimental setup in an environment with high relative humidity, certainly not in a fume cupboard. Also use humidified ventilation air instead of compressed air to simulate conventional ventilation values of storages in practice.

Also realisation of a cooling system to simulate real life storage temperatures is critical for further experiments to realise a more realistic simulation of a real bulk storage facility. Also in order to measure temperature differences between the healthy and rotten potatoes and their environment and also to inhibit sprout growth. The temperature determines the respiration rate and influences the evaporation rate, so it is critical that temperature differences could be measured.

Finally, the sprout growth was a problem while carrying out the experiment 2. Under warm and dry conditions the sprout growth is optimal, as discussed earlier. When cooling could be realised, as stated above this favourable condition for sprout growth would be prevented. Also closing the experiment off from direct daylight is considered as a good prevention method.

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Appendix A

Photos taken to determine the % rotten potatoes per day. Day 5 and 6 are missing due to the weekend.

A- 1 Experiment 3: Rotten potatoes in hermetically closed chest

day 1 100% rot = 3/50 potatoes		**day 2** 103% rot	
day 3 104% rot		**day 4** 106% rot	
day 7 109% rot		**day 8** 109% rot	

A- 2 Experiment 3: Rotten potatoes in ventilated chest

day 1		day 2	
day 3		day 4	
day 7		day 8	

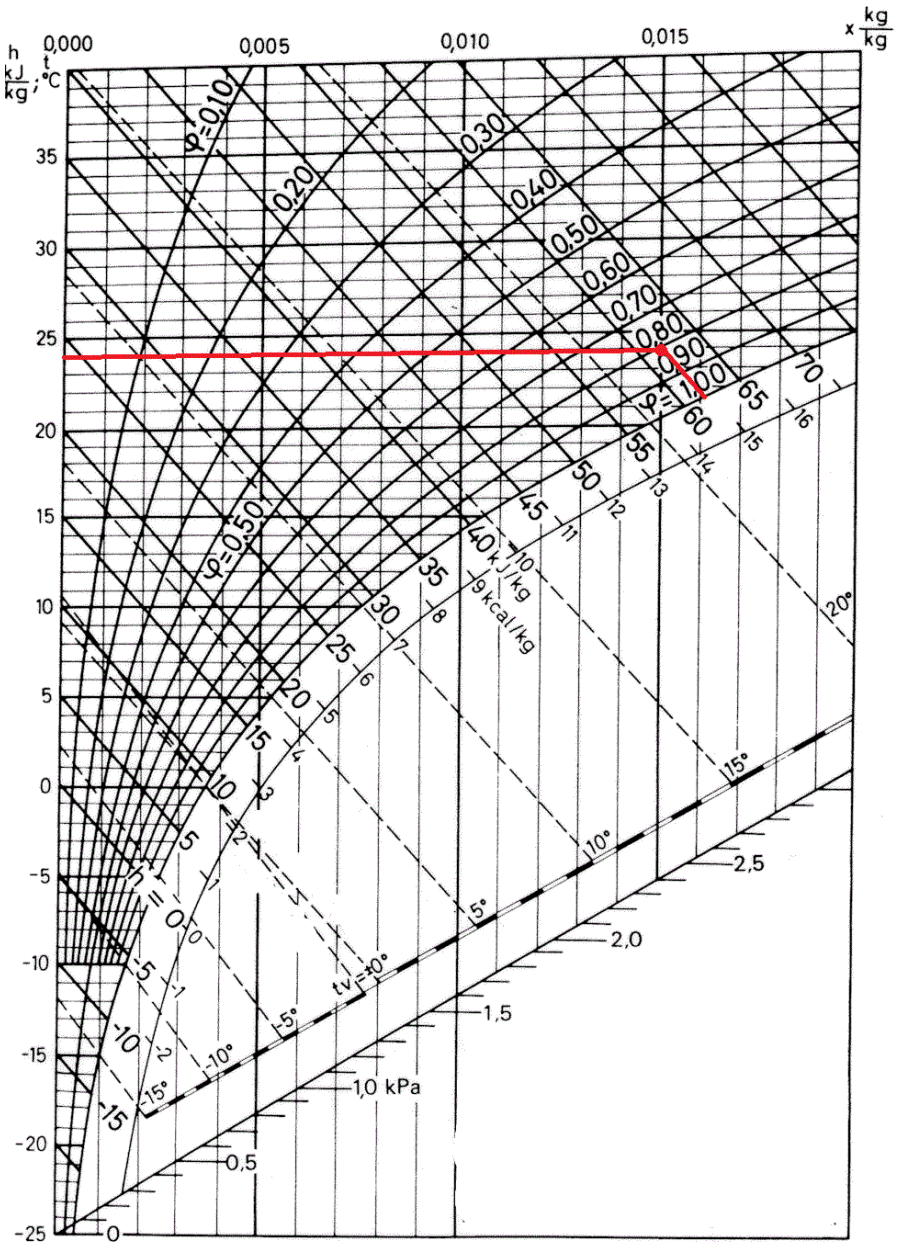
A- 4 Experiment 3: Rotten potatoes in hermetically closed chest

day 1 100%		day 2 102.5% = 5/50	
day 3 104%		day 4 107%	
day 7 108%		day 8	

A- 3 Experiment 4: Rotten potatoes in ventilated chest

day 1		day 2	
day 3		day 4	
day 7		day 8	

A- 4 Determining the absolute water content and the enthalpy content of the air with use of the Mollier-Diagram. For a water vapour content of 0.015 [kg/kg] with an enthalpy of ± 62 [J/kg]



Appendix B

Specifications of measurement instruments.

Table 20 Technical specifications RH transmitter

Measured Values (RH)			
	Sensor	HC101	
	Measurement range	0...100% RH	
	Accuracy at 20°C and 12V DC	±2% RH (0...90% RH)	±3% RH (90...100% RH)
	Temperature dependence	Typ. 0.03% RH/°C	
Measured Values (Temperature)			
	Senor	Pt 1000 (DIN A)	
	Accuracy at 12/24V DC		
Output			
	Digital (2 wire)	Output value RH: 0.00...100.00% RH Output value Temp: -40.00...+80.00°C	±3% RH (90...100% RH)
	Analogue 0...100% RH	0-1/2.5/5/10V	-0.2mA < IL < 0.2mA
General			
	Supply voltage	output 0-1V / 0-2.5V output 0-5V output 0-10V	4.5-15V DC or 7-30V DC 7-30V DC 12-30V DC
	Working/Storage conditions	-40 ... 80°C	

Table 21 Technical specifications carbon dioxide transmitter

Measured Values			
	Measurement range	0...2000/5000/10000 ppm	
	Accuracy at 25°C and 1013 bar	0...2000 ppm 0...5000 ppm 0...10000 ppm	< ± (50ppm +2% of measured value) < ± (50ppm +3% of measured value) < ± (100ppm +5% of measured value)
	Response time τ63	Standard	< 300s
	Temperature dependence		Typ. 1ppm CO_2/°C (-20 ... 45 °C)
	Sample rate	Approximately. 15s	
Output			
	0...2000/5000/10000 ppm	0 – 5/ 0 – 10V 4 – 20mA	-1mA < I_L < 1mA R_L < 500 Ohm
General			
	Supply voltage	24V AC ± 20%	15-35V DC
	Working/Storage conditions	-20 ... 60°C	0 ... 95 – 100% RH (non-condensing)

Table 22 Instrumentation

Carbon dioxide transmitter	RH transmitter
	
Thermocouple	**Windows Lifecam HD 3000**
	

Appendix C

Model simulation study for healthy potatoes, with the corrected evaporation 0.00095 [kg/m2/s] and respiration coefficient 1010.8 [J (kg produce)-1h-1] for this research.

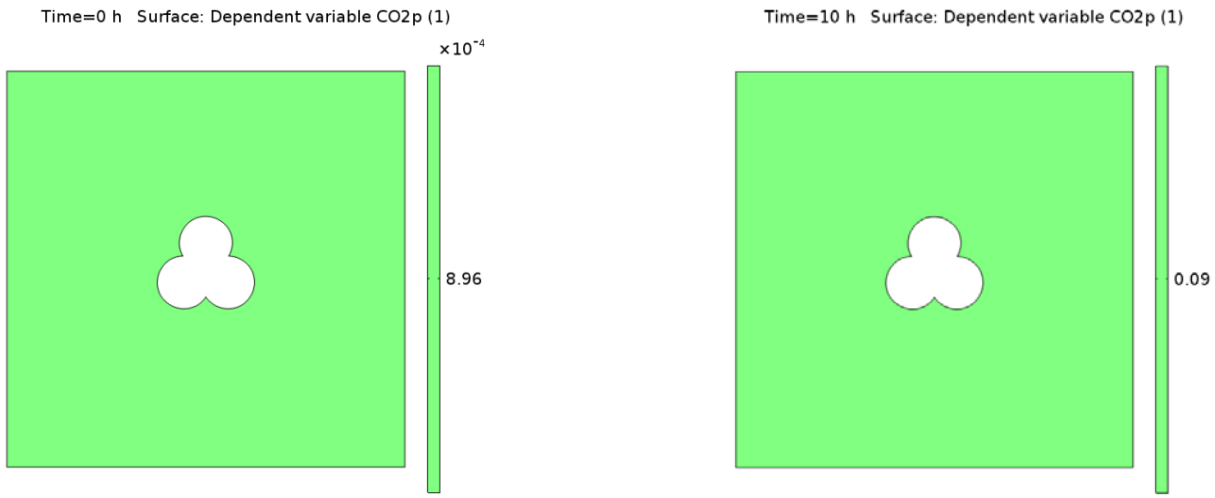


Figure 25 Carbon dioxide production healthy potatoes [kg/kg] at t=0h (left) and t=10h (right)

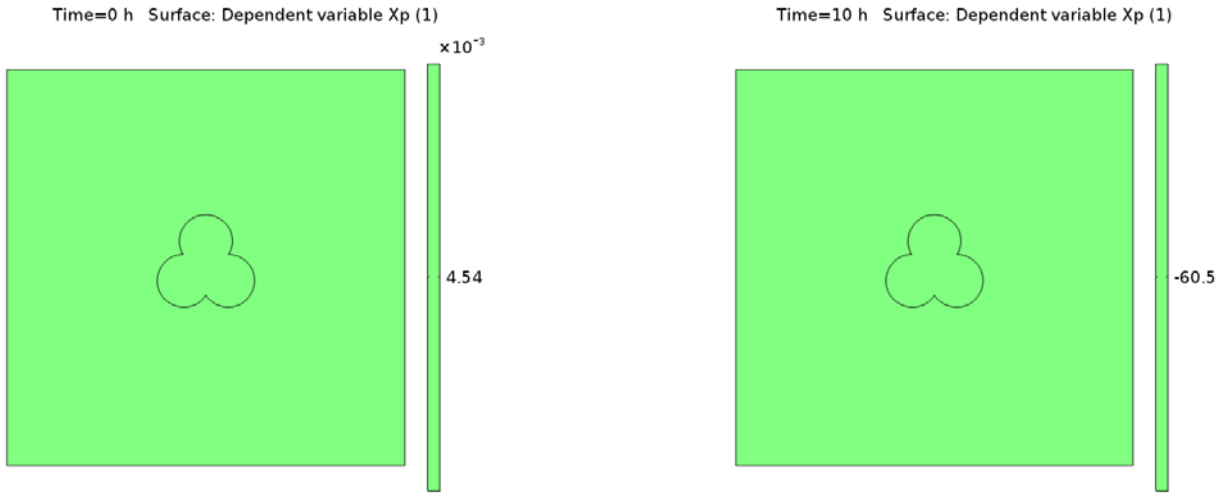


Figure 25 Moisture production healthy potatoes [g/kg] at t=0h (left) and t = 10h (right)

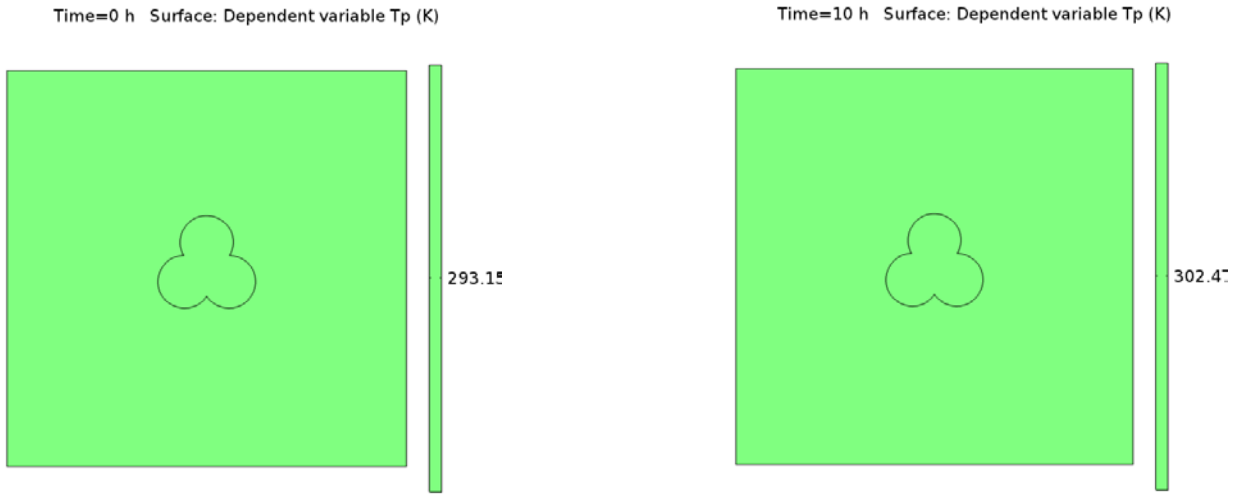


Figure 25 Temperature production [K] healthy potatoes at t=0h (left) and t=10h (right)