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Modelling and improving the nutritional content of yam during drying

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Preface

This MSc thesis project consisted of two parts: modelling and practical work. Since the drying equipment was not in good shape at the start of this project, a lot of time and effort was spent to bring it back in operation with technical assistance of Kees van Asselt.

The vitamin C analysis was carried out at the group Food Quality and Design of Wageningen University and I would like to thank research assistant Charlotte van Twisk for her advice on the extraction and measurement procedures. I would like to thank my supervisor, Ton van Boxtel, for providing moments of clarity when this was sometimes needed.

I hope this thesis will add to the popularity of solar drying as a preservation method. By decreasing post-harvest losses, food security in rural Africa could be increased and the economic situation improved. Furthermore, this thesis provides the necessary knowledge on drying in a nutrient-friendly way and increase food quality. Last but not least, I hope the reader can enjoy this thesis report.

Abstract

Nutrition is an important aspect in the quality of human life. Drying of food is an ancient conservation method, making it possible to spread consumption of the food source over a longer period than only during harvest. Current post-harvest losses can be up to 50%, increasing the need for adequate conservation techniques such as drying. Lower moisture content is advantageous as it stabilises the product in a lot of ways. However, fresh fruit and vegetables generally have a higher nutritional value than their processed (dried) products. To retain as many nutritionally valuable components as possible, an optimal drying strategy can be applied, which depends on environmental, product and processing parameters. In this research project, drying of white yam (*Dioscoreaceae rotundata)* is modelled and optimised with respect to vitamin C content. Vitamin C was chosen as a model component reflecting product quality because of its sensitivity to processing.

With the use of practical experiments, the outcomes of the model were validated, both in terms of drying and vitamin C retention. Drying time is the most important factor influencing vitamin C retention and is a combined effect of initial moisture content and drying rate. Drying yam (X_0=3.6 kg w·kg dm^{-1}) according to an optimised trajectory resulted in vitamin C retention of 26% after 30 hours. The drying trajectory with the lowest cost resulted in a vitamin C retention of 28%, in 32 hours. This small difference results from the differently chosen optimisation objectives, both the optimisation and the randomisation are good methods to find the optimal trajectory.

Furthermore, the model was used to simulate the drying of yam in a solar dryer. An optimal starting time of 5 PM resulted in 21% retention, almost twice as high as in the traditional open sun drying and a factor 2.6 higher than when drying was started at the worst time of the day. When drying vegetables with a considerably higher initial moisture content, this optimal starting time shifts slightly forward to 2PM. Additional advantages of the solar dryer is the protection against rodents, microbial spoilage and UV-light and is therefore strongly recommended to improve food security in West Africa.

The use of the Cranck diffusion equation was found to be inappropriate in describing dynamic systems. Instead, the use of ordinary differential equations were recommended for future research.

Nomenclature

Symbol	Description	Value	Unit
dt	Time step	3600	s
ρ_w	Density of water	1	kg·m^{-3}
F_a	Airflow	0.0243	kg·s^{-1}
E_a	Activation energy	44.06	kJ·mol^{-1}
R	Universal gas constant	8.314·10^{-3}	kJ·mol^{-1}·K^{-1}
$X_{a,in}$	Absolute moisture in the ingoing air	0.012	kg w·kg dry air^{-1}
X_0	Product moisture content at the start	1.68	kg w·kg dm^{-1}
D_0	Diffusion constant	8·10^{-4}	m^2·s^{-1}
M_{dm}	Dry weight of the product	0.08	kg dry matter
cp_a	Heat capacity of air	1.005	kJ·kg^{-1}·K^{-1}
cp_v	Heat capacity of water vapour	1.871	kJ·kg^{-1}·K^{-1}
ΔH_{vap}	Heat of evaporation	2408	kJ·kg^{-1}
λ_0	Slice thickness at the start	0.01	m
V_0	Slice volume at the start	0.09	m^3
$n_{shrinkage}$	Shrinkage factor	0.37	-
d	Fractal exponent	2.297	-
C_1 C_2 C_3	GAB model constants	8.26 0.76 10.14	-
a_1 a_2 a_3 a_4 a_5 a_6 a_7	Vitamin C degradation constants	7.94 -2.245·10^8 -33.33 5921 -1.585·10^6 4.711·10^8 -2.339	-
A B C	Constants for the Antoine equation	8.07131 1730.63 233.426	-
MW_{H_2O}	Molecular weight of water	18.00	g·mol^{-1}
MW_{air}	Molecular weight of air	28.93	g·mol^{-1}
MW_{Vc}	Molecular weight of vitamin C	176.1	g·mol^{-1}
P_T	Total air pressure	101	kPascal
$C_{titrant}$	Concentration of KIO_3	2·10^{-5}	mol·l^{-1}
N	Molar reaction ratio vitamin C per iodate	3	-

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Introduction

Yam cultivation

Yam is a tuber with a high nutrient content that grows in West-Africa. It is, next to cassava and maize, a highly important food crop in sub-Saharan Africa and part of 60 million people's regular diet (Asiedu and Sartie 2010). White yam, *Dioscoreaceae rotundata* or Guinea yam is mainly grown in Côte d'Ivoire, Ghana and Nigeria. It is best cultivated on a nutrient- and moisture-rich soil (Ng 1992). Harvest takes place on a yearly basis, in August. A common diet in sub-Saharan rural areas contains staple foods such as cereal (maize, sorghum) or tubers (cassava, yam) and a sauce or soup made of legumes (beans, lentils) and some green leafy vegetables (Aidoo 1993; Oniang'o, Mutuku et al. 2003). Yam is also used as infant food (Oniang'o, Mutuku et al. 2003), making the nutritional quality of dried yam (to make puree) an important aspect.

Food security

Since most food crops are harvested only during a certain time of the year, there is on the one hand a temporary surplus in summer and on the other hand a shortage in winter. Post-harvest spoilage is still very common, ranging from 20% (Aidoo 1993) to 50% (Okigbo 2004) and 60% (Dramani 2013), depending on the product and storage time. Common food spoilers are fungi and moulds, often present already on the field and growing on spots that are physically damaged. Furthermore, storage under (tropical) ambient conditions promotes microbial growth; high temperature and high humidity cause rapid spoilage of harvested crops (Aidoo 1993; Okigbo 2004). Preservation is a useful tool to minimise post-harvest losses and increase food security in rural areas. Food security is defined as: "when all people at all times have access to sufficient, safe, nutritious food to maintain a healthy and active life" (WHO 1996). Food crisis or chronic malnutrition, the opposite of food security, is a serious problem in West-Africa and estimated to affect one third of the population (Haile 2005). The main factors that influence food security are crop yield, food policies and the distribution of food through space and time. Farmers have difficulties selling their products in the cities due to poor infrastructure and therefore food security in each region is dependent on its own harvest. Due to insufficient storage facilities, farmers have to sell their tubers quickly, during harvest when prices are low. A longer shelf life of the tubers or tuber products would therefore increase income and improve the socio-economic situation of these farmers (Dramani 2013). Methods to conserve yam tubers will be discussed in the subchapter 'Conservation methods'.

Nutritional quality

Adequate nutrition consists of a diet containing sufficient macronutrients (carbohydrates, proteins and fat) and micronutrients (vitamins, minerals and other minor components). Carbohydrates and fats are mainly important for providing energy. Proteins are important for tissue maintenance and growth. All micronutrients are only needed in small amounts; however, absence of each compound results in a specific 'deficiency illness'. To obtain enough of each of these minor components, that are present in different vegetal products, it is recommended to follow a diet with a lot of variation. Research has shown that a varied diet prevents malnutrition and improves health status (Ruel 2003).

Yam contains a lot of starch, some essential amino acids, vitamins (vitamin C, thiamine, riboflavin, niacin, beta-carotene) (Ng 1992), phenolic compounds (catechin, ferulic acid) (Akissoe, Mestres et al. 2005) and trace elements (potassium, iron, zinc, calcium, phosphorus and magnesium) (Adepoju 2012). These minor components will be discussed now, whereas the compound most important during this research, vitamin C, will be discussed in a separate section.

Minor components

Beta-carotene is needed for vitamin A production in the body, which is important for vision and growth. Thiamine, also known as vitamin B1, protects against beriberi (deficiency illness prevailing mainly in Asia) and riboflavin (vitamin B2) is vital for growth and deficiency is common in developing countries. Niacin (vitamin B3) deficiency is also common in poorer parts of Africa and causes diarrhoea and dermatitis. Vitamin C (ascorbic acid) is a vitamin that cannot be stored in the body and therefore should be consumed regularly; it is regarded as indicator of fruit and vegetable intake. It protects against scurvy and is an important antioxidant.

Iron deficiency is common all over the world and especially in (pregnant) women and children. In Africa, 40% of the women and 60% of the children suffer from anaemia, accounting for 270.000 deaths a year (Stoltzfus 2003). Zinc deficiency is also a problem, leading to diarrhoea, malaria and growth retardation (FAO 2001). Yearly, 260.000 deaths in Africa are attributed to zinc deficiency (Walker, Ezzati et al. 2009).

Another compound present in yam is thiocyanate, a compound found to protect against sickle cell anaemia (SCA). SCA is an illness that is much more prevalent among the negroid race. The thiocyanate-rich diet (yam and cassava) in West-Africa probably explains the much lower occurrence of SCA in the African population compared to the Afro-American (Agbai 1986; Okpuzor, Adebesin et al. 2008).

The macronutrient and metal content in yam tubers is summarised in Table 1.

Table 1: Nutritional content of yam (*D. rotundata*)

Reference / per 100g fresh weight	(Bradbury and Holloway 1988)	(Trèche and Agbor-Egbe 1996)	(Opara 2003)	(Osunde and Orhevba 2009)	(Alinnor and Akalezi 2010)	(Addy 2012)	(Adepoju 2012)
Water (g)	65.3	60	80	71	54.5	64.5	58.8
Protein (g)	1.52	2.1	1.5	2.6	0.09	4.8	2.3
Fat (g)	0.09		0.1	0.27	2.7	0.55	0.8
Carbohydrates (inc. starch, g)	30.5	37.1	16	24.6	40.6	26.1	33.3
Fibre (g)		2	0.6	0.95	0.7	0.75	1.4
Calcium (mg)	4.6	10.8	36	12	132	74	68
Phosphorus (mg)	28	45.6	17	18	54	67	163
Iron (mg)	0.6	2	5.2		82	4.5	4.1
Magnesium (mg)		22.8			46		32
Potassium (mg)			350		209	1.2	470

It is clear that there is a lot of variance in data between authors, which might be explained by differences in subspecies, effectiveness of the extraction, freshness of the product, moisture content or measurement accuracy. Research on the comparison between four *D. rotundata* subspecies showed that there is a lot of difference between subspecies; carbohydrate content for example varied between 15% and 34% (Addy 2012). Especially for trace metals, the data is highly variable and unreliable.

Table 1 can be seen as an illustration of the unreliability of nutritional data available for yam. It is probable that the local population/consumers are not aware of the value of their food, and how to preserve this.

Daily intake

The values stated in Table 1 are quite meaningless without the daily requirements for each component given. To illustrate the importance of yam in the daily diet, the amount of a component present in a daily portion (assumed 0.5 kg) was calculated, expressed as percentage of the daily requirement of an adult. According to the table, measurements of Addy (2012) and Adepoju (2012) are most recent and quite similar, apart from potassium content. The results of Adepoju et al. are therefore taken as reference values. The specified daily portion of yam contains the following percentages of recommended daily intake (RDI): 34% for calcium, 35% for zinc, 45% for magnesium, 67% for potassium, 135% for phosphorus, 136% for iron (Norden 2012). Assuming vitamin C levels described by Coursey and Aidoo (1966) and accounting for a loss of 50% during processing, the same amount consumed accounts for 25 mg vitamin C per day. This is 56% of the amount recommended by the World Health Organisation (FAO 2001). Losses during processing are very common, as will be discussed in the section 'Vitamin C'. These figures show that consumption of yam contributes to the intake of vitamins and trace metals of the African population.

Health benefits

The consumption of fruit and vegetables has a lot of health benefits: it is correlated with lower incidence of breast cancer (Gandini, Merzenich et al. 2000), bladder cancer (Steinmaus, Nunez et al. 2000), coronary heart disease (He, Nowson et al. 2007) and other diseases. Vegetal food products are complex and contain a lot of different compounds together but mainly vitamins, antioxidants, minerals and phenolic compounds have a protective effect on the body. To find out what component is responsible for this protection, *in vivo* trials with vitamin C and E supplements were executed, but no protective effect was found (Lonn, Bosch et al. 2005; Sesso, Buring et al. 2008). When a mix of micronutrients (antioxidants, vitamins and minerals) was supplemented, an effect was seen for men but not for women (Hercberg, Galan et al. 2004). It seems that not only one supplemental micronutrient is responsible for this protection but a mix of micronutrients or only in the original configuration; as a plant product. All minor components together create a synergetic effect which is stronger than that of the separate vitamins and trace elements together (Liu 2003). This not fully explained health effect of fruits and vegetables indicates the importance of good nutrition and the need to preserve their nutritional value.

Antioxidants are regarded as a highly important part of the nutritional value of fruit and vegetables and their function will be explained in some more detail. Vitamin C, E and phenolic compounds can act as antioxidants. Antioxidants protect cells in the body against damaging free radicals. Free radicals, or reactive oxygen species, are metabolic products or formed when exposed to ultraviolet radiation or air pollutants such as cigarette smoke. Free radicals can easily harm cells in the blood and body and thereby cause the formation of dysfunctional cells and diseases. Anti-oxidants can either react directly with the free radical or inhibit their activity in another way, thereby protecting the body (Morton, Caccetta et al. 2000; FAO 2001).

Vitamin C

Vitamin C is one of the most important anti-oxidants and a valuable component in yam. But although it can protect the body against harm, it is also easily harmed itself, mainly by heat. At higher temperatures, vitamin C degrades and the nutritional quality of the product is therefore lower. Since vitamin C is generally the most sensitive compound present in a food, it is often used as a quality measurement. Excessive degradation can be avoided by mild processing. Lower temperatures and shorter exposure/processing time improve vitamin C retention. The vitamin C content in yam differs between subspecies and is for *D. rotundata* measured as 50-150 mg (Muzac-Tucker, Asemota et al. 1993), 7-11 mg (Coursey and Aidoo 1966), 6-12 mg (Evans, Yakubu et al. 2013) 4-18 mg (Opara 2003), 0.3-0.4 mg (Okwu and Ndu 2006) per 100 g of fresh product. Since vitamin C is very prone to degradation, analysis skills have a large impact on yield and this results in a lot of variance between authors.

Conservation methods

Yam is generally stored for a long time because it is consumed year round. If stored as tubers, it is important that they are well ventilated and protected against flooding, rodents and heat. Rodents physically damage the tuber, which then can easily rot. Some common methods are to simply make a pile on the ground, or bind them to vertical poles and save these as 'yam barns' (Coursey 1967). Storage in an underground pit structure resulted in sprouting of 70% of the tubers, indicating the conversion of carbohydrates to sprouts (Nwakonobi, Obetta et al. 2012). These less controlled methods have a high failure risk and result in the already mentioned high numbers of post-harvest spoilage, ±50% after 6 months of storage (Okigbo 2004; Dramani 2013). Research was conducted comparing 6 month yam storage in a traditional barn with and without a fan (Osunde and Orhevba 2009). It was found that the ventilated barn was about 4°C lower in temperature. Rotting in the unventilated barn was 12% after 6 months, compared to 2% in the other room. This shows that storage temperature has a high impact on quality and quantity of the product. But even if tubers do not rot, storage would consume 10% of the dry weight of yam on respiration (FAO 2001; Osunde and Orhevba 2009). Yam tubers can also be waxed with oil to effectively lower rotting and respiration rate (Dramani 2013). Several other processing methods can be applied such as chemical control, low storage temperature, curing and the recently developed biological control, where microorganisms are used to protect the tuber during storage (Okigbo 2004). All these methods have disadvantages; they require high investment, costs or technical demands from the farmer, which they cannot afford.

This leaves drying as a good option to preserve yam for a longer time and at low costs. Drying has the advantage that there is minimal microbial growth because of the lowered moisture content. If the surplus of harvested yam would be dried before turning into post-harvest losses, this would mean almost a doubling of income and a significant step towards food security, since the dried yam can be stored for a much longer time. Because there is no longer any respiration, an additional 10% of dry weight is saved (Osunde and Orhevba 2009). They are also more easily transported and sold it in the city; the product has a lower weight and is less vulnerable during transport.

A common small scale drying method in West-Africa is sun drying, where the yam is sliced and dried in open air. There is no equipment needed, making it also accessible for the poorest farmers. This method is not preferred since it can contaminate the food, is slower and requires more labour than convection drying (Özcan, Arslan et al. 2005). Contamination occurs because the product is exposed to the microorganisms of the environment (carried by dirt, children, animals) during the day. In the night, temperature drops and condensate is formed on the slices, promoting growth of the microorganisms and causing spoilage (Goddard and Perret 2005). It was for instance shown that sun dried yam contained traces of toxic aflatoxins produced by the mould Aspergillus flavus, while oven dried yam did not (Okigbo and Nwakammah 2005). Similar results were reported for total microbial count in sun and oven dried yam (Djeri, Ameyapoh et al. 2010). Therefore, products should be dried in a protected system and at the lowest (investment) cost possible. Drying with the warmth of the sun is a sustainable idea, since this is an abundant resource in West-Africa that provides energy for free. This research therefore focusses on the use of a solar dryer, a safe drying technology with low investment costs. The subchapter 'Solar drying' will explain in more detail how this technology works and what the advantages are.

Processing

Nutritional quality can be influenced by processing; most processes like boiling or frying decrease the overall quality because heat sensitive compounds are degraded. Cutting and washing is also not beneficial; cells are disrupted and nutritional compounds as vitamin C leak into the waste water. During drying, heat is the most important parameter influencing quality. As vitamin C is a valuable but vulnerable nutritional compound, several authors described vitamin C degradation in various vegetables during oven drying between 40 and 80 degrees. Vitamin C retention was usually below 50% (McMinn and Magee 1997; Inyang and Ike 1998; Chen and Lin 2007; Nicoleti, Silveira et al. 2007; Jin, van der Sman et al. 2014), which is a severe quality impairment. Since vitamin C is the most heat sensitive compound in yam, it is regarded as a model parameter describing nutritional quality (Khraisheh, McMinn et al. 2004; Jin, Oliviero et al. 2014).

Vitamin C kinetics

Next to temperature, also the product moisture content is an important factor in vitamin C degradation kinetics. They are described in equation 1 and illustrated by Figure 1, where C is the concentration of vitamin C (%), k_{Vc} the degradation constant of vitamin C (s^{-1}) and k_{Vc}^{0} , Ea_{Vc} , R and T show the Arrhenius dependence of the degradation constant on temperature.

$$\frac{dC}{dt} = -k_{Vc} \cdot C$$

$$k_{Vc} = k_{Vc}^{0} \cdot \frac{Ea_{Vc}}{R \cdot T} \qquad (1)$$

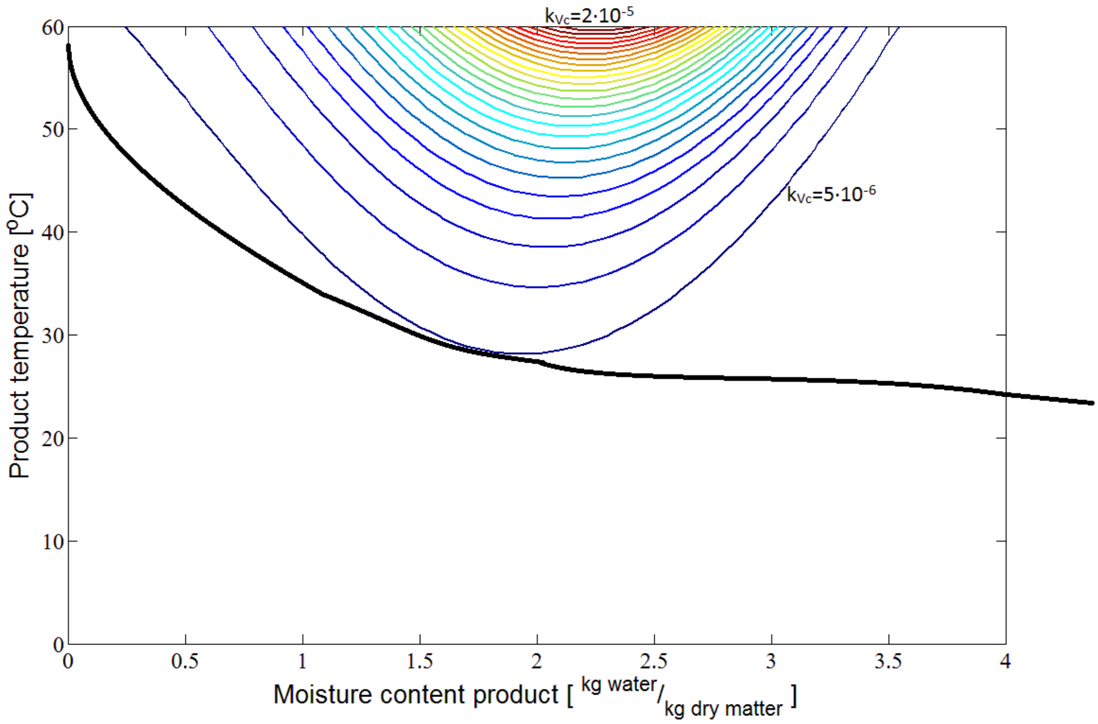

Figure 1. Contour lines represent the vitamin C degradation constant k_{Vc} ,depending on product moisture and temperature, warmer colours indicate a higher k_{Vc}. The black line depicts an optimised drying trajectory for broccoli (van Olst 2013; Jin, van der Sman et al. 2014).

Figure 1 shows a state diagram of a vegetable where degradation rate constant k_{Vc} is indicated by the contour lines. It shows that degradation does not only occur at very high temperatures but already at 30°C, a common temperature in West-Africa. This means that vitamin C degradation can already occur during storage of yam tubers. The figure also shows that vitamin C is more stable at high and very low moisture content, meaning the moisture content of the fresh product is important. Yam has a moisture content of 73%, corresponding to 2.7 kg water·kg dm^{-1}.

Figure 1 shows that this places fresh yam much closer to the degradation area than a vegetable with a higher moisture content, such as broccoli (9 kg w·kg dm^{-1}).

Of course, the time spent in this area of vitamin C degradation also determines the final vitamin C retention. It cannot be derived directly from the figure if it would be better to, for example, dry very quickly or at very low temperature. Therefore, modelling was used to calculate an optimised trajectory: a temperature drying profile that should be followed to obtain an efficiently produced product (in terms of energy use) with optimal vitamin C content. This was done by Jin et al. (2014), who designed an 8-stage drying trajectory for broccoli in a way that avoids the vitamin C degrading area, as displayed by the black line in Figure 1. Note, broccoli has a moisture content of 9 kg water·kg dm^{-1} but to clearly depict the degradation area , only part of the trajectory is shown. Van Olst (2013) optimised this trajectory further and this resulted in an optimal drying inlet temperature, seen in Figure 2.

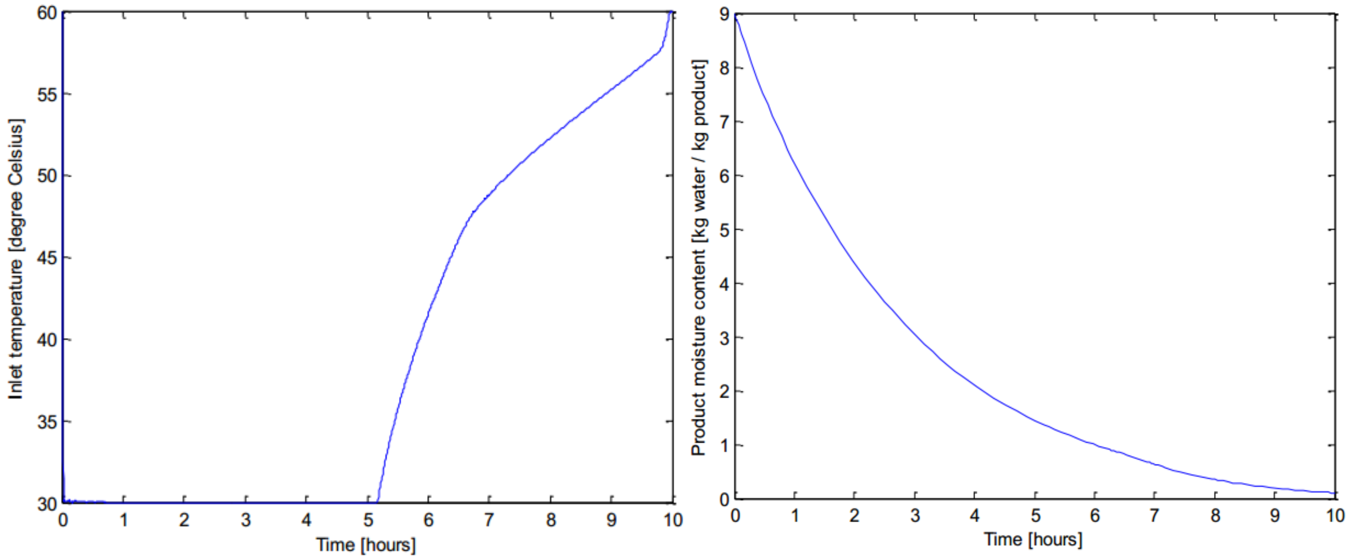

Figure 2: optimal drying inlet temperature (l) and drying behaviour(r) of broccoli (van Olst 2013).

The optimisation criteria where both vitamin C retention and energy efficiency and temperature was limited between 30°C and 60°C. The figure shows that temperature was only increased after 5 hours, when the moisture content was below 2 kg w·kg dm^{-1}. This is also the case for the drying trajectory by Jin, van der Sman et al. (2014) and avoids the high-degradation area (Figure 1).

Blanching

Quality can be measured by chemical analysis (for instance vitamin C retention) but can also be estimated visually. For yam, browning can be a problem that makes the product less appealing. Browning in yam is mainly caused by the activity of the enzyme polyphenol oxidase (PPO), which catalyses the reaction between oxygen in the air and phenolic compounds in the product (Akissoe, Mestres et al. 2005). After cutting, the surface of the yam is exposed to oxygen in the air and browns. This type of browning can be prevented by blanching; putting the product in hot water for a short period of time to inactivate the enzyme. Blanching is a common practice before drying of yam (Akissoe, Mestres et al. 2005). Vitamin C, as an antioxidant, can prevent enzymatic browning for some time by inhibiting PPO activity (Evans, Yakubu et al. 2013). This means that the valuable vitamin C is used far before it enters the human body, and is lost. Evans et al. showed that PPO activity is correlated to the degree of browning, it is therefore expected that browning and vitamin C degradation are positively correlated in unblanched drying products. It was shown that a blanched product after storage contains more vitamin C than without blanching, despite the degradation of vitamin C due to the heat treatment (Kadam, Samuel et al. 2005). Blanching does not need any specific chemicals or machines, and is therefore also possible in rural areas. Blanching should be considered as a way to improve vitamin C and decrease browning of dried or otherwise processed yam. The relation between vitamin C retention and browning is one of the questions examined during this research.

The drying principle

Industrial drying of agricultural products can be performed in a convection oven, where hot dry air passes the products, takes up the water and leaves the dryer as moist, colder air. This is illustrated with a Mollier diagram (Figure 3) with arrows indicating the different phases.

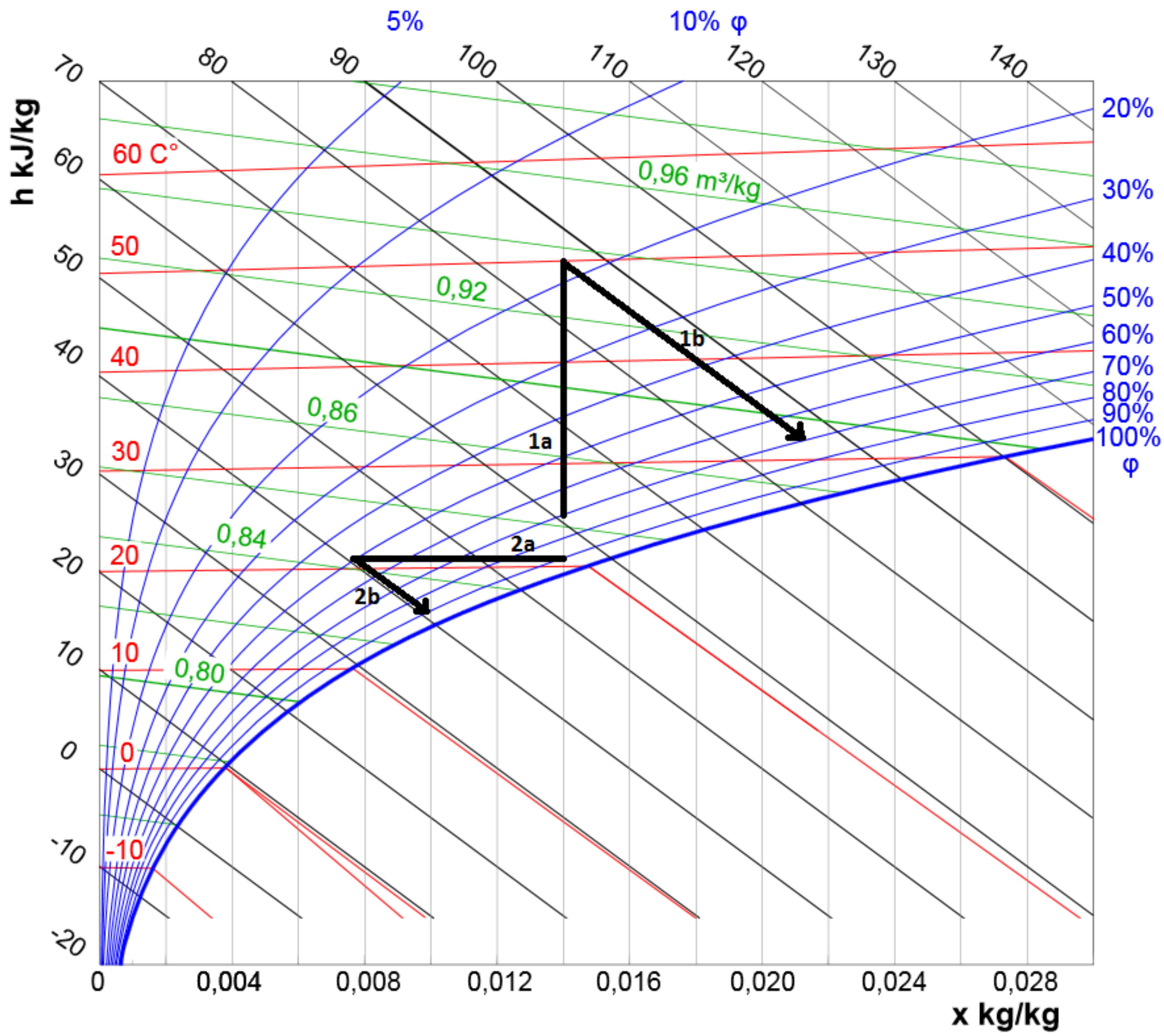

Figure 3: Mollier diagram with arrows indicating drying stages. Vertical lines (x-axis) indicate absolute moisture content, blue lines the relative humidity (RH), red lines the temperature and diagonal black lines the enthalpy of the air.

The driving force for a drying process is the difference between the vapour pressure above the surface of a product and the partial vapour pressure of water in the air, P_{H_2O}. P_{H_2O} is the saturated vapour pressure (P_{sat})· relative humidity (RH) and can be obtained from the Mollier diagram at known air humidity and temperature. The vapour pressure at the surface of a product is a function of temperature and relative humidity of the air, product moisture content and degree of water binding capacity (Earle and Earle 2004).

Heating of the air before it contacts the product (arrow 1a) increases the amount of water the air can absorb (P_{sat} increases) but does of course not change the absolute moisture content of the air. The hot air is then brought in contact with the product and takes up the water. This process, indicated by arrow 1b, causes the air to cool down since the overall enthalpy of a system always is conserved.

The vapour pressure at the surface determines the final moisture content of the product which is highly product specific: the equilibrium moisture content X_e. The RH of the endpoint of arrow 1b determines vapour pressure at the surface and therefore X_e. By increasing airflow, the air is constantly refreshed. This lowers P_{H_2O} and slightly lowers the vapour pressure at the surface, resulting in fast drying and low final moisture content, respectively.

Convective drying of agricultural products is used for several fruit and vegetables like banana (Jannot, Talla et al. 2004), carrot (Doymaz 2004; Liu, Chen et al. 2012), papaya (Kurozawa, Terng et al. 2014) and potato (Curcio and Aversa 2014). It is an energy consuming process, needing fuel to heat the air and advanced equipment that is not affordable for most farmers.

Solar drying

An alternative to sun drying and industrial drying is solar drying, described by several authors (Santos, Queiroz et al. 2005; Bolaji and Olalusi 2008). This is done in a closed container above the ground where air heated up by sun irradiation is led through the container, with the help of a fan running on solar energy. The solar dryer now considered is developed by Amankwah et al. and consists of a black absorber plate covered with a glass plate with an air gap in between. The length of the plates can vary between 1 and 10 meters. The speed of the air flowing between the plates is regulated with a van and can be set between 0.02 and 0.35 m/s. At low air flow, the outlet air temperature is around 66 °C, at high airflow the air temperature is lower. It is thus similar to oven drying using dry air but at a lower maximum temperature and lower costs. The lower temperature means a batch will not be finished in a day. During the night, the air is not heated up by the sun anymore and the drying rate drops. To keep a driving force for the drying process at night, the air humidity is lowered, which is done by contacting the air with silica gel. The silica absorbs the moisture from the air (Figure 3, arrow 2a), which can now take up the moisture of the product (arrow 2b). The moist silica is dried during the next day (from the endpoint of arrow 2b to the start of arrow 2a) and can be reused again.

This mechanism makes it possible to dry continuously, during day and night. The main advantage of this is that it prevents condensation of water on the product, leading to contamination, microbial growth and thus a lower quality. The product also dries faster than in a normal solar dryer. Since a dry product is in several aspects more stable than a fresh product, nutritional compounds are preserved and the product is microbiologically safe. Therefore, the overall quality will be higher when the product is dried faster.

Aim and research questions

The introduction gave a review on the importance of yam in the West-African society and its nutritional value. Also the necessity of a nutritious diet for human health was shown, which can be achieved by consumption of sufficient and high quality food. Vitamin C was shown to be sensitive to processing and can therefore be regarded as a quality parameter of processed fruits and vegetables.

Drying is a way to reduce post-harvest losses and therefore solar drying can be beneficial for the West-African society. This illustrates that although processing can have negative impact on several components, it is in fact a good tool to increase the availability of nutritious food. Combining the knowledge on temperature course during solar drying and vitamin C degradation during the day, there might be a difference in vitamin retention when drying is started at a different time of the day.

The aim of this research is to show that an optimised drying trajectory significantly enhances nutritional value of dried yam with respect to vitamin C content based on modelled drying kinetics. This leads to the following research questions:

- How to model the drying process of yam, taking shrinkage, moisture and temperature changes into account and does it agree to experimental data?
- What does the optimal drying trajectory for vitamin C retention look like?
- What is the best drying schedule (starting time) when using the solar dryer for agricultural products?
- Does browning correlate with vitamin C degradation?

Material & Methods

This section is divided into four parts. First, some background information on current drying theories will be discussed. The second part gives the equations that together describe the drying behaviour and vitamin C degradation of yam. To see the impact of different drying trajectories on the vitamin C content, three type of simulations were performed and described in the third part of this chapter. This made it possible to gain more insight into treatments that were not feasible with the experimental set-up explained in the fourth part of this chapter.

Drying theory

Modelling of moisture transfer during food drying can be done in several ways, as summarised in a review by Srikiatden and Roberts (2007). The main models assume either diffusion, flow through capillaries or pores or a combination. The driving force of these is a concentration gradient between the in- and outside of the product, assuming the temperature difference between the surface and core is negligible. Another possible mechanism is a combined heat and mass balance, taking into account the temperature difference between product surface and core. The different concepts and their applicability to yam drying will be regarded in the following section.

The basic principle of heat and mass balances is that no mass or energy can disappear from the system. The ingoing air takes up water from the product and simultaneously cools down, the water in the product takes up heat needed to convert water to vapour (heat of evaporation) and might slightly cool down the product and the product slowly heats up because of convective heat transfer. Heat and mass balances can describe these processes and are used in drying technology (Jin, Oliviero et al. 2014).

According to Srikiatden and Roberts (2007), drying of foods starts with a constant rate period, which is only determined by the speed of evaporation at the surface. Often, no constant rate period is observed and drying happens at the next stage: the falling rate period, determined by internal diffusion limitation. The second falling rate period begins when the partial pressure of water throughout the material is below the saturation level (Srikiatden and Roberts 2007).

Different authors investigated banana drying and described four phases, starting with a period of heating up, then a long period of exponentially decreasing drying rate until the critical point (moisture content X_w=0.8 kg w·kg dm^{-1}) where the drying rate decreases only linearly with moisture content X_w (Jannot, Talla et al. 2004). This continues until the second critical point X_w=0.12 kg w·kg dm^{-1}. They describe this transition as the moment that all the bound water is evacuated and highly bound water starts to diffuse. This point corresponds with the findings of Hernandez, Pavon et al. (2000), who reason that cell walls at this moisture content are broken down and form a layer of resistance to moisture transfer.

Porosity

Porous media have different diffusivity mechanisms than non-porous media; water and water vapour flow through the pores of the product since this is the way of least resistance. To be able to use other data, it was assumed that the porosity of yam is comparable to that of potato. Potato has a porosity of 0.02, which is well below the limit of 0.26 under which the material can be assumed non-porous (Srikiatden and Roberts 2007). Pores can also be formed during drying but this is negligible for potato, less than 10% (Srikiatden and Roberts 2007). It is assumed that yam will behave like potato concerning this matter.

Shrinkage

The volume of yam slices changes during drying, which influences the diffusion coefficient (Gekas and Lamberg 1991). This change is dependent on moisture content; the volume fraction of the water can be filled with air or the product shrinks (Perez and Calvelo 1984; Wang and Brennan 1995). If shrinkage is neglected, the water migration distance is larger and the effective diffusion coefficient overestimated (see equation 2). If shrinkage is taken into account, the effective diffusion coefficient decreases with moisture content, which is more realistic. During drying of banana, it was found that the surface corrected drying rate (min^{-1}) is constant until X_w=0.6 kg w·kg dm^{-1} (Katekawa and Silva 2007). This shows shrinkage has to be taken into account when calculating drying rates and diffusion coefficient, as shown by other authors (Mulet 1994; Ramallo and Mascheroni 2013).

External factors

The diffusion rate depends to some extend on air flow rate. A low airflow increases the size of the stagnant layer of air around the product. This means the driving force for moisture transfer is lower, resulting in a decreased drying rate. At higher air flow, above $1.5 \cdot 10^{-6}$ kg dry air·m^{-2}·s^{-1}, diffusion is not influenced by external factors (airflow) and internal moisture transfer in the product is limiting (Mulet 1994). The solar dryer has a minimal airflow of approximately $2 \cdot 10^{-3}$ kg dry air·m^{-2}·s^{-1} (Amankwah, Dzisi et al.) and this validates that only internal diffusion limitation has to be taken into account.

Model

This chapter provides the equations used to build the model. Modelling was done with the help of MATLAB® (2013a), the used scripts can be seen in Appendix D.

The structure of the model was according to the Euler method, calculating each value based on the previous one after time step dt.

The absolute moisture content and temperature of the air is given (by the simulations or by measurement), initial values and other constants are measured or set by the simulations and can be found in the nomenclature.

The drying model, expressed as the moisture content of the product, is based on Fick's second law of diffusion (equation 2)

$$\frac{\partial X_w}{\partial t} = \frac{D \cdot \partial^2 X_w}{\partial x^2}$$

where X_w is the moisture content of the product (kg water·kg dry matter^{-1}), t as the time (s), D as the effective diffusion coefficient (m^2·s^{-1}) and $\boldsymbol{x}$ as the diffusion length (m), the half thickness of a slice.

The integration of the differential diffusion equation is approximated by Crank (1979) as equation 3 and used by numerous authors (Gekas and Lamberg 1991; Doymaz 2004; Srikiatden and Roberts 2007):

$$X_w(t) = \sum_{p=0}^{b} \frac{8}{\pi^2} \cdot (X_0 - X_e) \left[\cdot \frac{1}{(2p+1)^2} \cdot e^{-(2p+1)^2 \cdot \pi^2 \cdot \frac{D \cdot t}{\lambda^2}} \right] + X_e \qquad 3$$

with $X_e(t)$ the equilibrium moisture content of the product at the end of drying and X_0 at the beginning (kg water·kg dry matter^{-1}), $\lambda(t)$ as the half thickness of the slice (m). At longer drying times, b=0 is accurate enough to predict the average moisture content in the end product (Liu, Chen et al. 2012).

Equation 3 is valid under the following conditions:

- initial product moisture content is uniform;
- the slice is infinite and moisture transfer is one-dimensional;
- volume and diffusion coefficient are constant.

These assumptions are often violated by authors because of practical reasons but this still gives decent results. During this research, the drying trajectory was regarded as consisting of several pieces of dt, under constant conditions (diffusion coefficient, slice thickness and equilibrium moisture content). To balance the violation of the first assumption with the flexibility of the system to variable conditions, dt was chosen to be large (1 hour). In this way, the drying model is sensitive to changes in the environment (air temperature and moisture content) and drying induced product changes (shrinkage). X_0 in equation 3 was replaced by $X_w(t-1)$, t by dt and b=90. The equation is than more accurately written as in equation 4, with time dependent variables.

$$X_w(t) = \sum_{p=0}^{b} \frac{8}{\pi^2} \cdot \left(X_w(t-1) - X_e(t) \right) \cdot \left[\frac{1}{(2p+1)^2} \cdot e^{-(2p+1)^2 \cdot \pi^2 \cdot \frac{D(t) \cdot dt}{\lambda(t)^2}} \right] + X_e(t) \qquad 4$$

$$dX_w(t) = X_w(t) - X_w(t-1)$$

Shrinkage

The drying behaviour of a slice is dependent on the distance the water has to diffuse, i.e. the slice thickness. Slice thickness λ (m) changes based on volume (Gekas and Lamberg 1991) according to equation 5.

$$\lambda(t) = \lambda(t-1) \cdot \left(\frac{V(t)}{V(t-1)} \right)^{\frac{1}{d}} \qquad 5$$

with fractal exponent d (-), λ_0 as the slice thickness at the start (m), V as the volume and V_0 as starting volume of the slice (m^3). The fractal exponent d is assumed to be constant with $t=t_{end}$, and is based on experimental results of start and end measurements of slice volume and thickness after drying (Gekas and Lamberg 1991), equation 6.

$$d = \frac{log\frac{V_0}{V(t)}}{log\frac{\lambda_0}{\lambda(t)}} \qquad 6$$

The volume of the slice is needed to determine the thickness and is assumed to consist of water, air and solids. The volume fraction of solids is assumed constant since dry matter will not disappear during a mild heat treatment and at the start, no air is present (Perez and Calvelo 1984). Combining this information, expressed as equation 7, 8 and 9:

$$V(t) = V_w(t) + V_s + V_a(t) \qquad 7$$

$$V_w(t) = \frac{X_w(t) \cdot M_0}{\rho_w} \qquad 8$$

$$V_0 = V_s + V_{w0} \qquad 9$$

$$V_s = V_0 - \frac{X_0 \cdot M_0}{\rho_w} \qquad 10$$

gives the change in volume of a slice, expressed as in equation 11

$$dV(t) = \frac{dX_w(t)}{\rho_w} \cdot M_0 + dV_a(t) \qquad 11$$

where V_w, V_s, $V_a(t)$, V_{w0} , V_0 are respectively the volume of water, solids, air, water at the start and total volume at the start of a slice (m3). M_0 is the starting weight of the slice (kg) and ρ_w the density of water (kg·m^{-3}). Air volume was assumed to increase with decreasing product moisture content until a maximal value (equation 12).

$$dV_a(t) = n_{shrinkage} \cdot V_0 \cdot \left(\frac{-dX_w(t)}{X_0}\right) \qquad 12$$

This value was obtained from experimental data and used to calculate the shrinkage factor (equation 27), which can be found in the nomenclature.

$$n_{shrinkage} = \frac{V_0 - V_{end}}{V_0} \qquad 13$$

Diffusion

The effective diffusion coefficient used in equation 4 is dependent on the volume, as shown in equation 14 (Gekas and Lamberg 1991).

$$D(t) = D_{ref}(t).\frac{V_0}{V(t)}^{-\frac{2}{d}} \tag{14}$$

The reference diffusion coefficient $D_{ref}(t)$ ($m^2 \cdot s^{-1}$) is temperature-dependent according to the Arrhenius equation (equation 15) (Srikiatden and Roberts 2007; Amankwah, Dzisi et al. 2014):

$$D_{ref}(t) = D_0 \cdot e^{-\frac{E_a}{R \cdot T_{a,p}(t)}} \tag{15}$$

where D_0 is the diffusion constant ($m^2 \cdot s^{-1}$), R the universal gas constant ($kJ \cdot mol^{-1} \cdot K^{-1}$) and $T_{a,p}(t)$ the drying temperature (K), measured just above the surface of the slice. The activation energy E_a ($kJ \cdot mol^{-1}$) was obtained from Srikiatden and Roberts (2007), who investigated drying potato slices with similar geometry. Values of the used parameters can be found in the nomenclature. D_0 was used as an adjustable parameter to fit the model to experimental data.

Air properties

The concentration of moisture in the outgoing air is described by a mass balance over the dryer (equation 16), assuming steady state because moisture uptake by the air is much faster than the drying rate (Jin, van der Sman et al. 2014).

$$F_a \cdot \left(X_{a,in}(t) - X_{a,out}(t)\right) + M_{dm} \cdot \frac{dX_w}{dt}(t) = 0 \tag{16}$$

In the mass balance, F_a symbolizes the airflow over the slices ($kg \cdot s^{-1}$), $X_{a,in}(t)$ and $X_{a,out}(t)$ the moisture content in the air going in and out of the dryer (kg water·kg dry air), M_{dm} is the weight of dry matter in the dryer (kg) and $\frac{dX_w}{dt}(t)$ (kg w·kg $dm^{-1} \cdot s^{-1}$) the rate of water lost by the product. Values can be found in the nomenclature.

The GAB model (equation 17) provides the equilibrium moisture content $X_e(t)$ that is used in the diffusion equation (4). Amankwah, Dzisi et al. (2014) determined C_1, C_2, C_3 for the drying of yam at 50 °C (values in nomenclature), assuming $X_e(t)$ is temperature

$$X_e(t) = \frac{C_1 \cdot C_2 \cdot C_3 \cdot RH(t) \cdot (1 - C_2 \cdot RH(t))}{1 - C_2 \cdot RH(t) + C_2 \cdot C_3 \cdot RH(t)} \cdot \frac{1}{100} \tag{17}$$

independent.

$X_e(t)$ is the moisture content of the product after infinitely long drying at the specific relative humidity (RH) of the air. $X_e(t)$ is therefore not constant but dependent of $RH(t)$ (%), which is again dependent on temperature.

The temperature of the outgoing air was calculated with the help of an enthalpy balance over the slice (equation 18).

$$F_a \cdot \begin{pmatrix} C_{pv} \cdot \left(X_{a,in}(t) \cdot T_{in}(t) - X_{a,out}(t) \cdot T_{a,p}(t)\right) \dots \\ +C_{pa} \cdot \left(T_{in}(t) - T_{a,p}(t)\right) + \Delta H_{vap} \cdot \left(X_{in}(t) - X_{out}(t)\right) \end{pmatrix} \dots$$
$$-C_{pp}(t) \cdot M_{p,f}(t) \cdot \frac{dT_p}{dt}(t) = 0 \quad (18)$$

The enthalpy balance takes into account both the heat needed to evaporate the water in the product and the heat to heat the product. $T_{a,p}(t)$ is the temperature of the air just above the surface of the slice, which is also the temperature used to calculate the diffusion coefficient (equation 15) and degradation rate constant (equation 23). With $T_{in}(t)$ as the temperature of the ingoing airflow (K), heat capacity of air, vapour (at 50 °C) and product C_{pa}, C_{pv} and $C_{pp}(t)$ and latent heat of evaporation ΔH_{vap} (Kessler 1996). Values can be found in the nomenclature.

To calculate the temperature of the air, also the heat capacity of the product $C_{pp}(t)$ must be known. Heat capacity of vegetables is mainly a function of moisture content, which is changing during drying. The Ashare relation (equation 19) was used to calculate the heat capacity of yam (Oniţa and Ivan 2005),

$$C_{pp}(t) = 1.675 \cdot F_{fat} + 0.8374 \cdot F_{non-fat}(t) + 4.1868 \cdot F_{water}(t) \quad (19)$$

with fraction F_{fat} =0 and $F_{non-fat}(t)$=1-$F_{water}(t)$.The conversion from moisture content (kg·kg dry matter^{-1}) to water fraction (kg·kg^{-1}) was done with equation 20.

$$F_{water}(t) = \frac{X_w(t) \cdot M_{dm}}{M(t)} \quad (20)$$

Where $M(t)$ is the current mass of the product (kg). The calculated heat capacities at high and low moisture content are very similar to that of tabulated values of peas, being 3.07 and 1.17 kJ·kg^{-1}·K^{-1} respectively (EngineeringToolbox 2014).

The product temperature in the simulations (not in the describing-model, where measured data was used) was estimated according to equation 21.

$$\frac{dT_p}{dt}(t) = \frac{0.1}{dt} \cdot \left(T_{a,p}(t) - T_p(t)\right) \quad (21)$$

The product temperature slowly approaches towards the temperature of the air just above the slice, estimated as 10% of the temperature difference per second. A rough estimation of product temperature was sufficient; the influence of heat transfer from the air to the product is minimal (lowering air temperature between 0.1 and 0.3 °C depending on temperature difference). This was found by neglecting the last term in the enthalpy balance over the slice, the heat transfer to the product.

Vitamin C degradation

The vitamin C content in the product depends on moisture content, time and temperature. Kinetics are well described by both Mishkin, Saguy et al. (1984) and Mishkin, Saguy et al. (1983), the latter one was used during this research because it describes a lower rate of degradation. This is more applicable to plant materials since degradation is often lower than in model systems, the structure of the material and other components present have a protective effect on degradation kinetics (Jin, Oliviero et al. 2014). The reaction follows first-order kinetics and is described by equation 1, the degradation rate constant is described by equation 23:

$$\frac{dC}{dt} = -k_{Vc}(t) \cdot C(t) \qquad (22)$$

$$\begin{aligned} ln\, k_{vc}(t) = a_1 \cdot F_{water}(t) + a_2 \cdot T_{a,p}(t)^{-3} + a_3 \cdot F_{water}(t)^3 + a_4 \\ \cdot F_{water}(t)^2 \cdot T_{a,p}(t)^{-1} + a_5 \cdot F_{water}(t) \cdot T_{a,p}(t)^{-2} + a_6 \\ \cdot F_{water}(t)^3 \cdot T_{a,p}(t)^{-3} + a_7 \end{aligned} \qquad (23)$$

where $C(t)$ is the concentration of vitamin C (%), $k_{Vc}(t)$ the degradation rate constant of vitamin C (s^{-1}) and parameters a_1 to a_7 as in the nomenclature.

Simulations

The simulations were used to obtain results on moisture, vitamin C content and drying time. The product was defined dry when the moisture content was below 0.1 kg w·kg dry matter^{-1}.

Solar dryer trajectory

The first simulation was used to mimic the solar dryer used by Amankwah et al., located in Ghana. The data of the temperature inside the solar dryer were obtained from Amankwah, Dzisi et al. (unpublished) and was assumed to be 22 °C between 6 PM and 6 AM, equal to the ambient temperature after sunset. The temperature course is depicted in Figure 4.

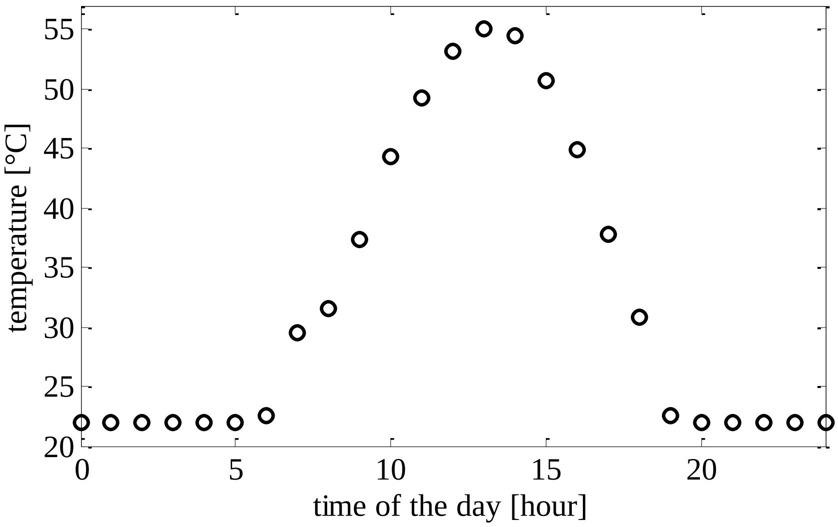

Figure 4: temperature course inside the solar dryer during 24 hours

The absolute moisture content of the air was assumed to be 12 g water·kg air^{-1}, corresponding to ambient conditions of 80% RH at 22 °C. With the absolute moisture content and temperature, the RH could be calculated which is needed to obtain equilibrium moisture content X_e(kg w·kg dm^{-1}) in equation 17. The temperature and calculated RH data are repeated every 24 hours until the product is dry, simulating a solar dryer.

Since Ghana is relatively close to the equator, there is only a small difference in solar hours and weather conditions, making the assumed moisture and temperature assumption reasonable for drying through the whole year. Keeping in mind the area with degradation rate constant (Introduction, Figure 1), it was suspected that solar drying starting hour could influence vitamin C retention. Therefore, this simulation was used to explore what would be a good starting point and what would be the worst moment to start drying. These temperature trajectories were tested in the experimental work as 'OptiSolar' and 'PoorSolar', respectively.

Random trajectory

When searching for the best drying trajectory that can be used in the future, an idea is to create a large number of possible trajectories and evaluate which one is best. A random path of the temperature profile was created based on the previous knowledge that:

- Temperature should start low (22 °C) since fresh yam is already in the hazardous area (Introduction, Figure 1).Temperature can only increase or stay the same. This can be concluded from the degradation contour lines in Figure 1.
- (Introduction), assuming shorter drying times are preferable to longer ones. This assumption is not applicable to vegetables with high moisture content.
- Temperature can never be outside the practical range of the solar dryer, between 22 and 60°C.

The random trajectory was created with the idea that the temperature at a certain time could be 0°C ,1°C or 2°C higher than the previous hour. Absolute moisture content of the air was kept constant and an example of the trajectories can be seen in Figure 5.

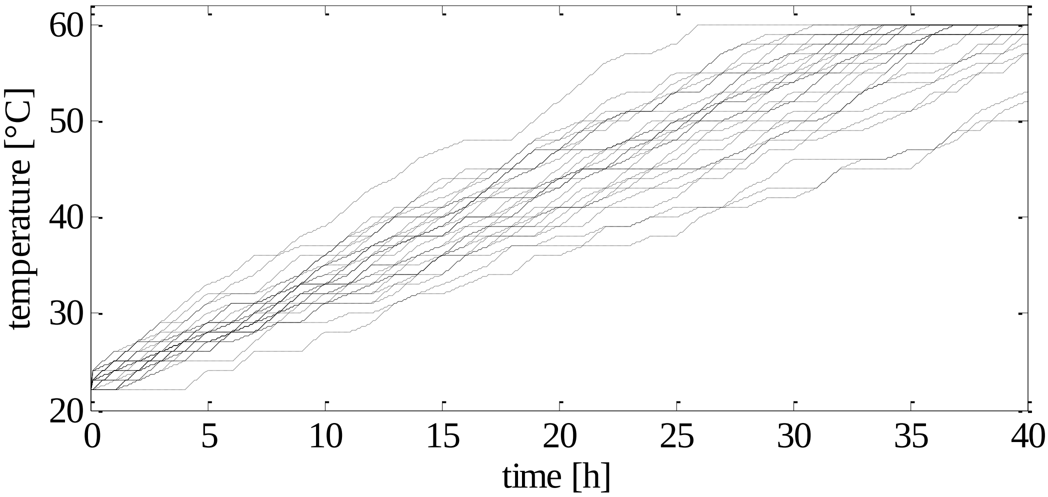

Figure 5: Example of 3000 randomly generated trajectories

All trajectories start at 22°C and diverge to various temperatures at the end. A complete drying trajectory consisted of maximally 40 hours, meaning $3^{40} \approx 10^{19}$ possible configurations. Due to limited computational memory, the number of random trajectories was restricted to 10^4. A cost function (equation 24) was set up to evaluate the results, being vitamin C content $C(t)$ and drying time.

$$cost = \left(\frac{t_{drying}^{min} - t_{drying}}{t_{drying}^{max} - t_{drying}^{min}}\right)^2 + \left(\frac{C_0 - C(t)}{C(t)^{max} - C(t)^{min}}\right)^2 \quad (24)$$

Drying time t_{drying} is defined as the time until the product reaches a moisture content of 0.1 kg water·kg dry matter^{-1}; only fully dried products were taken into account. Both were normalised by the difference between lowest and highest value of all trajectories evaluated, this expresses each outcome relative to the results of the other trajectories. It has the advantage that the maximal allowed drying time (40 hours) does not influence the cost optimisation, since most trajectories finish before that time. Since the costs are squared, the importance of small differences in costs is enlarged. With this formula, drying time and vitamin C retention costs are both reasonably well dispersed between 0 and 1 and no weight factor is needed.

Optimal drying trajectory

Based on findings on the drying of broccoli, the optimal drying temperature trajectory for vitamin C and energy consumption is displayed in the figure below. Boundary conditions used to create this optimal trajectory are temperature and time; between 30 and 60 °C and within 10 hours.

The optimal temperature trajectory proposed by van Olst (2013) (Introduction, Figure 2) is also applicable to the drying of yam, since it was assumed that vitamin C is the most vulnerable compound during both broccoli and yam drying. Figure 2a and b (Introduction) can be combined to form a relation between optimal drying temperature and product moisture content, seen in Figure 6.

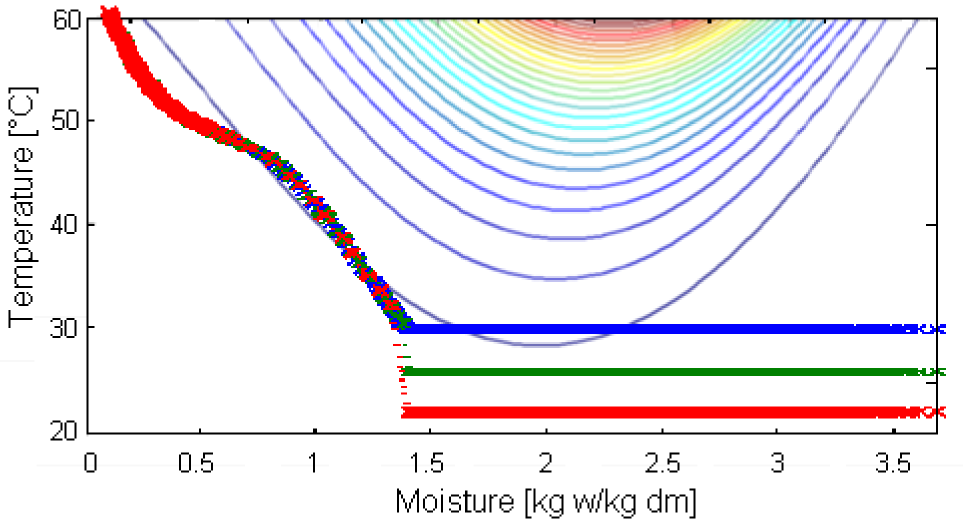

Figure 6: Original optimal drying trajectory (top, blue) and trajectories with lowered temperature boundary. Contour lines indicate degradation constant, warmer colours indicate a higher k_{Vc}.

The displayed contour lines indicate the vitamin C degradation constant as in Figure 1 (Introduction) which makes it easy to compare the trajectory of van Olst to the one from Jin et al. (2014). Above a moisture content of 1.4 kg·kg dm^{-1}, optimal drying temperature was equal to the lower boundary condition of 30°C. Below a moisture content of 1.4 kg·kg dm^{-1}, drying temperature was described by a polynomial, displayed in equation 25.

$$T_{in}(t) = 40.25 \cdot X_w(t)^4 - 143.41 \cdot X_w(t)^3 + 166.07 \cdot X_w(t)^2 - 89.112 \cdot X_w(t) + 68.156 \quad (25)$$

This relation makes it possible to apply the optimal drying trajectory to yam, which has a different structure and therefore drying behaviour. The temperature constraints used by van Olst are also reasonable assumptions for the solar dryer: it cannot reach much higher temperatures than 55 °C and ambient temperature in West-Africa is minimally 22°C. Since it is probable that lower temperatures during the first drying period are advantageous for vitamin C retention, the trajectory was therefore also modelled with a minimum of 26 and 22 °C (Figure 6, green and red). This of course increases drying time.

Experimental work

Sample preparation

Yam tubers from the specie *Dioscorea rotundata* variety 'Dente' were purchased from a retailer in Wageningen, October 2014. The tubers were sliced to exactly 1.0 cm thick to ensure homogeneous drying behaviour, this was done with an automatic slicing machine (Bosch Snijmachine MAS6200N). Slices were examined on colour and when no dark spots were visible, cut to 3x3cm squares without any peel.

A batch of ±170 grams of yam was used for each drying experiment. The drying apparatus used convective hot air to dry products and is described previously by Atuonwu et al. (2013). This apparatus can simulate a solar dryer because of the adjustable airspeed and temperature, but not humidity. A heater heats up the ingoing air which flows into a chamber with a 20x20 cm drying tray. The tray is a flat mesh, allowing the air to flow freely along the drying slices. It is connected to an analytical balance (placed on top of the dryer cabin) measuring weight loss. A thermocouple inserted in the middle of the slice measured the product temperature. Air flow and temperature were continuously controlled by a feed-back mechanism of PID controllers, connected to flow and temperature sensors shortly after the air valve and heater, respectively. The temperature is controlled by a thermocouple measuring air temperature just above the slice (3 mm); this is the assumed drying temperature. The airflow is kept constant at 0.0243 kg air·second^{-1}. All data was logged every 2 seconds by an Agilent34970A data logger.

Slices were put flat in the dryer tray, with ±2 cm space in between. Figure 28 shows the drying tray with yam slices and Figure 27 the dryer used (Appendix C).

Treatments used were:

- fresh yam: unprocessed piece of yam without peel, directly analysed after cutting
- room temperature: dried at 22 °C until constant weight
- OptiSolar: dried for 24 hours according to the temperature course in a solar dryer according to Amankwah, Dzisi et al. (unpublished) with the optimal starting time, regarding vitamin C retention.
- PoorSolar: dried for 24 hours according to the temperature course in a solar dryer according to Amankwah, Dzisi et al. (unpublished) with the worst starting time, regarding vitamin C retention.
- open sun drying: The drying trajectory used during traditional open sun drying was obtained E. Amankwah and was based on measured data of air temperature during five days (100 hours). During the night, no temperatures are measured and it is assumed to be linear between the last night and first day measurement. The slices were wrapped in foil in this time since this is also common practice in the traditional way.

It is important to note that during all treatments, only the temperature was adapted and not the humidity, since this was not possible in practice. After drying treatment, the sample was ground to flour with a hammer and used for colour measurement and vitamin C determination. The fresh yam was grated and directly analysed for vitamin C content, colour measurement was done on an intact slice.

Product properties

The density and moisture content of the fresh product and the shrinkage factor of the dried product were measured.

Density

The density of the raw material was determined by measuring the weight and dimensions of a slice. The square was weighed as fast as possible to prevent water evaporation. The density of the sample is calculated according to equation 26, with M_{slice} in kg and V_{slice} in m^3. Measurement was done in triplicate.

$$\rho_{yam} = \frac{M_{slice}}{V_{slice}} \tag{26}$$

Moisture content

The moisture content of the raw material was measured by drying a slice in a vacuum oven at 105 °C for 24 hours. The sample was weighed before and after drying.

Shrinkage

The shrinkage of the slice was calculated by measuring the dimensions of a slice before and after drying and following equation 27.

$$n_{shrinkage} = \frac{V_0 - V_{end}}{V_0} \tag{27}$$

The volume of a slice was calculated by assuming rectangular shape and the experiment was repeated 5 times. It was assumed that all drying strategies result in the same amount of shrinkage, e.g. volume of air incorporated in the slice.

Colour measurement

The colour of the samples was determined by the CIE 1976 L*a*b* (CIELAB) colour scale with illuminant D65 and light observer at an angle of 10°. This colour scale was chosen because it has higher sensitivity in the yellow range and is widely used, also in previous work on yam. The flour sample was poured into a glass container of ±4 cm diameter, pressed to 2 cm height to avoid air spaces and covered with a lid. Also the fresh solid yam was analysed by the chromameter by cutting it into exact dimensions fitting in the glass container. The procedure was repeated in duplicate for each yam sample. The sample name and L*a*b* values were recorded.

Vitamin C determination

Vitamin C was extracted from 5 grams of sample with 15 ml 3% metaphosphoric acid (MPA) during one hour of incubation in a shaking machine at room temperature, under reduced light (Hernández, Lobo et al. 2006; Nojavan, Khalilian et al. 2008). MPA and reduced light are used to stabilise the vitamin C, which is very vulnerable to degradation. After centrifugation at 3000 rpm for 15 minutes, 0.5 ml of 2 mol·l^{-1} sulphuric acid, 2 ml of 100 g·l^{-1} potassium iodide (KI) and 2 ml of 1 g·l^{-1} starch solution were added. The sample (analyte) was titrated with 2·10^{-5} mol·l^{-1} potassium iodate (KIO_3) (titrant) using an automatic titrating machine until the colour changed from slightly yellow to brownish, indicating that all the vitamin C in the sample has reacted. All measurements were done in duplicate. Concentration of vitamin C (g·g dm^{-1}) was calculated as in equation 27, with $V_{titrant}$ as the volume of titrate added (l), $C_{titrant}$ as the concentration of potassium iodate (mol·l^{-1}), N as the reaction ratio (mol· mol^{-1}) between vitamin C and potassium iodide, MW_{Vc} as the molecular weight of vitamin C and M_{sample} as the mass of sample used for the experiment (g) (values in the nomenclature). A correction was made for the difference between volume of extract added $V_{extract}$ (l) and volume of extract used for determination $V_{analyte}$ (l). This was done to correct for the difference in moisture content between the samples; the fibrous material of the dried yam retained a lot of liquid from the extract.

Data collection

Data obtained from the data logger included the humidity and temperature of the incoming air, the weight of the product on the drying tray, the product temperature, the temperature of the air just above the slice, and the airspeed. The results from the density, moisture content, shrinkage measurements were used for the model and simulations described before. For the describing-model, all data points for temperature and moisture of the ingoing air and weight of the sample were recorded and used. To compare the describing model to the experiments, the moisture content and temperature of the outgoing air and product temperature were recorded. With the use of Excel (2010), the data from the data logger was adapted and the absolute moisture content of the air X_a (g water·g dry air^{-1}) calculated using the Antoine equation (equation 28) and psychrometric calculation (equation 30) (Kessler 1996). The Antoine equation is used to calculated the saturated vapour pressure of water P_{sat} valid between 1 and 100 °C with values for A, B, C and P_T as in the nomenclature, temperature T in °C and $P_{H_2O} = \frac{RH}{100}$ (DDBST 2014). To convert from mm Hg to kPascal, the saturated vapour pressure is divided by a conversion factor (equation 29).

$$log_{10} P_{sat} = \left(A - \frac{B}{C + T}\right) \quad mm\,Hg \tag{28}$$

$$P_{sat} = \frac{10^{log_{10} P_{sat}}}{7.500616} \quad kPa \tag{29}$$

$$X_a = \frac{MW_{H_2O}}{MW_{air}} \cdot \frac{P_{H_2O}}{P_T - P_{H_2O}} \tag{30}$$

Results

Simulations

Solar dryer trajectory

By running the model according to the temperature profile of the solar dryer, a final result in vitamin C content and drying time were obtained. Since drying continued until a set moisture content of 0.1 kg w·kg dm^{-1}, all products were equally dry. The value for D_0, E_a and other properties of yam and slices are stated in the nomenclature. The initial moisture content of the product was variable and indicated in the results.

Figure 7 shows the influence of starting hour (the moment the slices are cut and put into the solar dryer) on the vitamin C content of the dried product.

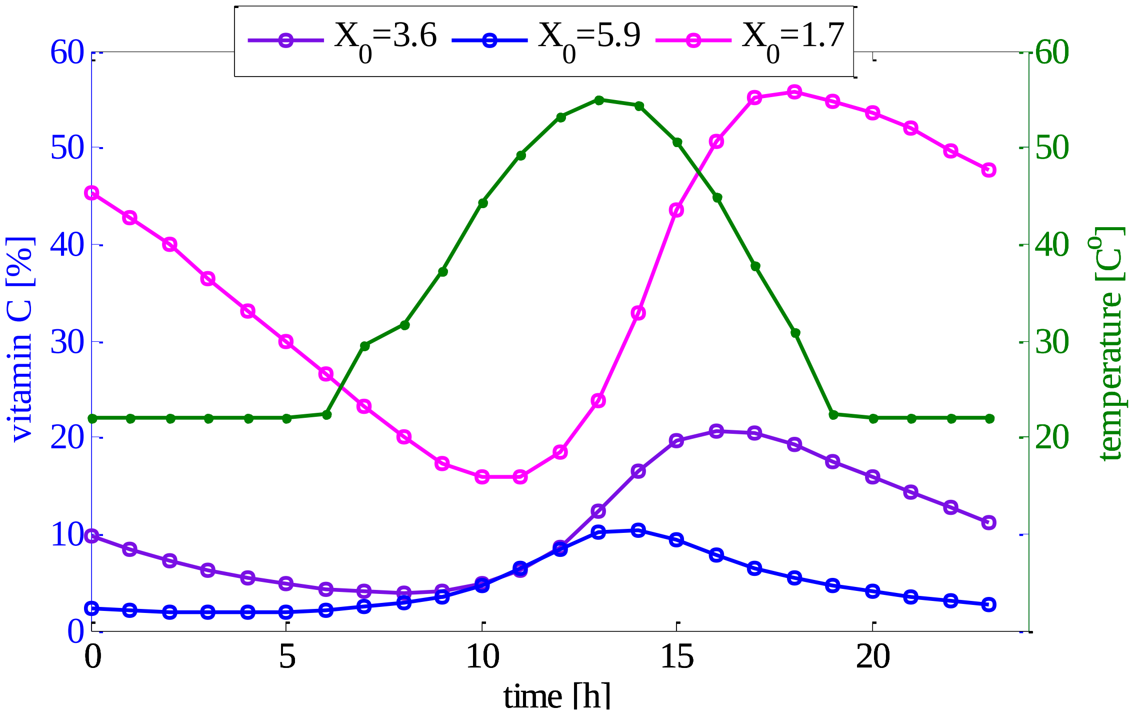

Figure 7: Left y-axis: Simulated vitamin C content of the final product, depending on the moment solar drying is started (x- axis). This is shown for products differing in initial moisture content X_0(kg w·kg dm^{-1}). Right y-axis: Internal temperature of the solar dryer over the course of a day.

The pink line represents yam as used in the practical experiments of this research, it can be seen that vitamin C retention is much higher when drying is started in the evening than in the morning. With this information, the optimal starting time was defined as 5 PM and the worst starting time as 11 AM. The temperature courses resulting from these starting times were used in the drying treatments OptiSolar(1,2) and PoorSolar, respectively. It can be seen that a higher moisture content of the fresh product (comparing the pink, purple and blue line) only results in lower vitamin C retention and have roughly the same optimal starting time. Of course, the drying time needed for these products also differ (not shown in Figure 7).

Because temperatures in a solar drying trajectory are repeated every 24 hour cycle (as shown by the green line in Figure 7) the drying time determines the exposure to high temperatures. Products with a high moisture content require a much longer drying time and follow the temperature course of the day (green line, Figure 7) more than once. This was depicted in Figure 8, where the trajectories travel through or circumvent the vitamin C degradation area.

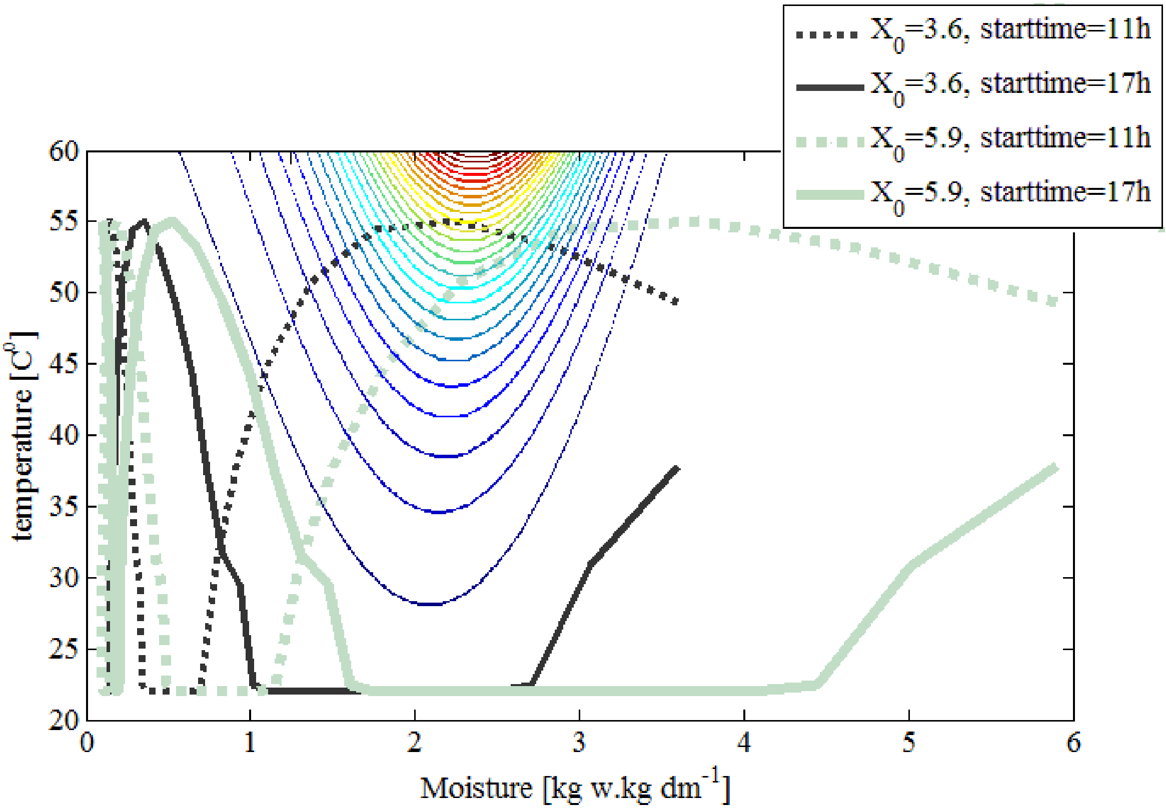

Figure 8: Solar drying trajectories in a state diagram for two initial moisture contents and starting times.

The vitamin C retentions of the four trajectories are respectively 4, 21, 2, 10 %, in order as mentioned in the legend. The lines visualise what happens, the trajectory with an initial moisture content of 3.6 kg w·kg dm^{-1}, starting at 11 o'clock directly crosses the contour lines that indicate high degradation rates and also result in a very poor retention.

Figure 8 shows that at a moisture content X_w of 2 kg w·kg dm^{-1}, the drying trajectory is nearest to the degradation contour lines. The temperature at this moisture content is critical for vitamin C retention in the final product. Figure 26 (Appendix B) shows a correlation between a low temperature at X_w=2 and high vitamin retention. Also, it shows that this critical moisture content should be reached in the evening, which is the same as in Figure 7.

Also products with higher initial moisture content X_0 have the same optimal temperature at this critical moisture content, but lower overall vitamin C retention. Figure 7 also shows the effect of initial moisture content, the optimal time to start solar drying slightly shifts backward for higher moisture content.

Random trajectory

The simulation using random temperature trajectories resulted in a large amount of end products with each a different drying time, vitamin C content and temperature course followed. Figure 9 shows the moisture decrease according to the trajectories, the temperature course and the final drying time that is the result of the trajectories in Figure 5. The meaning of the colours will be clarified later.

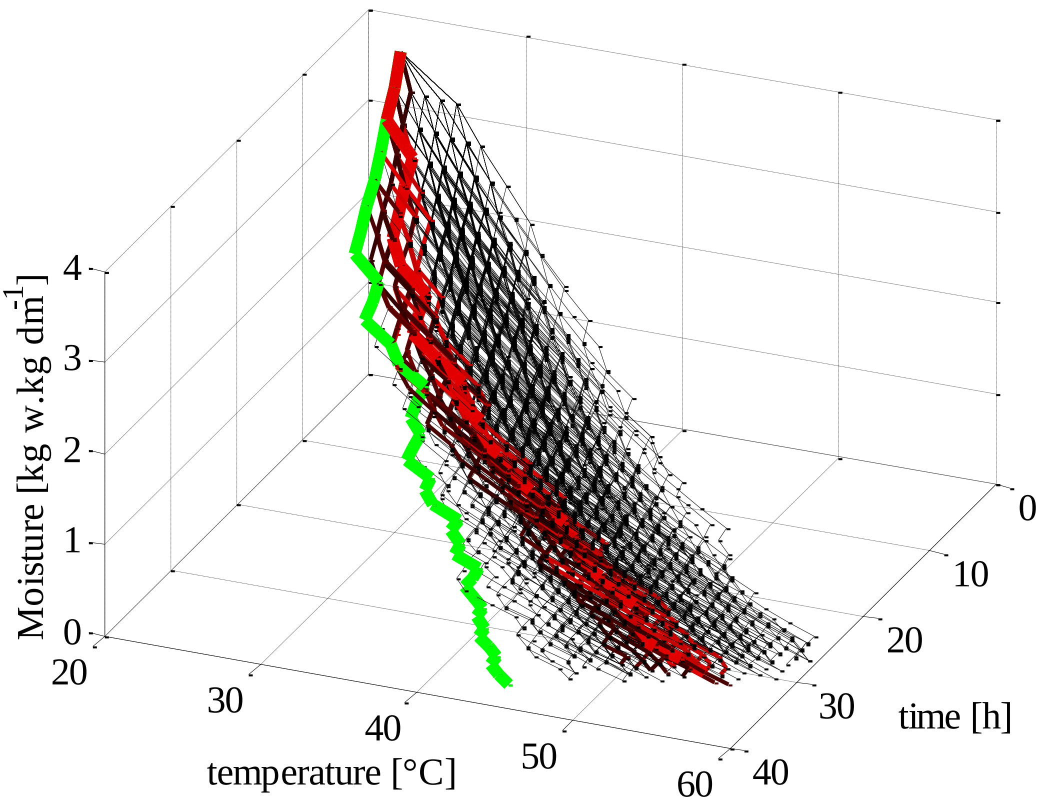

Figure 9: Randomly generated drying trajectories depicted in a state diagram. Intensity of red colour indicates low total costs, green line indicates trajectory with highest final vitamin C content, X_0=3.6 kg w·kg dm^{-1}.

Since the drying in the model is terminated as soon as the moisture content is below 0.1 kg w·kg dm^{-1}, this is the final moisture content of most of the results. The trajectories of fully dried products can be recognised in the figure by lines with an ending before the final time (40 hours), in the case of Figure 9 all trajectories. Together, these lines form a Pareto like area below which no final product can exist, the high-temperature-long-time corner on the bottom of Figure 9.

With the cost function in equation 24, costs for all drying trajectories were calculated and compared in Figure 10.

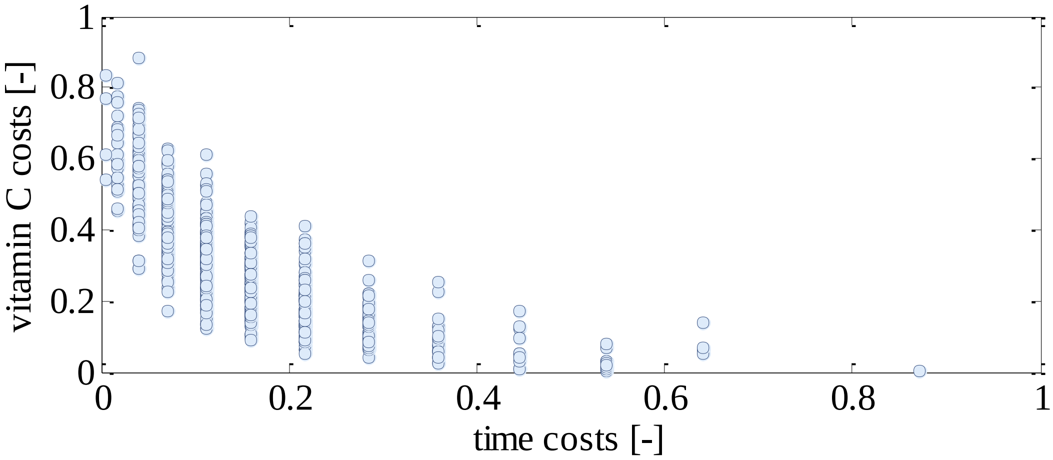

Figure 10: Vitamin C costs vs time costs of randomly generated trajectories, X_0=3.6 kg w·kg dm^{-1}.

Because dt is relatively large, the drying end point of each trajectory can only occur at fixed intervals. This resulted in trajectories with equal time costs but different vitamin C costs, in the figure recognised as vertical bands. Figure 10 also shows that vitamin costs and time costs were both equally dispersed, meaning their weight in the cost function (equation 24) is similar.

A negative correlation can be seen between vitamin and time costs, shorter drying trajectories appear to result in higher vitamin degradation. This can be explained by the fact that shorter drying trajectories require higher temperatures at some point in time, which increases vitamin degradation rate.

The bottom left corner of Figure 10 is the optimal situation, the trajectories closest to this are the best tested. The followed trajectories to obtain these two best results are shown in Figure 9. The best drying trajectory according to total costs (bright red) and with the highest vitamin C content in the final product (green) have a somewhat different trajectory (Figure 9, Figure 12). Both trajectories follow a low temperature course in the first drying period. The costs-optimal trajectory increases earlier in temperature, reaches higher temperatures at the end and is also finished several hours earlier than the vitamin C optimised trajectory. The exact vitamin retention of these trajectories can be seen in Figure 11.

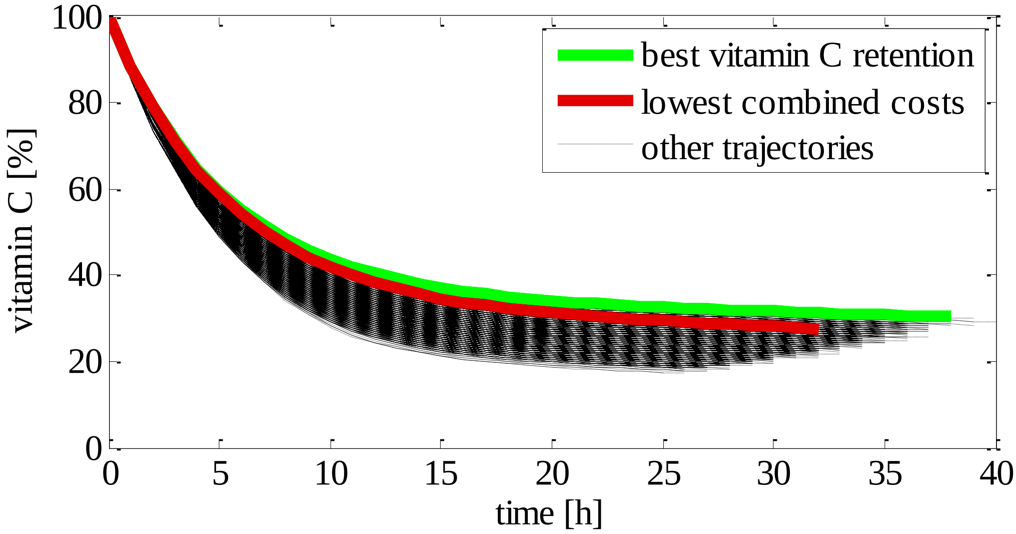

Figure 11: Vitamin C concentration during drying according to the random trajectories, X_0=3.6 kg w·kg dm^{-1}.

Although there is a significant difference in trajectory between the red and green line, the vitamin C retention is relatively similar (27.6% and 30.3%). By accepting an additional reduction in vitamin C content of 2.7%, a time reduction of 6 hours can be reached. This shows the cost optimisation is a very useful tool to decide what trajectory needs to be followed.

Optimal drying trajectory

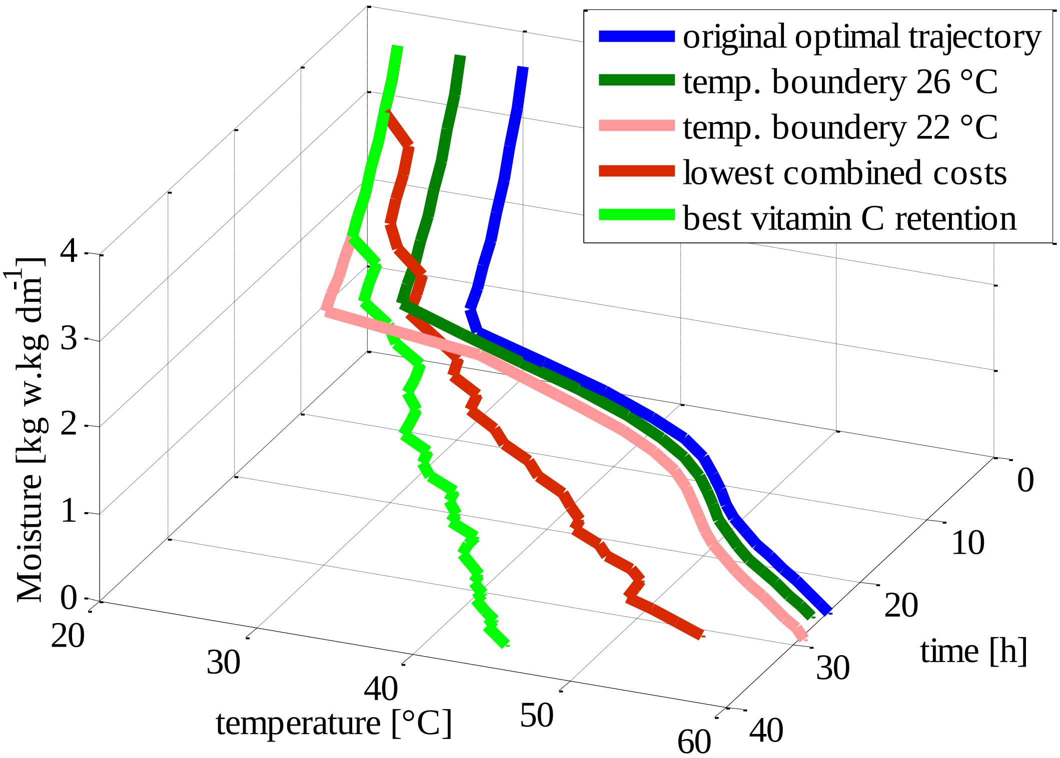

Figure 12: Original optimised drying trajectory, its modified versions and the best trajectories of the random generation method. Displayed in a state diagram, with X_0=3.6 kg w·kg dm^{-1}. Vitamin C retentions were 18, 22, 26, 28 and 30% (in order as displayed in the legend).

Figure 12 shows the optimal drying trajectories (original and with modified temperature boundaries of 26°C and 22°C), combined with the two best trajectories obtained from the random generation method.

The drying time of the original optimal trajectory and with lowered temperature boundary is 27, 28 and 30 hours respectively. This is a bit shorter than the lowest combined costs trajectory, which took 32 hours.

The original optimal drying trajectory, introduced earlier and displayed in Figure 12, gave a vitamin retention of 17.7% when drying a product with initial moisture content X_0=3.6 kg w·kg dm^{-1}. The trajectories with lower temperature boundary resulted in vitamin retention of 21.9% and 26.0%, the lowered boundary temperature effectively increased vitamin C retention.

The vitamin C retention of all optimised trajectories was lower and drying time shorter than in the lowest cost trajectory from the random trajectory method. This fits in the result of Figure 10, there is a trade-off between high vitamin retention and reduced drying time. The difference in best trajectory can be explained by a difference in objective: although in both this thesis and the thesis of van Olst (2013) vitamin C content is optimised, van Olst (2013) optimised his trajectory also on energy efficiency and this research on time efficiency. Also the weight of the respective cost functions determine the optimal trajectory.

Experimental work

The two yams used during the experiments were not completely comparable, although purchased at the same time from the same source. This might be due to the longer storage time or a difference in starting quality. The moisture and vitamin C content of the two fresh yams used were measured and used in the model and calculations. The dimensions, density and shrinkage factor were assumed constant or of negligible influence on drying and degradation kinetics. The initial density, water and vitamin C content and the shrinkage factor are displayed in Table 3, Appendix A and used in the model and calculations.

Treatments used were:

- fresh yam: unprocessed piece of yam without peel, directly analysed after cutting
- room temperature: dried at 22 °C until constant weight
- OptiSolar: dried for 24 hours according to the temperature course in a solar dryer according to Amankwah, Dzisi et al. (unpublished) with the optimal starting time, regarding vitamin C retention.
- PoorSolar: dried for 24 hours according to the temperature course in a solar dryer according to Amankwah, Dzisi et al. (unpublished) with the worst starting time, regarding vitamin C retention.
- open sun drying: dried for 100 hours according to the traditional method, meaning at the ambient temperature course of the day (Amankwah 2014).

Water diffusion constant

The value for the diffusion constant D_0 ($m^2 \cdot s^{-1}$) is based on the D_0 of all treatments that gave the best visual fit. From the open sun treatment, only the first drying period was representative of drying rate since the model could not take into account the effect of the wrapping foil that was applied during the night. Table 2 shows the best diffusivity constant for each treatment, for the activation energy provided by both Srikiatden and Roberts (2007) (for potato) and by Amankwah, Dzisi et al. (2014), for yam.

Table 2: Best diffusion constant for each treatment, for two values of activation energy E_a

D_0 ($m^2 \cdot s^{-1}$)	$\cdot 10^{-7}$	$\cdot 10^{-4}$
Activation energy ($J \cdot mol^{-1}$)	**23610**	**44060**
OptiSolar1	4.8	7
OptiSolar2	4.5	8
Room temperature	1.2	5
PoorSolar	6.5	15
Open sun	6.6	6

Although D_0 is in theory temperature independent, there is quite some difference between best values for the different drying treatments, for both values of activation energy. During this research, E_a=44060 $J \cdot mol^{-1}$ and D_0=$8 \cdot 10^{-4}$ $m^2 \cdot s^{-1}$ were used for all treatments and simulations.

Values for the effective diffusion coefficient D ($m^2 \cdot s^{-1}$) is in literature estimated as $5 \cdot 10^{-10}$ at 40 °C, $8 \cdot 10^{-10}$ at 60 °C for potato drying(Srikiatden and Roberts 2007), $6 \cdot 10^{-10}$ at 40 °C, $11 \cdot 10^{-10}$ at 60 °C (Srikiatden and Roberts 2007) or $5.5 \cdot 10^{-9}$ at 60 °C (Liu, Chen et al. 2012) for carrot drying, ±$2.2 \cdot 10^{-10}$ at 40 °C for broccoli drying (Jin, van der Sman et al. 2014) and $5 \cdot 10^{-11}$ for yam drying (Amankwah, Dzisi et al. 2014). During this research, D was $6.5 \cdot 10^{-12}$ $m^2 \cdot s^{-1}$ for drying at room temperature and $3.4 \cdot 10^{-11}$ $m^2 \cdot s^{-1}$ at 50 °C. This falls within the range described by literature.

Drying treatments

Room temperature

This treatment gave a clear result of the temperature course during drying, displayed in Figure 13.

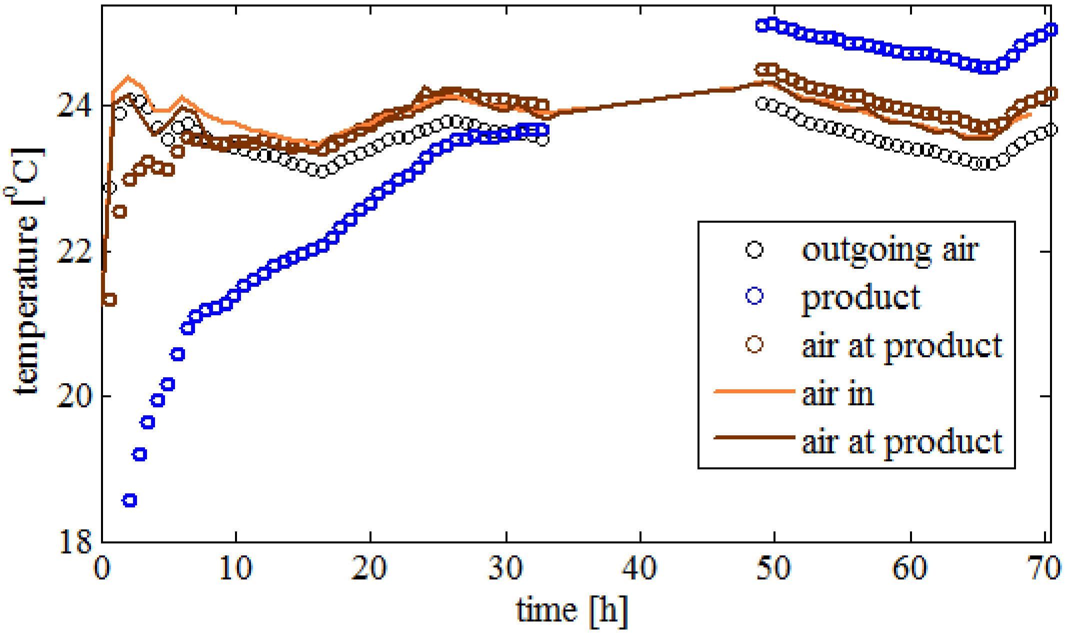

Figure 13: temperature during drying of Room temperature, where circles represent data and lines the model.

The variation in temperature of the ingoing air (and therefore also all other temperatures) is the natural fluctuation of the temperature in the room. The temperature of the air next to the product is, after some time, quite accurately described by the enthalpy balance in the model (compare the brown line and circles).

At the start, the temperature of the ingoing air is highest, followed by the temperature of the outgoing air and the air next to the product. The lower temperature of air at the product than of the outgoing air can be explained by the fact that it is a local temperature: the air cools down due to the evaporation heat that is absorbed by the moisture in the product. After mixing with air that did not pass the product, the air is warmer.

The temperature of the air next to the product needs ± 10 hours and the product more than 30 hours to reach the temperature of the ingoing air. This is the moment that the drying rate is so low that water evaporation and heat transfer to the product do not influence air temperature any more. Because of an error in the data logger, no data was recorded between 33 and 48 hours. In this time, the temperature of the product increased to 25°C, which is even higher than the temperature of the ingoing air. Also after the 48th hour, product temperature does not decrease. One possible solution would be that there is a difference in measurement accuracy between the thermocouple inside the product and one in a constant air flow.

Figure 14 shows how the model fits the experimental drying data for drying at room temperature.

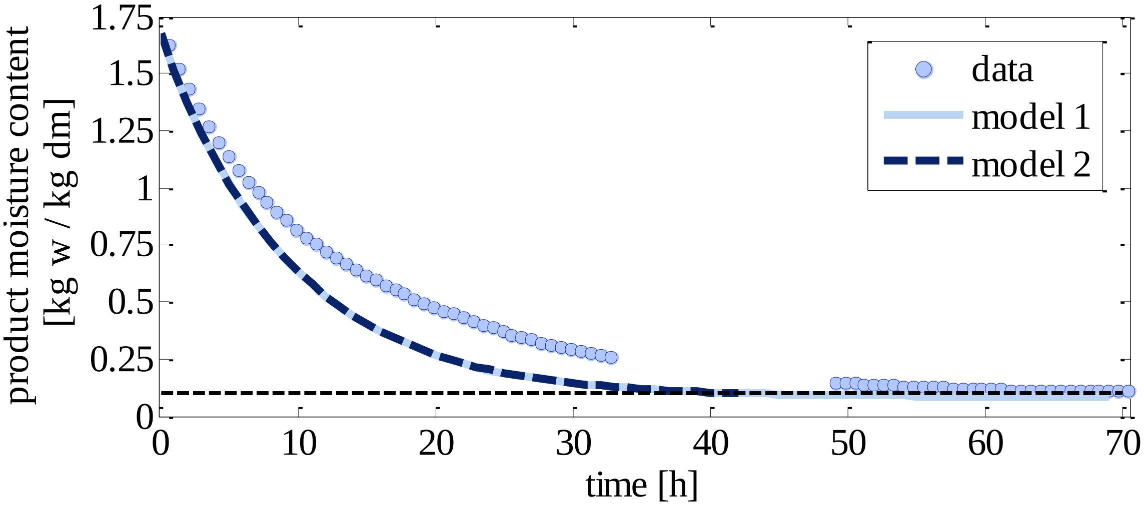

Figure 14: Product moisture content in Room temperature, with the model using experimental input values (model 1) and the simulation model at constant conditions (model 2). The end point of drying is defined in model 2 (used in all simulations) as 0.1 kg w·kg dm^{-1}, depicted in the figure by a dotted line.

The shape of the curve is well described by the model but the modelled drying rate is higher than seen in the data. This is because of the choice of value for the diffusion constant D_0, the best value for D_0 for drying at room temperature was lower than for the other drying treatments.

The model that used experimental data (model 1) and the model using constant conditions (model 2) were identical, validating the use of model 2 for the simulations. The difference between the two models is the estimation of product temperature which were resp. experimentally measured and calculated according to equation 21.

Optisolar1 and 2

These treatments were the same besides the raw material used and the results can therefore be very well compared. The moisture content of fresh yam in Optisolar1 and OptiSolar2 can be seen in Table 3 (Appendix A), the change during drying is displayed in Figure 15.Figure 16 shows the temperatures measured during drying of OptiSolar2, which is also valid for OptiSolar1 (Figure 23, Appendix A).

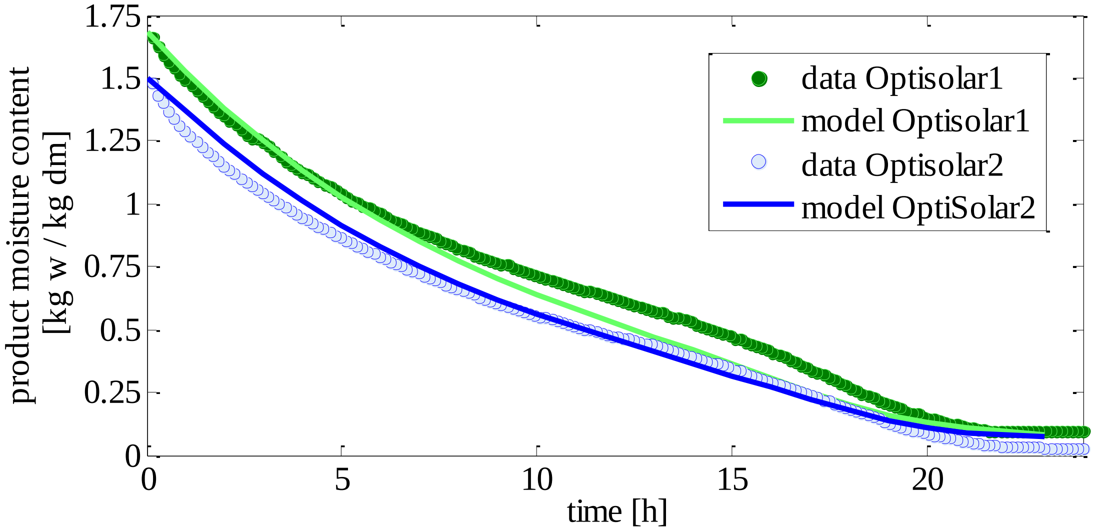

Figure 15: Moisture content in OptiSolar1 and OptiSolar2

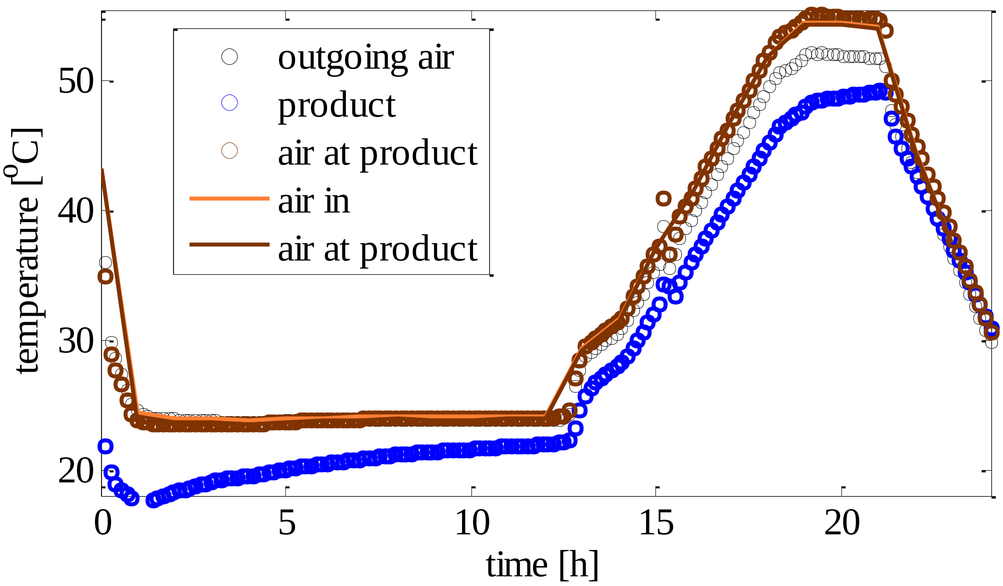

Figure 16: Temperatures in OptiSolar2 where dots represent data, lines the model.

In the beginning, there is a temporary drop in product temperature from 20 °C to 18 °C. This can be explained by evaporation of moisture at the surface, the required heat of evaporation cools down the product (as explained in the section 'The drying principle', introduction). Figure 15 also shows that the drying rate is slowly decreasing until the temperature is increased, after 13 hours. The modelled drying rate responds a bit too strong to this.

PoorSolar

The drying curve and temperatures during drying according to the PoorSolar treatment can be seen in Figure 17 and Figure 18, respectively. Since the difference between OptiSolar and PoorSolar is a difference in starting time along the temperature course of the day (Figure 7, Figure 8), Figure 18 can be seen as a shifted version of Figure 16.

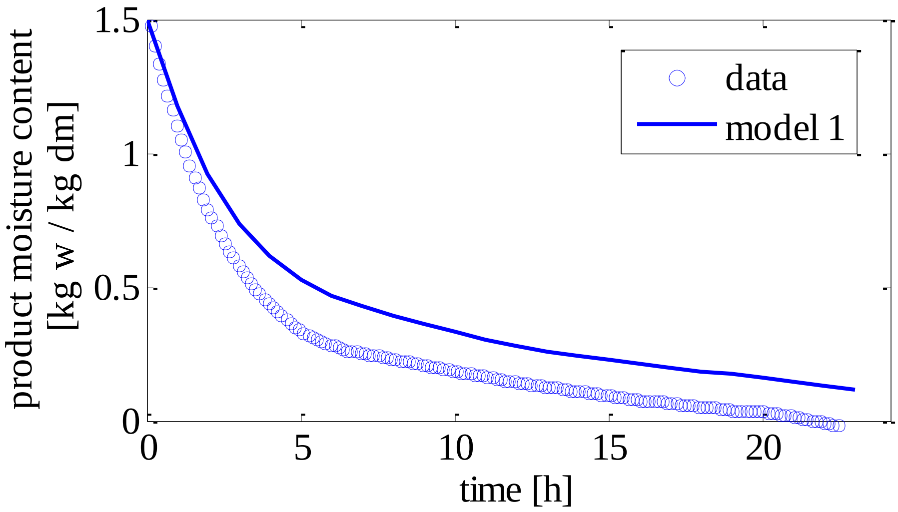

Figure 17: Moisture content in PoorSolar

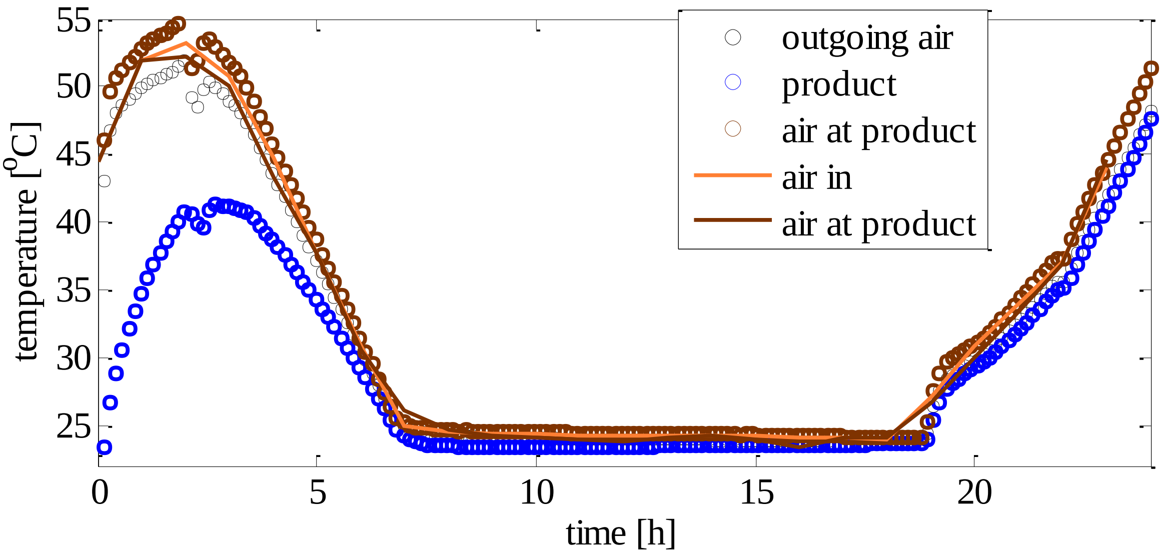

Figure 18: Temperatures in PoorSolar where dots represent data, lines the model.

Similar to the drying at room temperature, the shape of the modelled curve is good but the drying rate according to the model deviates from the data. The final moisture content of the model is below zero, which is not possible and indicates an inaccuracy in initial moisture content.

Open sun drying

Figure 19 shows the moisture content of yam during drying as in the open sun treatment.

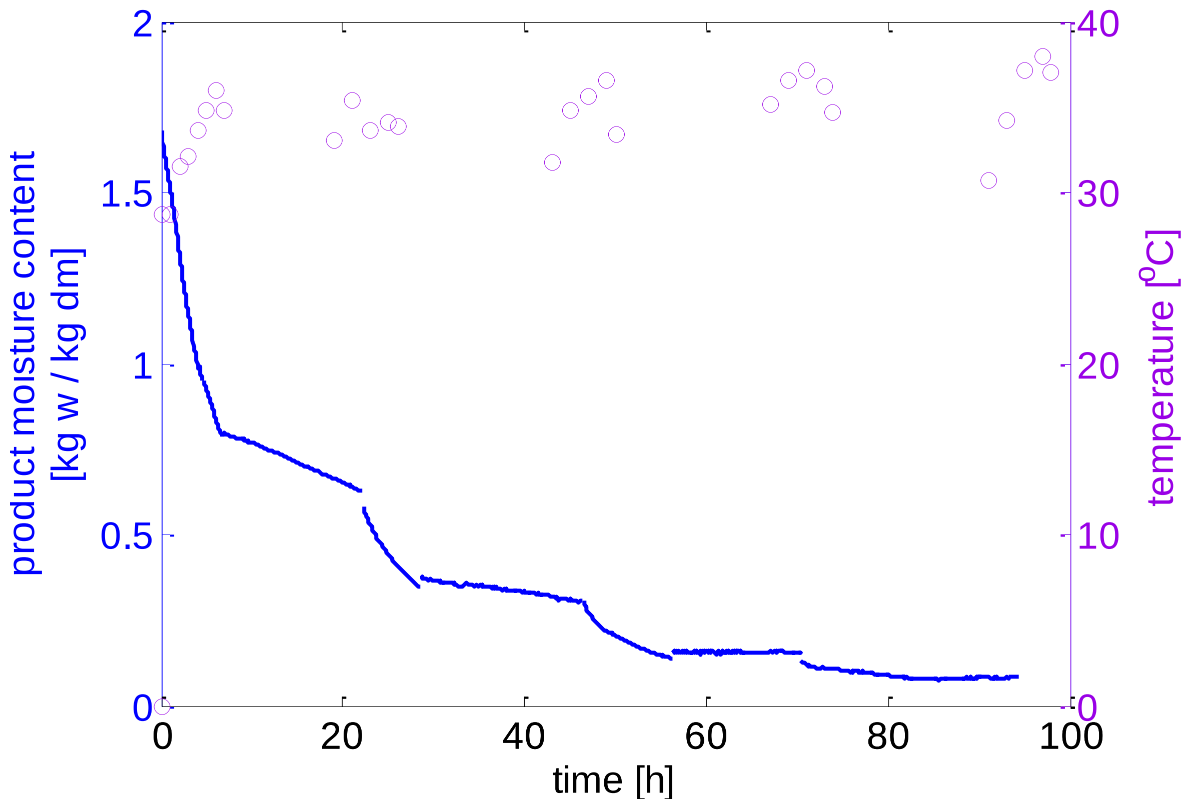

Figure 19: Drying according to the open sun treatment (experimental data), the purple circles indicate the followed temperature course, obtained from E. Amankwah.

At the moments the slices where wrapped in plastic, drying rate is much lower. This can be seen in the figure as a relatively flat line, for example in the second night between 26 and 43 hours. In theory, there should be no loss of moisture during drying in plastic. Probably, the slices were not as tightly wrapped as desired or water could slowly diffuse through the plastic.

The moisture content of the slices was calculated from the weight of the batch and was corrected for the weight of the plastic foil. The gap between the moisture content at end of the night and the beginning of the day can be explained by the loss of condensate on the plastic foil. Because the product had a constant moisture content after already 4 days, the experiment was stopped. The shorter drying time in the experiment compared to the traditional way was probably due to the lower humidity of the air.

Vitamin C

The results of vitamin C retention after the treatments is displayed in Figure 20.

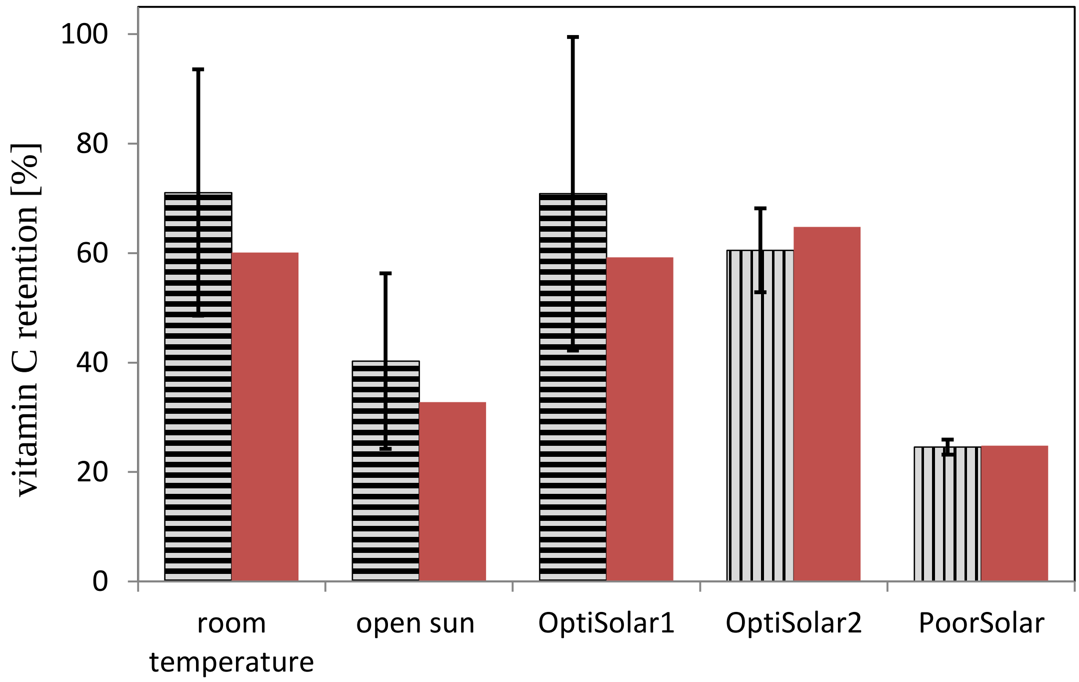

Figure 20: Vitamin C retention after the treatments. Horizontal and vertical stripes indicate the use of the first and 2nd yam, respectively. Solid red bars indicate the prediction by the model. The end of the error bars indicate the highest and lowest value of the duplicate.

From each treatment, two samples were analysed and averaged. The concentrations were normalised to the initial vitamin C content, which was much lower for the first four samples than for OptiSolar2 and PoorSolar (Table 3, Appendix A).

The difference in measurement between duplicates is quite high for the first yam but better for the second. Nevertheless, the prediction by the model fits the experimental data quite well. Figure 20 also shows the vitamin C retention in the OptiSolar2 sample is a factor 2.5 higher than in PoorSolar, which shows the trajectory is indeed effective, as predicted by the model. The difference between the two OptiSolar model values can be explained by the difference in initial moisture content (1.68 vs. 1.5). The retention of OptiSolar1 is just as high as drying at room temperature, showing the degradation area in Figure 1is effectively avoided. The sample open sun drying is not representative for the traditional method, where the product is subjected to UV-light. This means vitamin retention according to the traditional method will be lower than in the sample open sun drying. Also, all treatments will result in lower vitamin retention rates when drying products with a higher moisture content (see Figure 7).

Vitamin C concentration (mg·g dm^{-1}) in fresh yam was in the lower range of values reported in literature and deviation between measurements was quite high, as can be seen in Figure 24, Appendix A. This can be caused by several factors. Firstly, the purchased yams were likely to be quite old (since the moisture content was less than 50% of reported values) and the vitamin level might have decreased during storage. Secondly, it was difficult to extract the vitamin C from the tough structure of fresh yam. The fresh yam had to be processed fast as possible because exposure to heat, light or oxygen is enough to start degradation. Vitamin C might not have diffused out of the grated pieces completely or was degraded during extraction. Since it is estimated that the extraction yield of vitamin C from the fresh yam was lower than from the dried powder, vitamin C retention is likely overestimated for all treatments. This does not influence the relative differences in vitamin C retention between drying treatments.

Colour measurements

Figure 21 shows the normalised values of the colour of the samples after each treatment.

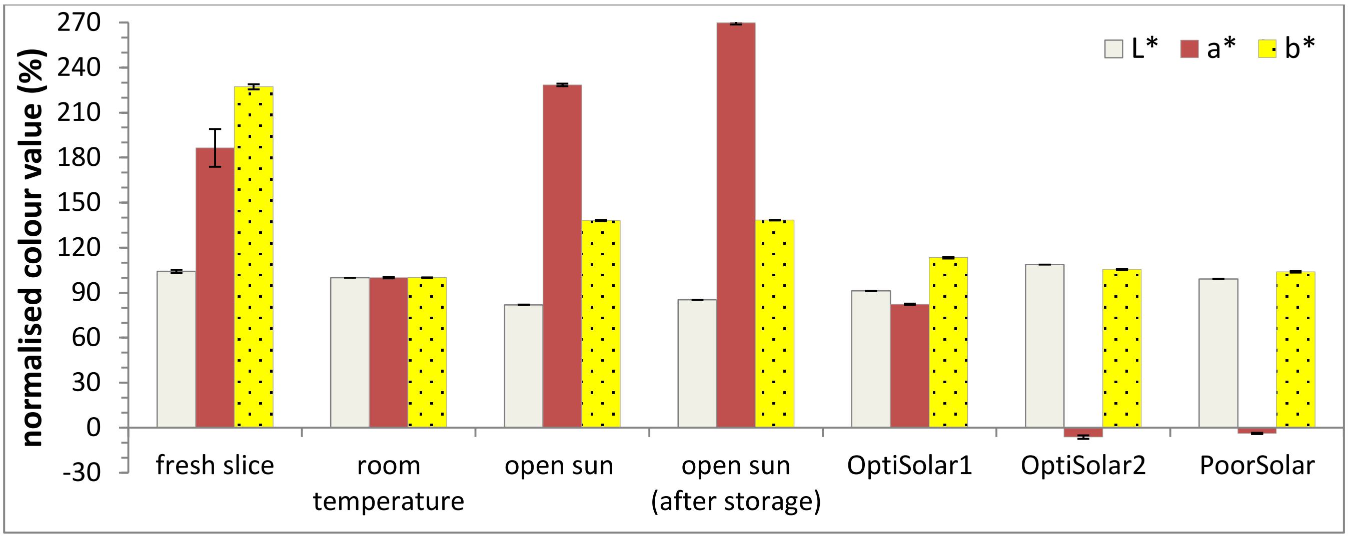

Figure 21: Normalised colour values of the samples, according to the L*a*b colour scale where L* indicates lightness, a* red and b* yellow colour.

Error bars in Figure 21 indicate the accuracy of the duplicate measurements, which is very high. The normalisation was done towards the colour values of yam dried at room temperature because this is the sample with the lowest processing impact. The fresh slice is measured as an intact slice and therefore less comparable to the other samples, which were measured as dry flour. The colour (values a* and b*) seems to have faded during drying, while lightness (L*) is same in the fresh slice and the room temperature dried sample.

The first five samples in the figure originated from a different yam than the Optisolar2 and PoorSolar samples. All these samples have high a* values (indicating redness), which is absent in the samples Optisolar2 and PoorSolar. PoorSolar was slightly darker than OptiSolar2 and the open sun sample a lot darker than the sample dried at room temperature. The open sun drying sample was measured directly after drying and after 30 days of storage. L* and b* values are the same but the redness increased due to storage. The treatment open sun drying yields a flour with higher b* values (yellow colour) and lower L* values, indicating darkening during drying. When comparing the open sun treatment to OptiSolar1 (originating from the same raw material), it seems high temperature-short time

(OptiSolar1) gives a lighter colour than the low temperature-long time combination in the open sun treatment.

Figure 22: Flour and yam pieces obtained from the drying treatments. Clockwise, starting at the bottom: room temperature, open sun, PoorSolar, OptiSolar2, OptiSolar1.

The photo displayed in Figure 22 shows the samples of each drying treatment together, as pieces and as flour. Also here the difference between the first and second yam (lower three vs. upper two samples, resp.) is clear. The open sun drying resulted in the darkest flour, this treatment had the longest drying time (100 hours). The photo clearly gives less information than the colour measurement. The lowest vitamin retentions (after the open sun and PoorSolar treatment) had a darker colour, taking room temperature and OptiSolar as respective references.

Discussion

The drying rate and end point of the modelled trajectories were not independent of the chosen step size dt. This indicates a fundamental problem in the model and it is not applicable when varying dt. However, since step size and diffusion constant were not varied during this research and the model was fit to experimental data, the results of the simulations are still promising. The origin of the instability in the model will be discussed further.
According to the Euler method, the error in a local value is proportional to the square of the step size and to reduce this error, the steps have to be small. By implementing the Euler method in the diffusion equation of Crank (equation 3), the first assumption of this equation (initial moisture content is uniform) is repeatedly used, every step of dt seconds. During drying, this assumption is not valid: the moisture content of the product is not uniform across the diffusion length. Equation 3 assumes a high drying rate at the start because the diffusion distance is still short, since the product surface is wet. When the actual product is not uniform, drying rate is overestimated. This leads to a conflict in the choice of dt: a low value increases the accuracy and the sensitivity to external input (temperature, moisture) but increases the drying rate by violation of the assumption on initial moisture. This shows that the Crank equation is not suitable for systems with varying conditions (temperature etc.) and a different model structure, such as ordinary differential equations, should be used to describe drying accurately.

The drying rate (drying time) influences vitamin C degradation significantly and therefore, vitamin C retention values are only valid for products with a similar drying rate (D_0, E_a) and initial moisture content. It is expected that vegetables with similar drying time for a given temperature trajectory will have the same vitamin C retention.

The fit of the drying model on the data largely depends on the assumption on activation energy E_a (kJ·mol^{-1}) and diffusion constant D_0 (m^2·s^{-1}). The assumed E_a was obtained from literature on yam drying (Amankwah, Dzisi et al. 2014) and should in theory fit to the data for a single value for D_0, but this was not entirely achieved (Table 2). Because air conditions differed between treatments, it is difficult to determine the cause of this. The role of X_e and its assumed temperature independence should be investigated in further research.

Conclusion

A reasonable fit between drying model and experimental data was obtained, which validates the use of this model in this research. The use of the Euler method in solving the Cranck diffusion equation was not recommended, future research should instead use a model of ordinary differential equations when varying conditions during drying are modelled.

Vitamin retention after drying was highly dependent on drying rate and initial moisture content. Both these factors influence drying time and are fixed by the agricultural product that needs to be dried. The adverse effect on vitamin retention of an increased temperature at the end of the drying process was smaller than the positive effect of the decreased drying time, resulting in increased retention due to a higher temperature.

Vitamin C retention of the optimal drying trajectory for yam (X_0=3.6 kg w·kg dm^{-1}) with a lowered temperature boundary of 22 °C was 26% after 30 hours. The drying trajectory with the lowest cost resulted in a vitamin C retention of 28%, in 32 hours. This small difference results from the differently chosen optimisation objectives and actually shows both the optimisation and the randomisation are good methods to find the optimal trajectory. Both trajectories start at the lower temperature boundary of 22 °C and increase after some time, Figure 12 clearly displays these drying trajectories.

When drying conditions were restricted to the circumstances in a solar dryer, 21% vitamin C retention could be obtained when drying was started at 5 PM. This can be explained by a correlation between a low temperature at the moment the product reaches the critical moisture content (X_w=2 kg w·kg dm^{-1}) and high vitamin retention. The benefit of solar drying (at optimal starting time) is a vitamin retention almost twice as high as achieved in traditional open sun drying. Additionally, the product in a solar dryer is protected against rodents, microbial spoilage (night drying prevents the formation of condensate on the product, inhibiting bacterial growth) and harmful UV-light. The improved start time (5 PM) increases vitamin retention by a factor 2.6 compared to the poorest start time (11 AM). When drying products with a considerably higher initial moisture content, this optimal starting time shifts forward to ± 2PM.

Browning might be positively correlated with vitamin degradation but the number of experiments was too small to obtain significant results. The initial quality of the yam had a high impact on the colour of the yam flour. It is suspected that a prolonged drying time has a higher negative impact on final colour than elevated drying temperature.

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Appendices

Appendix A

Experimental data

Table 3: Yam properties

Property	Yam 1	Yam 2	unit
Density	1.17±0.03	-	$kg \cdot m^{-3}$
Shrinkage factor	0.373±0.005	-	-
moisture content	1.68	1.50±0.02	$kg\ w \cdot kg\ dm^{-1}$
Vitamin C	1.99±0.25	5.98±0.02	$mg \cdot 100g\ dm^{-1}$

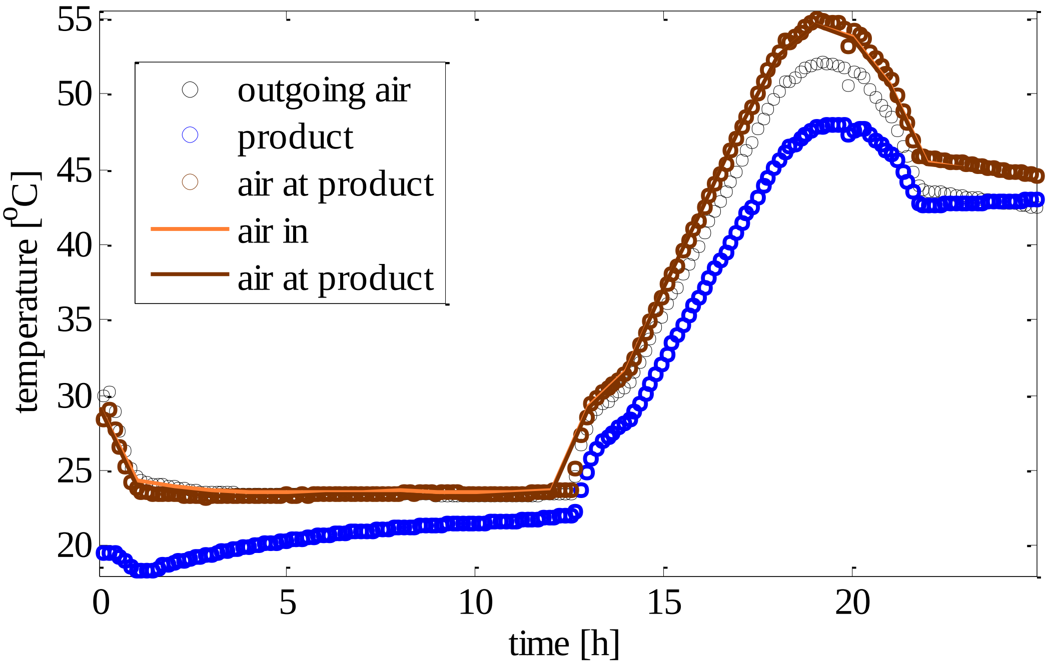

Figure 23: Temperatures in OptiSolar1 where dots represent data, lines the model.

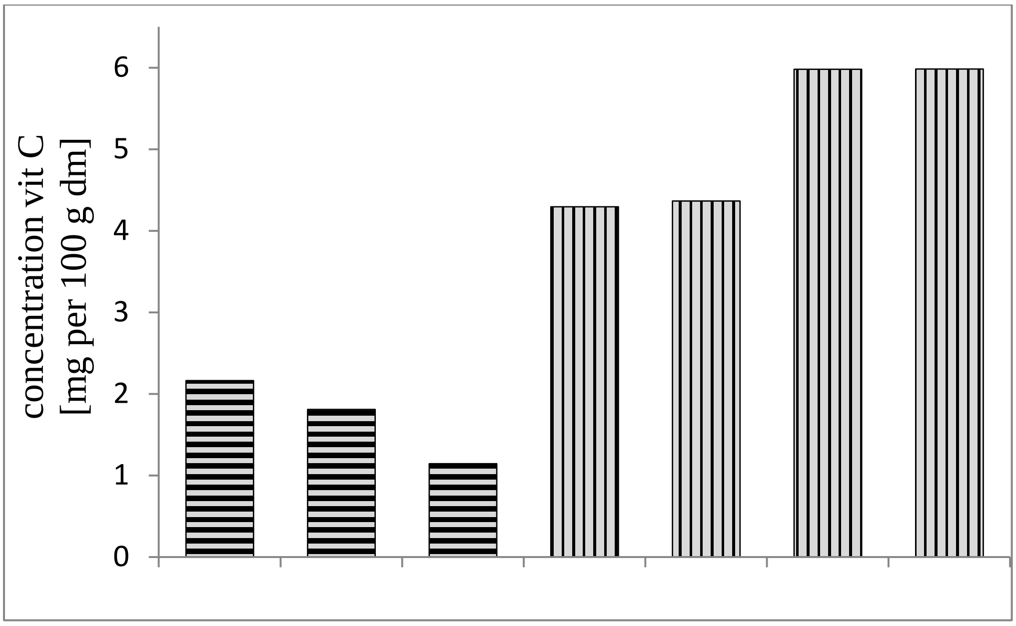

Figure 24: Vitamin concentration in fresh yam, on dry weight basis. The number on the x-axis indicates the number of the experiment, a and b are duplicates. Horizontal and vertical stripes indicate the use of the first and second yam, respectively. Number 1(a,b) and 4(a,b) were used as reference values for vitamin content of fresh yam of the first and second yam.

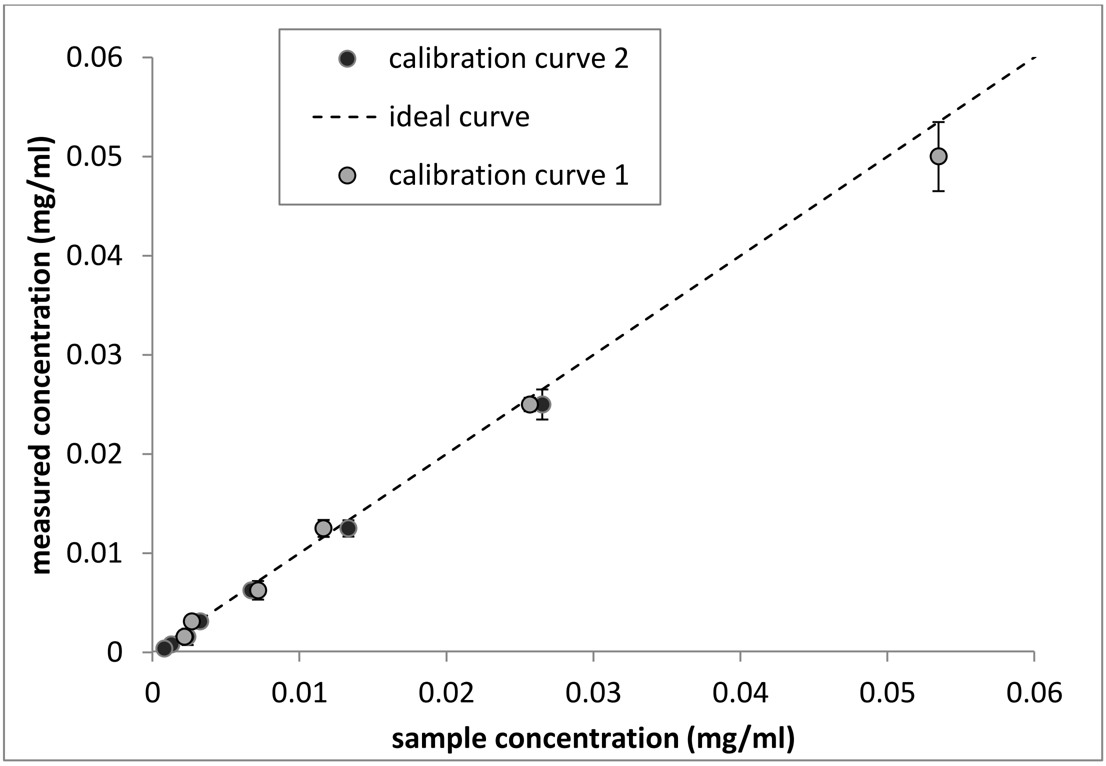

Figure 25: Calibration curve vitamin C concentration. Samples with less than 0.003 mg per ml extract where considered out of range.

Appendix B

Simulations

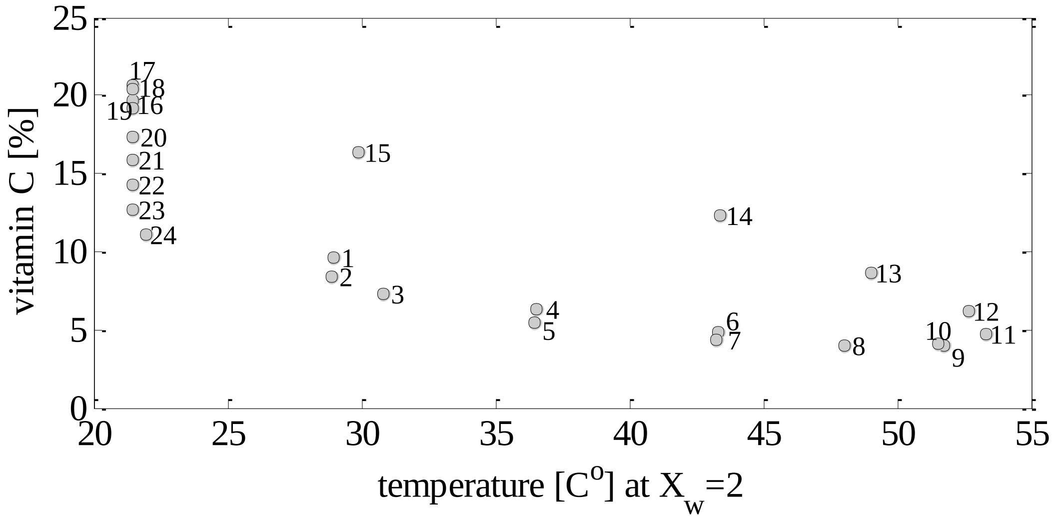

Figure 26: influence of temperature at X_w=2 on final vitamin retention, when initial moisture content X_0=3.6 kg w·kg dm^{-1}. Numbers indicate solar drying starting hour.

Appendix C

Experimental setup

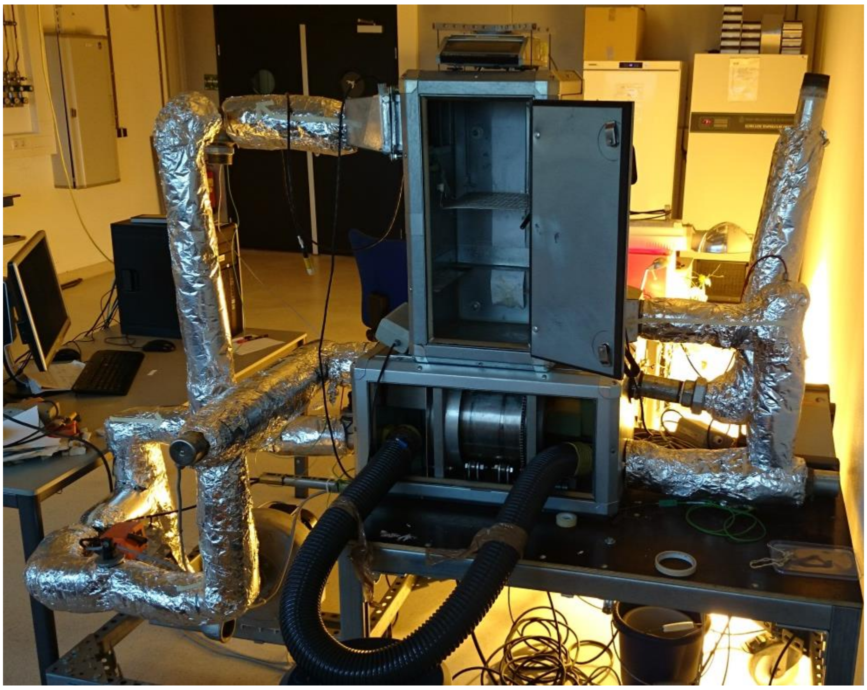

Figure 27: Experimental set up used during this research, with the drying chamber in the middle.

Figure 28: Slices in the drying tray. Sensor A measures air temperature just above the slice (3 mm), sensor B is inserted in the middle of a slice.

Appendix D

Matlab scripts

Data based model

```
clear all
%close all
load('M:\My Documents\master thesis\MATLAB\datasets\optisolar.mat');
ts=round((time(400)-time(200))/200);          %time difference between measurements,
in seconds.
last=round(size(time,1)*ts);                  %the data vector 'time' is a measure
of data size.
for j = 2 : size(time,1)
   if ~(time(j)>1)
      last=j-1;
        break
    end
end
%% constants
rho_start=1172;                               %measured density of fresh yam (kg/m3)
rho_w=1000;                                   %density of water (kg/m3)
airflow=0.0243;                               %airflow (kg/s)
C1=8.26; C2=0.76; C3=10.14;                   %constants needed for air equilibrium
moisture content
R=8.3145;                                     %universal gas constant
cp_air=1.005;cp_vapour=1.871;                 %heat capacity of dry air and water
vapour (kJ/kg/K)
heat_evap=2408;                               %specific heat of water evaporation
(kJ/kg)
vitC_start=100;                               %percentage vit C start
a1=17.94; a2=-2.245E8; a3=-33.33; a4=5921;
a5=-1.585E6; a6=4.711E8; a7=-2.339;           %constants needed for vitamin C
degradation kinetics,
                                               Mishkin 1983

P1=16.38 ;P2=1.78 ;P3= 1.89; P4=14831;
P5=241.1; P6=656.2; P7=236.8; Rc=1.987;       %constants needed for vitamin C
degradation kinetics,
                                               Mishkin 1984

%% properties of raw material
thickness_start=0.01; length_start=0.03;      %initial thickness and length of the
slice (m)
volume_start=thickness_start*length_start^2;  %%initial volume of the slice (m)
d=2.297;                                      %shrinkage parameter,from measurements
D0=0.8E-3;  Ea_yam=44060;                     %theoretical Diffusion constant and
activation energy
Xw_start=1.68;                                %water content (kg water /kg dry
matter)
Xdm=1/(Xw_start+1);                           %dry matter content (dm/kg fresh
weight)
X_start_wb=1-1/(Xw_start+1);                  %water content (kg water/kg fresh
weight, wet basis);
dry_matter=mean(weight(1:5))/1000*Xdm;           %starting weight (kg dry weight in
the dryer)
Mass_slice_dm=volume_start*rho_start*(1-X_start_wb); %kg dry matter per slice
delta_Xw=0;
%% times
sec_hour=3600;                                %multiply to convert hours to seconds
realtime=last*ts/sec_hour;                    %duration of the experiment (hours)
dt=3600;                                      %step size (s)
s=1;                                          %step(i), one step at the time
start=s+1 ;                                   %starting point (i) of the model
final_loop=(realtime*sec_hour+1)/dt;          %end point (i) of the model
b=0:90;                                       %needed for Crank diffusion equation

%% starting values
thickness(start-1)=thickness_start;
volume(start-1)=volume_start;
Xw(start-1)=Xw_start;
mass(start-1)=dry_matter/Xdm;
```

```
Ta_in(start-1)=Tdryerin(1)+273;
Tp(start-1)=Tproduct(1)+273;
Tair_p(start-1)=Ta_in(start-1);
Xa_in(start-1)=Xairin(1);
Xa_out(start-1)=Xairin(1);
Cv_84(start-1)=vitC_start;
Cv_83(start-1)=vitC_start;
 %% the drying model
for i=start:s:final_loop;                       %number of the loop, running from
start to final_loop
    current_time=dt*(i-start+1);                %current time for each loop in seconds
    if current_time<=0.1*dt+1 || final_loop*dt-current_time<=0.1*dt+1
        Xa_in(i)=Xairin(round(current_time/ts));
        Ta_in(i)=Tdryerin(round(current_time/ts))+273;
        Tp(i)=   Tproduct(round(current_time/ts))+273;
        RH=      RH3(round(current_time/ts))/100;          %the relative humidity
determines the equilibrium moisture content and therefore at the end the moisture
content of the product (Xe)
    else
        Xa_in(i)= mean(Xairin(round((current_time-
0.1*dt)/ts):round((current_time+0.1*dt)/ts)));
        Ta_in(i)= mean(Tdryerin(round((current_time-
0.1*dt)/ts):round((current_time+0.1*dt)/ts)))+273;
        Tp(i)=    mean(Tproduct(round((current_time-
0.1*dt)/ts):round((current_time+0.1*dt)/ts)))+273;
        RH=       mean(RH3(((current_time-
0.1*dt)/ts):round((current_time+0.1*dt)/ts)))/100;
    end
    Xe=C1*C2*C3*RH/((1-C2*RH)*(1-C2*RH+C2*C3*RH))/100;
    Xa_out(i)=Xa_in(i)-dry_matter*delta_Xw/(airflow*dt);   %watercontent outgoing
air (kg w/kg air)
    Fwater=Xw(i-s)*dry_matter/mass(i-s);                   %water content (g w/g
current product)
    cp_p= 0.83736*(1-Fwater)+4.1868*Fwater;                %heat capacity of the
product (kJ/kg)
    delta_Vair=(-delta_Xw/Xw_start)*0.34*volume_start;     %air incorporated in the
slice (m3)
    volume(i)= volume(i-s)+Mass_slice_dm*(delta_Xw)/rho_w+delta_Vair;    %slice
volume (m3)
    thickness(i)= thickness(i-s)*(volume(i)/volume(i-s))^(1/d);          %slice
thickness (m)
    Tair_p(i)=(cp_p*mass(i-s)/airflow*(Tp(i-s)-
Tp(i))/dt+cp_air*Ta_in(i)+Ta_in(i)*Xa_in(i)*cp_vapour+heat_evap *(Xa_in(i)-
Xa_out(i)))/(cp_air+cp_vapour*Xa_out(i-s));                %air temp. above the
product surface, an
                                                            enthalpy balance (K)
    D_eff(i)= D0*exp(-Ea_yam/(R*Tair_p(i)))*(volume_start/volume(i))^(-2/d);
    k(i)= -D_eff(i)*pi^2/((thickness(i)/2)^2);

    Xw(i)= 8/pi^2*sum((1./(2*b+1).^2).*exp((2*b+1).^2*k(i)*dt))*(Xw(i-s)-Xe)+Xe;
                                                           %moisture content yam
                                                      (w/kg dm)
    delta_Xw=(Xw(i)-Xw(i-s));                              %negative, difference in
                                                           moisture   content after
                                                           dt (kg w/kg dw)
    mass(i)=mass(i-s)+dry_matter*delta_Xw;                 %current slice weight
(kg)
    %% vitamin C degradation
    k_Vc_83=exp(a1*Fwater+a2*Tair_p(i)^-3+a3*Fwater^3+a4*Fwater^2*Tair_p(i)^-
1+a5*Fwater*Tair_p(i)^-2+a6*Fwater^3*Tair_p(i)^-3+a7);
Cv_83(i)=Cv_83(i-s)*exp((-k_Vc_83/60)*dt);                 %vitamin C degradation
according to
    kvc0=exp(P1+P2*Xw(i)+P3*Xw(i)^2);                      Mishkin(1983) and
Mishkin(1984, resp)          Ea_Vc=P4+P5*Xw(i)+P6*Xw(i)^2+P7*Xw(i)^3;
    k_Vc=kvc0*exp(-Ea_Vc/(Rc*Tair_p(i)));
    Cv_84(i)=Cv_84(i-s)*exp((-k_Vc/60)*dt);
end
control_endpoint=mass(floor(final_loop))/mean((weight(last-5:last))/1000);
if control_endpoint<0.98
```

```
    disp(['decrease Diffusion Coefficient, model/data weight : '
num2str(control_endpoint)])
end
if control_endpoint>1.02
    disp(['increase Diffusion Coefficient, model/data weight : '
num2str(control_endpoint)])
end
 %% plotting printable graphs
set(0,'DefaultAxesFontName', 'Times New Roman')            %Change default axes
fonts.
set(0,'DefaultAxesFontSize', 14)
set(0,'DefaultTextFontname', 'Times New Roman')            %Change default text
fonts.
set(0,'DefaultTextFontSize', 14)

timeperiod=[0:dt/sec_hour:realtime-s*dt/sec_hour];

figure(1);
plot1=subplot(2,2,1);
plot(timeperiod,Xw,'m--');
axis([0 realtime 0 Xw_start]);
legend 'model';
title 'water content', xlabel 'time [h]', ylabel ({'product moisture content','[kg
w / kg dm]'}), grid on
hold on

plot2=subplot(2,2,2);
plot(timeperiod,Ta_in-273,'b--',timeperiod,Tair_p-273,'g--');
axis([0 realtime 15 max(Ta_in-273)]);
legend 'air in' 'air product';
title 'Temperature', xlabel 'time [h]', ylabel '[^oC]'
hold on

plot3=subplot(2,2,3);
[ax,h1,h2]=plotyy(timeperiod,[thickness'*1000,volume'*1000000],timeperiod,D_eff);
set(h1,'LineStyle','--');
set(h2,'LineStyle','--','LineWidth',0.5,'Color',[0.6 0 0.9]);
xlim(ax(1),[0,realtime]),xlim(ax(2),[0,realtime]), xlabel 'time [h]'
ylim(ax(1),[5,10]),ylabel(ax(1),{'length [mm]', 'volume [cm^3]'}),
ylabel(ax(2),'diffusion coefficient [m^2/s]')
legend 'length' 'volume' 'diffusion';
title 'dimensions and diffusivity';
hold on; grid on;

plot4=subplot(2,2,4);
plot(timeperiod,Cv_84,timeperiod,Cv_83);
axis([0 realtime 0 vitC_start]);
legend( 'Mishkin 1984','Mishkin 1983','Location', 'Best');
title 'Vitamin C degradation', xlabel 'time [h]', ylabel '[%]'
hold on ;

linkaxes([plot1,plot2,plot3,plot4],'x');
```

Data

```
% first, run data_based_model to bring the data into the workspace

%% To smoothen the data points without losing information, averages are taken. This
also speeds up the run.
lessdata = 8;
t_odd=[1:2:j-1]';
t_even=[2:2:j]';
Tain=(Tdryerin(t_odd)+(Tdryerin(t_even)))/2;
Taout=(Tdryerout(t_odd)+(Tdryerout(t_even)))/2;
Tpr=(Tproduct(t_odd)+(Tproduct(t_even)))/2;
Xai_av=(Xairin(t_odd)+(Xairin(t_even)))/2*1000;       % moisture content ingoing
air[g w/kg air]
```

```
Xao_av=(Xairout(t_odd)+(Xairout(t_even)))/2*1000;     % moisture content outgoing
air[g w/kg air]
weight_av=(weight(t_odd)+(weight(t_even)))/2/1000;   % current weight in kg
Tairpr=(TC5(t_odd)+(TC5(t_even)))/2;

for i = 1:lessdata-1
    t_odd=[1:2:size(t_odd,1)-1]';
    t_even=[2:2:size(t_even,1)]';
    Tain=(Tain(t_odd)+(Tain(t_even)))/2;
    Taout=(Taout(t_odd)+(Taout(t_even)))/2;
    Tpr=(Tpr(t_odd)+(Tpr(t_even)))/2;
    Xai_av=(Xai_av(t_odd)+(Xai_av(t_even)))/2;
    Xao_av=(Xao_av(t_odd)+(Xao_av(t_even)))/2;
    weight_av=(weight_av(t_odd)+(weight_av(t_even)))/2;
    Tairpr=(Tairpr(t_odd)+(Tairpr(t_even)))/2;
end
%% constants needed for unit conversion of data
timeH=time/3600;                                     % time in hours
rhoa=1.15;                                           % air density (kg/m3)
Fa=airspeed*0.00264*rhoa;                            % air flow (kg/s)
drymatter=1/(Xw_start+1);                            % dry matter content (dm/kg
fresh weight)
Mp0=mean(weight(2:10))/1000*drymatter;               % dry weight (kg)
wcontent=(weight_av-Mp0)/(Mp0);                      % watercontent on dry weight
basis

%% plotting data
v1=1:size(Tain);                                     % determines vector length for
plot
v2=2^lessdata*v1;                                    % determines vector length for
plot
q=35;                                                % size of data points
orange = [1 0.5 0.2];                                % colours
grey=[0.8 0.1 0.6];
brown=[0.5 0.2 0];

figure(3);                                           % temperatures during drying
scatter (timeH(v2),Taout(v1),0.6*q,'k','LineWidth',1.2);  hold on
scatter (timeH(v2),Tpr(v1),q,'b','LineWidth',1.5);   hold on
scatter (timeH(v2),Tairpr(v1),q,brown,'LineWidth',1.5); hold on
[h1]=plot(timeperiod,Ta_in-273,'Color',orange,'LineWidth',1.8); hold on
[h2]=plot(timeperiod,Tair_p-273,'Color',brown,'LineWidth',1.6); hold on
xlabel 'time [h]', ylabel ' temperature [^oC]'
legend([{'outgoing air','product','air at product','air in' ,'air at product'}])
axis([0 realtime 18 max(Ta_in-273+1)]);
box on

figure(6);                                           % moisture content during
drying
scatter (timeH(v2),wcontent(v1),'bo','SizeData',q,'LineWidth',1.2); hold on
plot(timeperiod,Xw,'b-','LineWidth',2); hold on
axis([0 realtime 0 Xw_start]);
[~,~,~,names] = legend;
legend([{'data ', 'model 1'}]); hold on
%title 'water content'
xlabel 'time [h]', ylabel ({'product moisture content','[kg w / kg dm]'})
box on

% figure(10);                                        % only for open sun
% amat =[0  1   2   3   4   5   6   7 19  21  23  25  26 43  45  47  49  50 67  69
71  73  74 91  93  95  97  98 0];
% amatem=[28.734    28.699  31.492  32.13   33.67   34.759  35.948  34.852 32.988
35.395  33.61   34.055  33.821 31.773 34.846    35.579  36.608  33.353 35.111
36.574  37.11 36.225 34.689 30.7 34.2 37.1 37.9 37 0];
% [ax,h1,h2]=plotyy(timeH(v2),wcontent(v1),amat,amatem);
% xlabel 'time [h]';
% ylabel(ax(2),{'temperature [^oC]'},'Color',[0.6 0 0.9]); ylabel(ax(1),{'product
moisture content','[kg w/kg dm]'}','Color','b')
```

```
% set(ax,{'ycolor'},{'b';[0.6 0 0.9]})
% set(h1,'LineStyle','-','LineWidth',2,'Color','b');
% set(h2,'Marker','o','LineStyle','none','LineWidth',1,'Color',[0.6 0 0.9])

%% figure(1);                                       % subplots using figure 1
data_based_model to plot
% subplot(2,2,1); scatter (timeH(v2),wcontent(v1),'m.','SizeData',q);
% [~,~,~,names] = legend; legend ([names {'data'}], 'Location','Best');
% subplot(2,2,2); scatter (timeH(v2),Taout(v1),'c.','SizeData',q);  hold on
% %subplot(2,2,2); scatter (timeH(v2),Tain(v1),'b.','SizeData',q);  hold on
% subplot(2,2,2); scatter (timeH(v2),Tpr(v1),'m.','SizeData',q);   hold on
% subplot(2,2,2); scatter (timeH(v2),Tairpr(v1),'g.','SizeData',q); hold off
% [~,~,~,names] = legend; legend([names{'outgoing air','product','air at
product'}],'FontSize', 12)
```

Simulations

```
%simulations script, uses model_without_data
clear all; %close all
l=3;                        % number of iterations of the script
                            % changes the colour of plotted line in 1 run of iterate
plotting=0;                 % if a plot is wanted, plotting=1
simulation=4;               % code of simulation that is executed
realtime=60;                % allowed maximal drying time (hours)
dt=3600;                    % seconds between steps in the model
starttime=1;
Xw_start=3.6;               % starting moisture content of the product
lasthour=realtime;          % no recirculation of temperature values except if
otherwise specified
Xa_in=0.012;                %absolute moisture content incoming air (g w/g da), 0.012
is corresponding
                             to 22 degrees RH=80%
grey=[0.2 0.2 0.2];

w=0;                        %if w=0, choose the type of simulation
if w==0
    question=input('What would you like to simulate? solar dryer=1, constant air
temperature=2, randomised trajectory=3, optimised trajectory=4?', 's');
    if strcmp(question,'1')==1
        simulation=1;
    elseif strcmp(question,'2')==1
        simulation=2;
    elseif strcmp(question,'3')==1
        simulation=3;
    elseif strcmp(question,'4')==1
        simulation=4;
    end
end

for h = 1:l;
    if simulation==1;                           %solar dryer
        starttime=h-1;                          %starttime=1 at 12 o clock at night
        lasthour=24;                            %solar dryer temperatures are reused
after 24h
        %timeSD= [0  1  2  3  4  5  6   7    8    9    10   11   12   13  14  15
16   17    18   19  20 21 22 23 24];
        tempSD= [22 22 22 22 22 22 22.5 29.5 31.6 37.3 44.3 49.3 53.1 55 54.4 50.7
44.9 37.8 30.8 22.5 22 22 22 22 22];                              %hourly
temperatures in the solar dryer (Celsius)
        TEMP=tempSD;

        elseif simulation==2;                   %constant temperature,
            TEMP=[ones(1,lasthour+1)*23.9];
            Xa_in=0.00555;
            realtime=100;

            elseif simulation==3;               %random drying trajectory
                c(1)=22;
```

```
                realtime=50;
                for i=1:lasthour;
                    linpiece=[c(i)+2;c(i)+1;c(i)];
                    c(i+1)=linpiece(randi(3,1,1));  %a new air temperature every
hour
                    if c(i+1)<22 || c(i+1)>60
                        c(i+1)=c(i);
                    end
                end
                TEMP=c;

                elseif simulation==4;          %van Olst optimal drying trajectory,
details in
                                                model_without_data
                    TEMP=34-4*h;
    end

    if h==1
        temperature=zeros(realtime*3600/dt,1); %allocate space
        vitamin=zeros(realtime*3600/dt,1);
        moisture=zeros(realtime*3600/dt,1);
    end

    f=h+1;                                     %change plotting colour
    [Cv_83,Xw,D_eff,current_time,Psat,Ta_in,crucialTemp,currentVit]
=model_without_data
(Xw_start,realtime,dt,starttime,plotting,TEMP,f,lasthour,Xa_in,simulation);
    Tverloop=Ta_in-273;
    Cvverloop=Cv_83;
    Xvverloop=Xw;
    %Dverloop=D_eff;

    endtime(h)= current_time(end)/3600;
    moisture_final(h)=Xw(end);                 %to check if the product is dry
    vitaminC_end(h)=Cv_83(end);
    T_crucial(h)=crucialTemp;
    V_Tcrucial(h)=currentVit;
    if simulation==1
        starthour(h)=starttime;                %record starttimes (hours of the day)
    end
    temperature(1:length(Tverloop),h)=Tverloop;
    vitamin(1:length(Cvverloop),h)=Cvverloop;
    moisture(1:length(Xvverloop),h)=Xvverloop;
    %diffusion(1:length(Xvverloop),h)=Dverloop;
end
%% for all simulations
A = zeros(1,4);                                %table with final results of the
simulation
A(:,1)=moisture_final;
A(:,2)=vitaminC_end;
A(:,3)=endtime;
if simulation==1
    A(:,4)=starthour;
end
table2=[num2cell('XCt');num2cell(A(:,[1 2 3]))];

temperature(temperature==0)=NaN;               %where there is a zero, make a NaN
vitamin(vitamin==0)=NaN;
moisture(moisture==0)=NaN;
% plots
t_start=0;
t_end=realtime;
t=[t_start:dt/3600:t_end-1/60]';
%%
if simulation==1&&l>20
    figure(2); [ax h1 h2] = plotyy(starthour,vitaminC_end,starthour,tempSD(1:l));
    set(h1,'Marker','o','MarkerSize',5,'Color','m');
    set(h2,'Marker','.');
```

```
    %title 'best time of the day to start drying'
    ylabel(ax(1), 'vitamin C [%]'), ylabel(ax(2), 'temperature [C^o]')
    xlabel(ax(2), 'time [h]'), xlim(ax(1),[0,24]), xlim(ax(2),[0,24]); hold on
    ylim(ax(2),[0,60]);
    [~,~,~,names] = legend; legend ([names {['{X_0=}' num2str(Xw_start)]}])
    table1=[num2cell('XCth');num2cell(A(:,[1 2 3 4]))];

    figure(11)
    scatter(T_crucial-273,vitaminC_end,28,grey,'filled'); hold on
    labels = cellstr( num2str([1:24]') );
    xlabel('temperature [C^o] at X_w=2');
    ylabel('vitamin C [%]' ),text(T_crucial-273, vitaminC_end,
labels,'FontSize',10);
    box on

    figure(3);
    [h1]=plot(moisture(:,[11,18]),temperature(:,[11,18]));
    set(h1,'Marker','o','MarkerSize',2)
    ylabel('temperature [C^o]')
    xlabel( 'Moisture [kg w.kg dm^{-1}]'); hold on
    [~,~,~,names] = legend; legend ([names {['{X_0=}' ,num2str(Xw_start),',
starttime=11h'],['{X_0=}' ,num2str(Xw_start),', starttime=17h']}])
end
%%
if simulation==2
    figure(6);
    [ax] =plot(t,moisture(1:size(t),:)); hold on
    set(ax,'Marker','.', 'Color','b');
    xlabel('time [h]')
    ylabel('Moisture [kg w.kg dm^{-1}]')
    ylim([0,Xw_start]);
    [~,~,~,names] = legend; legend ([names {['model 2']}])
end
%%
if simulation==3
    % what is the optimal trajectory? cost function
    dry=find(moisture_final<=0.1);
    bestV=max(vitaminC_end(dry));              %vit C retention in the sample with
highest vit C
    highestvitamin=find(vitaminC_end==bestV);
    b=find(vitaminC_end(dry)>=0.9*bestV);      %a few dried,best preserved
trajectories
    cost_vitamin=((max(vitaminC_end(dry))-
vitaminC_end(dry))'./(max(vitaminC_end(dry))-min(vitaminC_end(dry)))).^2;
    cost_time=((min(endtime(dry))-endtime(dry))'./(max(endtime(dry))-
min(endtime(dry)))).^2;
    cost=cost_time+cost_vitamin;               %the lowest value is the best option
    [sorted_cost, SortIndex] = sort(cost(b));
    bsorted = b(SortIndex);                    %best trajectories ordered in terms
of total costs
    tablebest=[num2cell('XCt');num2cell(A(bsorted,[1 2 3]))];

    q=4-12*(sorted_cost/sorted_cost(end));     %provide colours to lines based on
their costs
    n=find(q<0,1); q(n:end)=0;
    colour(:,1)=q';                            %bright red indicates best option,
darker=less good
    colour(:,2:3)=0;
    if l>=100
        figure(3)
        %title 'vitamin C retention of randomized drying trajectories'; hold on
        plot(t,vitamin(:,highestvitamin),'g-','LineWidth',5); hold on

                                               %when only vitamin retention is
                                        important
        plot(t,vitamin(:,bsorted(1)),'-','LineWidth',5,'color',colour(1,:)); hold
on
                                               %when also drying time is taken into
                                        account
```

```
        plot(t,vitamin(:,dry),'k:','LineWidth',0.1); hold on
        axis([0, max(endtime(dry)), 0, 100]);
        xlabel('time [h]')
        ylabel('vitamin C [%]')
        legend('best vitamin C retention','lowest combined costs', 'other
trajectories'); hold on
        plot(t,vitamin(:,highestvitamin),'g-','LineWidth',5); hold on
        plot(t,vitamin(:,bsorted(1)),'-','LineWidth',5,'color',colour(1,:)); hold
on

        if l>=2000
            figure(1);scatter(cost_time,cost_vitamin,3,grey); hold on
            xlabel('time costs [-]')
            ylabel('vitamin C costs [-]')
            box on
        else
                figure(5)
                AZ=113;EL=38;

plot3(t,temperature(:,dry(1:300)),moisture(:,dry(1:300)),'color','k','LineWidth',0.
5); hold on;
                                                %all possible trajectories resulting
                                        in a dry product
                for number=1:20

plot3(t,temperature(:,bsorted(number)),moisture(:,bsorted(number)),'color',colour(n
umber,:),'LineWidth',2);hold on;                                %the best
trajectories
                end
plot3(t,temperature(:,bsorted(1)),moisture(:,bsorted(1)),'color',colour(1,:),'LineW
idth',5);hold on
plot3(t,temperature(:,highestvitamin),moisture(:,highestvitamin),'color','g','LineW
idth',5);hold on
axis([t_start max(endtime(b)) min(min(temperature))-1 max(max(temperature))+1 0
moisture(1,1)]);
       xlabel('time [h]')
       ylabel('temperature [°C]')
       zlabel('Moisture [kg w.kg dm^{-1}]')
       view(AZ,EL); grid on
        end
    end
end
if simulation==4
     figure(10);
     plot3(t,temperature(1:size(t),:),moisture(1:size(t),:),'LineWidth',5); hold on
%optimal traj.
     [~,~,~,names] = legend; legend([names {'original optimal trajectory','temp.
boundery 26 °C','temp. boundery 22 °C'}])
End
```

model without data

```
function
[Cv_83,Xw,D_eff,current_time,Psat,Ta_in,crucialTemp,currentVit]=model_without_data(
Xw_start,realtime,dt,starttime,TEMP,lasthour,Xa_in,simulation)

%% constants
dry_matter=0.08; airflow=0.0243;               %starting weight (kg dry weight) and
airflow (kg/s)
thickness_start=0.01; length_start=0.03;       %initial thickness and length of the
slice (m)
volume_start=thickness_start*length_start^2;   %initial volume of the slice (m)
rho_start=1172;                                %measured density of fresh yam
(kg/m3)
rho_w=1000;                                    %density of water (kg/m3)
Xdm=1/(Xw_start+1);                            %dry matter content (dm/kg fresh
weight)
```

```
X_start_fresh=1-1/(Xw_start+1);                   %water content (kg water/kg fresh
weight);
Mass_slice_fresh=volume_start*rho_start*(1-X_start_fresh); %kg dry matter per slice
d=2.297;                                          %shrinkage parameter
Diff=8E-4;  Ea_yam=44060;                         %theoretical Diffusion constant and
activation energy
C1=8.26; C2=0.76; C3=10.14;                       %constants for air equilibrium
moisture content
R=8.3145;                                         %universal gas constant
cp_air=1.005;cp_vapour=1.871;heat_evap=2408;   %heat capacity of dry air and water
vapour and
                                                  specific heat of water
                                           evaporation(kJ/kg)
vitC_start=100;                                   %percentage vit C start
a1=17.94; a2=-2.245E8; a3=-33.33; a4=5921;
a5=-1.585E6; a6=4.711E8; a7=-2.339;               %Mishkin 1983
P1=16.38 ;P2=1.78 ;P3= 1.89; P4=14831;
P5=241.1; P6=656.2; P7=236.8; Rc=1.987;           %Mishkin 1984

%% times
s=1;                                              %step (i), only s=1 possible
start=s+1 ;                                       %starting point (i) of the model
final_loop=realtime*3600/dt;                      %end point (i) of the model
b=0:90;                                           %needed for Crank diffusion equation
%% starting values
thickness=zeros(1,floor(realtime/dt));
volume=zeros(1,floor(realtime/dt));
D_eff=zeros(1,floor(realtime/dt));
Xw=zeros(1,floor(realtime/dt));
mass=zeros(1,floor(realtime/dt));
Tair_p=zeros(1,floor(realtime/dt));
Tproduct=zeros(1,floor(realtime/dt));
k=zeros(1,floor(realtime/dt));
Cv_84(start-1)=vitC_start;
Cv_83(start-1)=vitC_start;
Xw(start-1)=Xw_start; mass(start-1)=dry_matter/Xdm;
Tproduct(start-1)=293; Ta_in(start-1)=TEMP(1)+273;
Tair_p(start-1)=Ta_in(start-1);Xa_out(start-1)=Xa_in;
delta_Xw=0;
crucialTemp=[];
volume(start-1)=volume_start;
thickness(start-1)=thickness_start;
 %%
if simulation<=3
    Psat=[10.^(8.07131-1730.63./(233.426+TEMP))./7.50061561303]; %saturated vapour
pressure
    RH=(Xa_in*101)./(Psat*Xa_in + Psat*0.622);                 %relative humidity
    Xw_eq=C1*C2*C3*RH./((1-C2*RH).*(1-C2*RH+C2*C3*RH))./100;      %product moisture
content in
end                                                             equilibrium with
the RH of the air

  %% the drying model
for i=start:s:final_loop;                                %loop number, running
from start to a
    current_time=dt*(i-start+1);                         %current time for each
loop in seconds
    n=mod(starttime+floor(current_time/3600),lasthour)+1;   %to loop within a
temperature cycle of
                                                         a day, the hours are
                                                  numbered by n
    if simulation==4;                                    %van Olst optimal
drying trajectory
        Psat=[10.^(8.07131-1730.63./(233.426+Ta_in(i-s)-273))./7.50061561303];
        RH=(Xa_in*101)./(Psat*Xa_in + Psat*0.622);
        Xe=C1*C2*C3*RH/((1-C2*RH)*(1-C2*RH+C2*C3*RH))/100;
         if Xw(i-s)>=1.4
             Ta_in(i)=TEMP+273;                          %temperature of the
ingoing air (K)
```

```
        else
                Ta_in(i)=(40.25*Xw(i-s).^4-143.41*Xw(i-s).^3+166.07*Xw(i-s).^2-
89.112*Xw(i-s)+68.156)+273;
        end
    else
            Ta_in(i)=(TEMP(n+1)-TEMP(n))/3600*mod(current_time,3600)+TEMP(n)+273;
            Xe=(Xw_eq(n+1)-Xw_eq(n))/3600*mod(current_time,3600)+Xw_eq(n);
    end
    Tproduct(i)= Tproduct(i-s)+(Tair_p(i-s)-Tproduct(i-s))/10;     %estimation of
product temp. (K)
    Xratio=(mass(i-s)-dry_matter)/mass(i-s);            %moisture content (g water/g
current product)
    Xa_out(i)=Xa_in-dry_matter*delta_Xw/(airflow*dt); %water in the outgoing air
(kg w/kg da)
    cp_p= 0.83736*(1-Xratio)+4.1868*Xratio;             %heat capacity of the product
(kJ/kg)
    delta_Vair=(-delta_Xw/Xw_start)*0.34*volume_start;%air volume incorporated in
the slice (m3)
    volume(i)= volume(i-s)+Mass_slice_fresh*(delta_Xw)/rho_w+delta_Vair;   %slice
volume (m3)
    thickness(i)= thickness(i-s)*(volume(i)/volume(i-s))^(1/d);            %slice
thickness (m)
    Tair_p(i)=(cp_p*mass(i-s)/airflow*(Tproduct(i-s)-
Tproduct(i))/dt+cp_air*Ta_in(i)+Ta_in(i)*Xa_in*cp_vapour+heat_evap*(Xa_in -
Xa_out(i))) /(cp_air+ cp_vapour*Xa_out(i)); % air temperature above the product
surface, based on enthalpy balance (K)

     D_eff(i)= Diff*exp(-Ea_yam/(R*Tair_p(i)))*(volume_start/volume(i))^(-2/d);
     k(i)= -D_eff(i)*pi^2/((thickness(i)/2)^2);
     Xw(i)= 8/pi^2*sum((1./(2*b+1).^2).*exp((2*b+1).^2*k(i)*dt))*(Xw(i-s)-Xe)+Xe;
                                                        %moisture content yam
                                                 (water/kg dm)
     delta_Xw=(Xw(i)-Xw(i-s));                          %negative, difference in
moisture content
                                                        after dt seconds (kg w/kg dw)
     mass(i)=mass(i-s)+dry_matter*delta_Xw;             %current slice weight (kg)

     %vitamin C degradation
     k_Vc_83=exp(a1*Xratio+a2*Tair_p(i)^-3+a3*Xratio^3+a4*Xratio^2*Tair_p(i)^-
1+a5*Xratio *Tair_p(i)^-2+a6*Xratio^3*Tair_p(i)^-3+a7);
     Cv_83(i)=Cv_83(i-s)*exp((-k_Vc_83/60)*dt);       %vitamin C degradation
     kvc0=exp(P1+P2*Xw(i)+P3*Xw(i)^2);
     Ea_Vc=P4+P5*Xw(i)+P6*Xw(i)^2+P7*Xw(i)^3;
     k_Vc=kvc0*exp(-Ea_Vc/(Rc*Tair_p(i)));
     Cv_84(i)=Cv_84(i-s)*exp((-k_Vc/60)*dt);
     if Xw(i)<=2&&isempty(crucialTemp)
         crucialTemp=Tair_p(i);
         currentVit=Cv_83(i);
     end
     if Xw(i)<0.10                               %the product has finished drying
(by definition)
         break
     end
end
```