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Industrial storage of root vegetables: Energy and quality aspects of existing cold-storages.

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ABSTRACT

After harvesting, the Norwegian root vegetables are normally stored at refrigerated temperatures for 5 to 7 months. During this period, up to 30% of the products are lost. The goal is to reduce the diseases, the product loss and energy consumption, in addition to increase shelf-life and storage period. Twenty-eight commercial root vegetable cold-stores were instrumented to measure air temperature, relative humidity and product temperature. The study was done over two years. The cold-stores were located in four different regions of Norway. The three focus-products carrot, swede and celeriac were harvested from one field in each region in open wire nets. The nets were placed in the various cold-stores in the respective regions and put in the wooden bins together with the producer's own products. The quality and yield of the products were determined and correlated to the storage condition. The various storage condition negatively affects the respiration and quality of the root vegetables, storage-life, and influence on the cooling capacity of the refrigeration systems.

Keywords: industrial cold-store, refrigeration, yield, storage-life, carrot, swede, celeriac, post-harvest

1. INTRODUCTION

Long-time storage of vegetables in Norway is necessary but challenging, with an estimated loss of 20-30% mostly due to weight loss and diseases. In 2017, Norwegians consumed 50,200 tons (10.7 kg per capita) of carrot, swede and celeriac (SSB, 2017), and 10-15,000 tons are expected lost before consumption. It is important to reduce the loss of root vegetables during storage, considering global climatic aspects, and economical aspects for the producers who has invested time and cost to grow, harvest and store products.

Traditional refrigeration media have high Global Warming Potential (GWP), and according the Kyoto-agreement, this media will be fased out from the market the next years (Regjeringen, 2014). Already, media like R401a and R22 is not allowed to refill into refrigeration systems due to Ozone-damage effects. To address the coming challenge to phase out traditional refrigeration media with high GWP, the existing refrigeration systems were mapped. Challenges with refrigeration media with high GWP are notified from all around the world, regarding the restrictions according to the EU Reg. No. 517/2014 (i.e. Cardoso et al., 2017, Zhao et al., 2018). Research on new environmentally friendly refrigeration systems show that it is possible with energy-saving rates of 55% to 65% by using CO2 heat pumps (Liu et al., 2016). Systems with hydrocarbons like propane and butane is also suited (Kauffeld and Gund, 2019), with high coefficient of performance (COP) for refrigeration purposes. A more general consideration to reduce energy for systems with a short period with high cooling demand, is use of thermal energy storage (TES). Any improvements in thermal energy management practices can significantly benefit the producers (Alva et al., 2018).

Several hundred vegetable stores in Norway alone, needs to be optimized to maintain the quality of the products. Newer, more stable, energy efficient and environmentally friendly cold-stores are preferred, but it is realistic to assume that it will take decades to renew all the existing stores. An intention to reduce loss of products and go green, with focus on a sustainable food chain are taken all around the world (Wu and Huang, 2018, and Halloran, 2014). To reduce the loss of vegetables in Norway is a small but important contribution to the predicted statement that we must increase global food production by 70% before 2050 (Mc Carthy et al., 2018).

If stored in conditions with misfit relative humidity and higher temperatures, it is known that many vegetables will lose weight and get more diseases. This in interaction with series of biological factors (Baugerød et al., 1986). The temperature should be 0-1°C and relative humidity 95-99%. Studies have shown that storage conditions may play a significant role in creating conditions suitable for latent infections to develop and spread within the bins and packing houses (Thomsen et al., 2018).

In the project Optiroot (2016-2019), the goal is to reduce the product loss of root vegetables during storage by 10%, in addition to increase shelf-life and storage period by two months by linking biology and technology closely together. The work includes i) studies of various fertilisers (balanced micro- and macronutrients) during growing to make the harvested products 'prepared' for storage, ii) studies of optimal wound healing periods before stable storage, iii) optimization of existing vegetable cold-houses, presented in this paper, iv) designs for future cold-stores, and v) optimization of plastic layers inside the wooden bins.

2. MEASUREMENTS AND METHODS

2.1 Survey areas and location of cold-stores

Norway is a long country far up north, where the golf stream gives mild and moist winters by the cost, but cold and dry climate inland. A study to see how the climate variations affect the storage air in cold-stores was performed in four different regions in Norway: i) Mid – Middle part of Norway, north of Trondheim, ii) Rog – Southwest, south of Stavanger, iii) Osl – Southeast, both sides of the Oslo-fjord, and iv) Inn – East, Inland around Lillehammer. Weather data like air temperature and relative humidity for the regions were collected for the periods of two season (Sept to April) from MET (The Norwegian Meteorological Institute).

2.2 Storage of root vegetables, product temperature and weight lose measurement

Carrot, swede and celeriac were harvested from one field in each region in 10-20 kg (100 carrot or 25 swede/celeriac roots) open wire nets. The nets were placed in the twenty-eight various cold-stores in the respective regions and dug down in four wooden bins at each store together with the producer's own products. The weight of the root vegetables was weighed before and after the two storage seasons. The temperature and relative humidity were measured in the circulation air and inside the product in the wooden bins placed randomly together with the other bins. Signatrol SL51T ibuttons and EasyLog USB-2-LCD+ dataloggers were used.

2.3 Calculation of cooling demand

A new, more tailored excel-based calculation program has been developed (NLR, SINTEF), and linked to MET data for outdoor air- and ground (product) temperatures for the various regions. The respiration energy as function of temperature were included (Hoftun, 1980). The daily rate of stocking was defined by total storage capacity and expected harvesting period. Removing heat from the products were linked to the empirical data on measured cooling rate of the root vegetables. Other factors included were heat through buildings, condensation of moist on evaporators due to respiration, and air change (prevent CO_2 accumulation).

3. RESULTS AND DISCUSSION

3.1 Calculation of cooling demand

The respiration energy as function of temperature were included (Fig. 1a). There was not found any verified data for respiration loss for celeriac (Fig 1b), but the temperature dependent loss is assumed to be close to the ones for carrot and swede (Fig.1a). Removing the respiration heat is the most significant factor regarding cooling demand during stocking, closely followed by the cooling demand to lower the product temperature. The calculated worst-case scenarios resulted in a designed cooling capacity 20% lower for some regions in Norway, compared with the general worst-case scenarios used by refrigeration suppliers. The average cooling demand mid-term was around 10% compared to the stocking period.

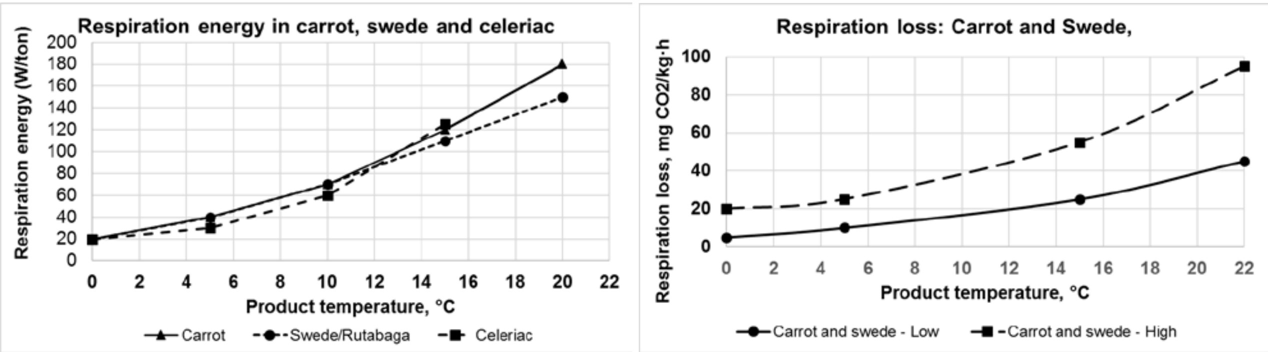

Figure 1: Respiration energy (1a, left) and respiration loss (1b, right) for carrot, swede, celeriac

3.2 Principles for air distribution in cold-stores

Between the twenty-eight cold-stores, there were seven different strategies to distribute the air through and between the bins. The four most used principles are shown in Fig. 2.

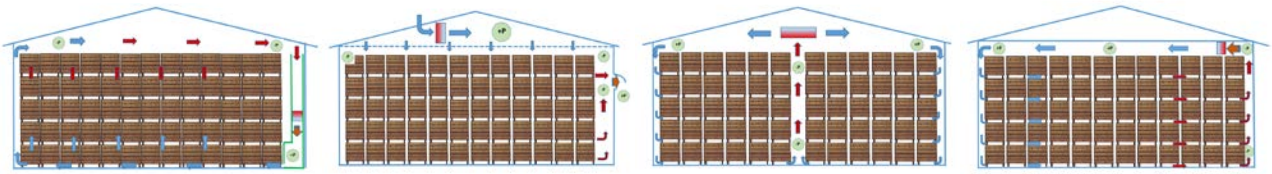

Figure 2: Four most common principles for air distribution in the cold-stores. From left: a) Findus, b) Grae, c) Trad. air circulation – mid-evaporator and d) Trad. air circulation – rare-evaporator.

The seven different strategies to circulate the air: a) Chimney heat rise (Findus), b) Ceiling suction (Grae), c) Traditional air circulation, evaporator placed in the ceiling in the mid-part of storage and distribute air to both sides, d) Traditional air circulation, evaporator placed in the ceiling in the rare of storage, e) Traditional air circulation, evaporator near floor in the rare of storage and air distributed by ventilation pipes up and forward, f) Concrete basement of farmhouse, no mechanical air distribution, g) Suction wall system, fans sucks air through channels in back wall.

Ten cold-stores have installed humidifiers. The two main types installed were high pressure nozzles (Noz. - atomise small water droplets), and mechanically sprayed evaporator (Evap.- water vaporized and brought to the circulated air).

3.3 Mapping of existing cold-stores

An overview of the twenty-eight cold-storse are presented in Table 1. From Table 1, the necessary cooling demand can be found empirical. Enough cooling capacity was judged by the ability to maintain the circulated air temperature close to set-point during the storage period. It seems that cold-stores with a cooling capacity less than 0.12 kW/ton did not have enough capacity(-). Between 0.13 and 0.20, it seemed ok(+), and over 0.20 it was more than needed(++). One exeption was a larger, new system (Inn3/Inn7) with 0.09 which had ok(+) cooling capacity.

Table 1: Operating and mechanical parameters for the twenty-eight cold-stores.

Producer code	Product	Plastic liner in bin	Storage capacity, tons	Air circ. System *1)	Humidifier	Fresh air	Cooling capacity, kW *2)	Energy Efficiency Ratio (EER)	kW cooling cap per ton product	Abs. power, kW at 10°C	Installed kW/ton	Enough cooling capacity *3)	Installed kW per 100 tons	Refrigeration media	Dir evap., DX
Mid1	Carrot	yes	250	a)	Noz.	Fan	114	3.00	0.46	38	0.15	++	15.2	R410a	No
Mid2	Carrot	yes	1200	c)	No	Fan	170	4.05	0.14	42	0.04	+	3.5	410a	no
Mid3	Swede	no	350	e)	Noz.	Slot	62	3.44	0.18	18	0.05	+	5.1	R1234z	yes
Mid4	Swede	no	520	a)	No	-	123	3.00	0.24	41	0.08	++	7.9	410a	no
Mid5	Carrot	yes	1100	c)	No	-	133	3.00	0.12	44.4	0.04	-	4.0	R22	no
Mid5b	Carrot	yes	345	c)	yes	-	165	3.37	0.48	49	0.14	++	14.2	R134a	yes
Rog1	Carrot	yes	400	d)	No	-	86	3.31	0.22	26	0.07	?	6.5	R22	yes
Rog2	Carrot	yes	350	e)	Noz.	Slot	62	3.44	0.18	18	0.05	+	5.1	R1234z	yes
Rog3	Carrot	yes	1800	d)	no	Fan	166	3.29	0.09	50.4	0.03	-	2.8	CO2	yes
Rog4	Swede	yes	330	d)	no	-	32	2.42	0.10	13.2	0.04	?	4.0	507a	yes
Rog5	Swede	no	360	d)	no	-	90	2.81	0.25	32	0.09	++	8.9	401a	yes
Inn1	Carrot	no	500	a)	no	Slot	57	2.71	0.11	21	0.04	-	4.2	R407c	no
Inn2	Carrot	yes	800	d)	Noz.	-	243	3.00	0.30	81	0.10	++	10.1	R134a	yes
Inn3	Carrot	yes	3050	c)	Noz.	Slot	265	4.05	0.09	65.5	0.02	+	2.1	R1270	no
Inn4	Swede	no	80	f)	no	Gate	Air	-	-	-	0.00		0.0		
Inn5	Swede	no	180	a)	no	Fan	Air	- .	- .	-	0.00		0.0		
Inn6	Swede	no	300	b)	Evap.	Fan	20	3.64	0.07	5.5	0.02	-	1.8	R404a	yes
Inn7*	Swede	no	3050	c)	Noz.	Slot	265	4.05	0.09	65.5	0.02	+	2.1	R1270	no
Inn8	Swede	no	200	d)	Noz.	-	30	3.00	0.15	12.6	0.06	+		R22	yes
Osl1	Carrot	yes	2700	c)	no	Fan	474	3.00	0.18	158	0.06	+	5.9	R507a	no
Osl2	Carrot	yes	110	c)	no	-	66	3.00	0.60	22	0.20	?	20.0	R22	yes
Osl3	Carrot	yes	350	d)	no	-	50	3.00	0.14	16.5	0.05	+	4.7	R22	yes
Osl4	Swede	no	700	c)	no	-	200	2.82	0.29	71	0.10	++	10.1	R134a	no
Osl5	Swede	no	400	a)	no	Slot	126	3.00	0.32	42	0.11	++	10.5	R407a	no
Osl6	Swede	no	220	d)	no	-	50	3.33	0.23	15	0.07	?	6.8	CO_2	yes
Osl7	Celeriac	no	300	g)	Evap.	Slot	60	3.00	0.20	20	0.07	+	6.7	134a	yes
Osl8	Celeriac	no	360	a)	no	-	114	3.00	0.32	38	0.11	?	10.6	R410a	no
Osl9	Celeriac	no	225	d)	no	Slot	77	3.00	0.34	25.6	0.11	++	11.4	R404a	yes
Osl10	Celeriac	no	50	b)	Evap.	Fan	8,4	3.00	0.17	2.8	0.06	? .	5.6	134a	yes

*1) Air circulation system refers to the listed air distribution principles in 3.2. *2) The cooling capacities marked in red are unknown, but calculated by an energy efficiency ratio (EFR) of 3.0. *3) Sufficient cooling capacity was judged by the ability to maintain the circulation air temperature close to set-point during the stocking period, (-) Not enough, (+) ok, and (++) more than enough. Inn7* - same refrigeration system as Inn3, but different room/cooling cell.

Traditional refrigeration media have high global warming potential, and the GWP values in Table 2 refered to kg CO_2-eqv. per kg gas. Only 5 of the 26 cold-stores with refrigeration contain refrigerants suited for the future. It could be risky to postpone a change to environmentally friendly refrigeration units, and hope for not a leakage. During season 1, eleven cold-stores and in season 2, seven cold-stores had a breake-down influencing the product temperature. It will be necessery for the industry to plan a significant reinvestment in new environmental friendly systems in the years to come. An increase in product temperature and respiration rate is especially critical at the end of the storage period, for the development of diseases that had been suppressed for a long time.

Table 2. Refrigeraion media in the mapped cold-stores

Producer	Refrig. media	GWP	Year of phase-out (EU)
Rog4, Osl1	R507a	3985	2020
Inn6, Osl9	R404a	3922	2020
Mid1, Mid2, Mid4, Osl8	R410a	2088	2022
Inn1, Osl5	R407a	2107	2022
Mid5b, Inn2, Osl4, Osl7, Osl10	R134a	1430	2025
Rog5	R401a	1182	Not allowed, O_3
Mid5, Rog1, Inn8, Osl2, Osl3	R22	1810	Not allowed, O_3
Mid3, Rog2	R1234ze	7	
Inn3 = Inn7	R1270	2	
Rog3, Osl6	CO_2/R744	1	

3.4 Outdoor climate correlated with cold-store air

The storage air parameters (Temperature and relative humidity) in cold-stores with no humidifiers are presented in Fig. 3 and correlated with average outdoor air for the regions Mid, Osl, Inn and Rog. The weather varies among the regions, and the ambient air influences the indoor storage air parameters negatively for the stores without humidifiers. The indoor air tended to have parameters closer to the ambient air. It is most essential to manipulate the storage air by adding moist mechanically in regions with higher winter temperatures (coastal regions in Norway). This was opposite of what might be expected regarding the facts that the relative humidity in the ambient air increases when entering the cold-store (Fig. 4b). The higher ambient temperature increased the time for the refrigeration system to run, and more water from the air condensate on the evaporators.

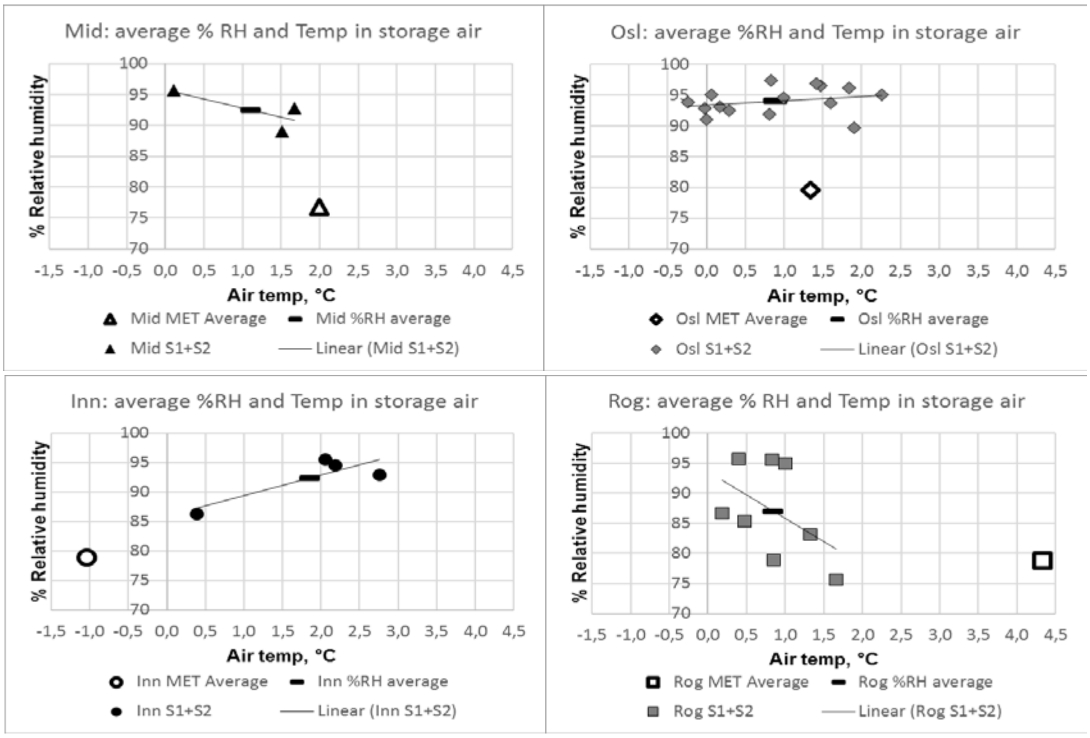

Figure 3: Temperature and relative humidity in cold-store air correlated to ambient air. Each dot in the figure represents one cold-store, and S1 and S2 refers to season one and two.

Fig. 4a shows that the ten cold-stores with humidifiers had significant higher relative humidity than most of the cold-stores without humidifiers. Swede and celeriac are normally stored without plastic liners inside the wooden bins and are more exposed for dehydration. Carrot is mostly stored with plastic liners with small holes and is not affected much by lower humidity in the air.

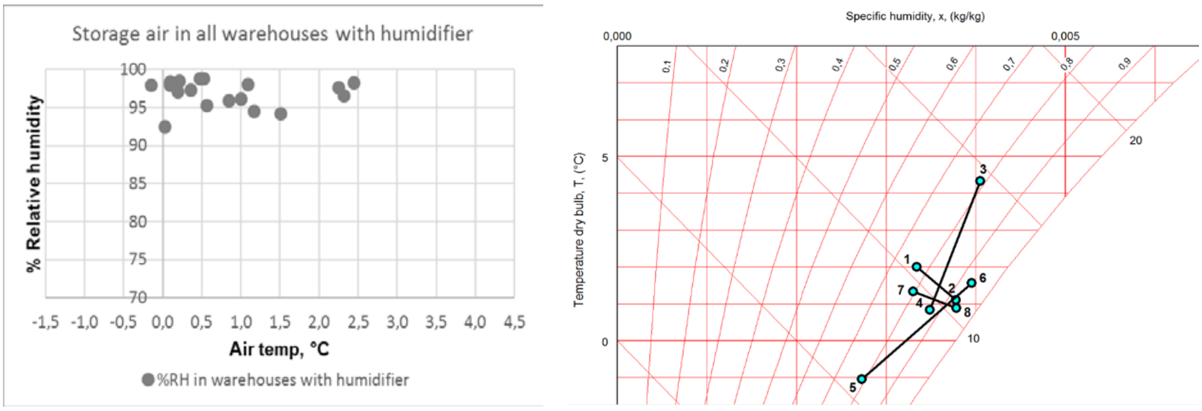

Figure 4: Relative humidity in cold-stores with humidifiers is higher and more stable than without (Fig. 4a-left). Refrigerated air in correlation with ambient air in Mollier diagram (Fig. 4b-right).

3.5 Mapping of cold-store air temperature and relative humidity

The circulation cold-store air and the product temperature (inside the bins) were measured during two storage seasons. The weekly average temperatures are shown in Fig. 5-12.

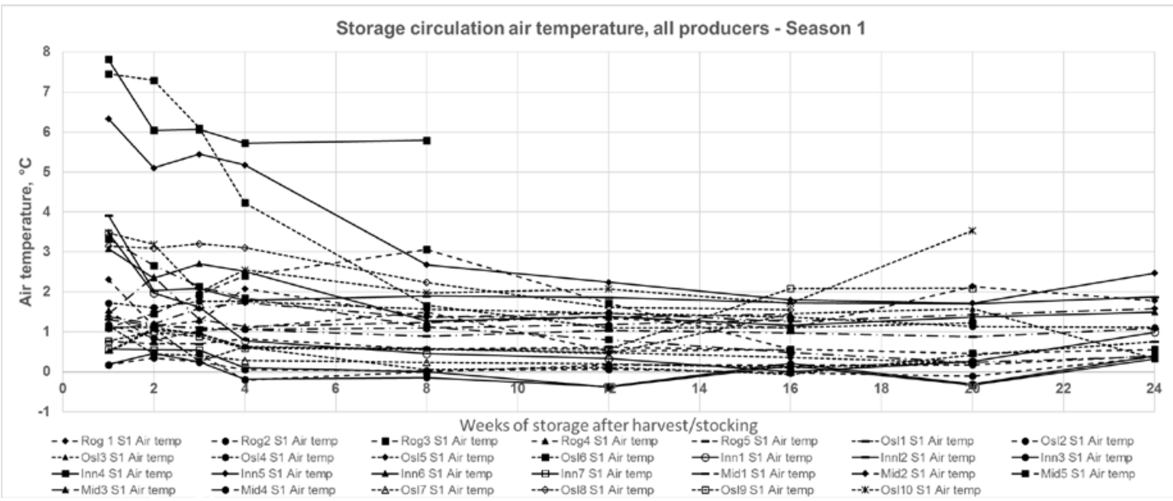

Figure 5: Air temperature during storage in 28 cold-stores season 1, all producers

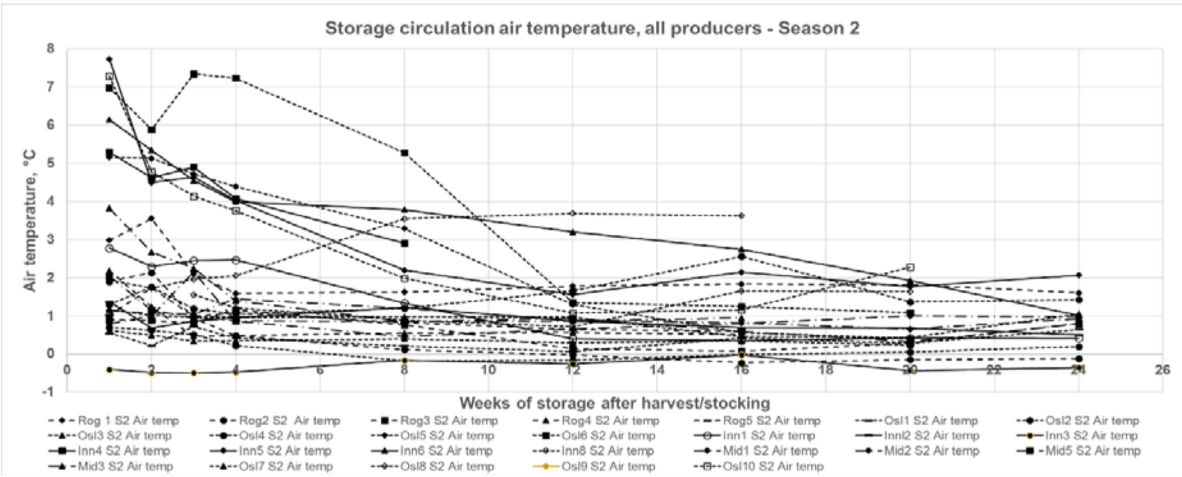

Figure 6: Air temperature during storage in 28 cold-stores season 2, all producers

3.6 Mapping of product temperature during storage

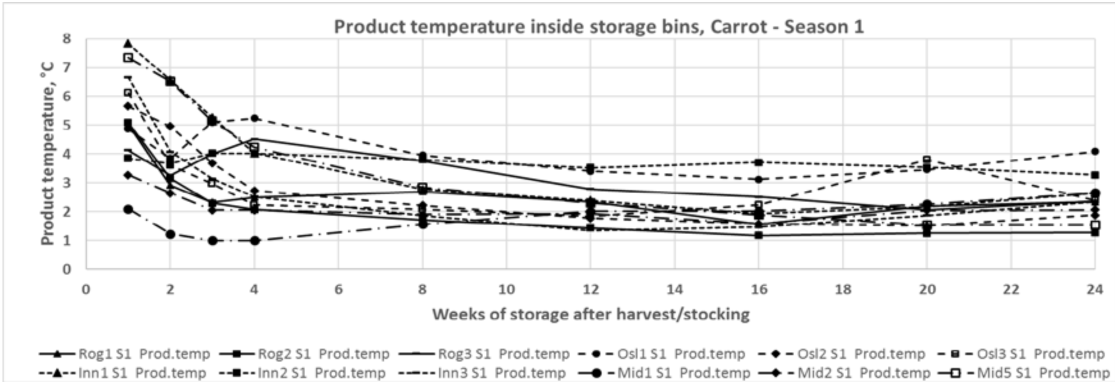

Figure 7: Carrot, season 1: Product temperature (inside bins) during storage

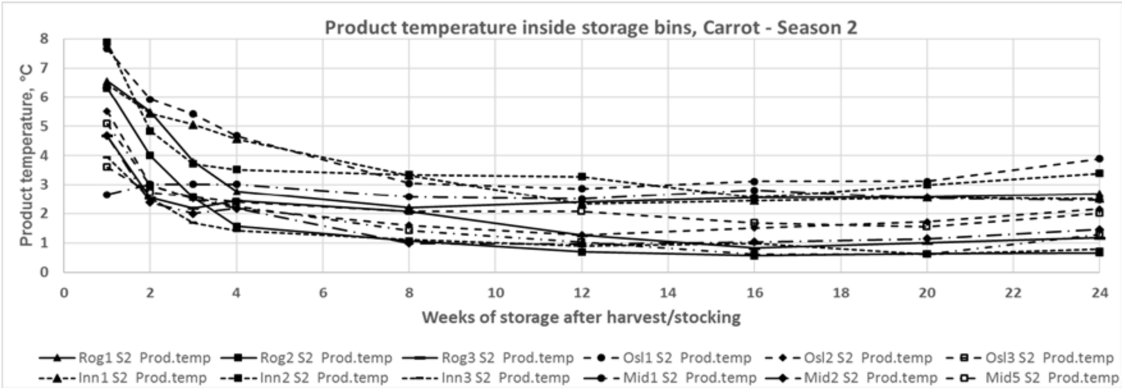

Figure 8: Carrot, season 2: Product temperature (inside bins) during storage.

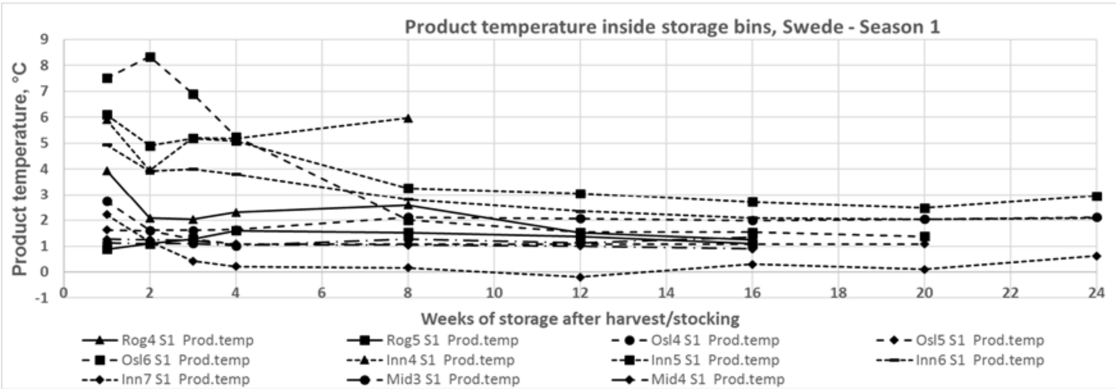

Figure 9: Swede, season 1: Product temperature (inside bins) during storage.

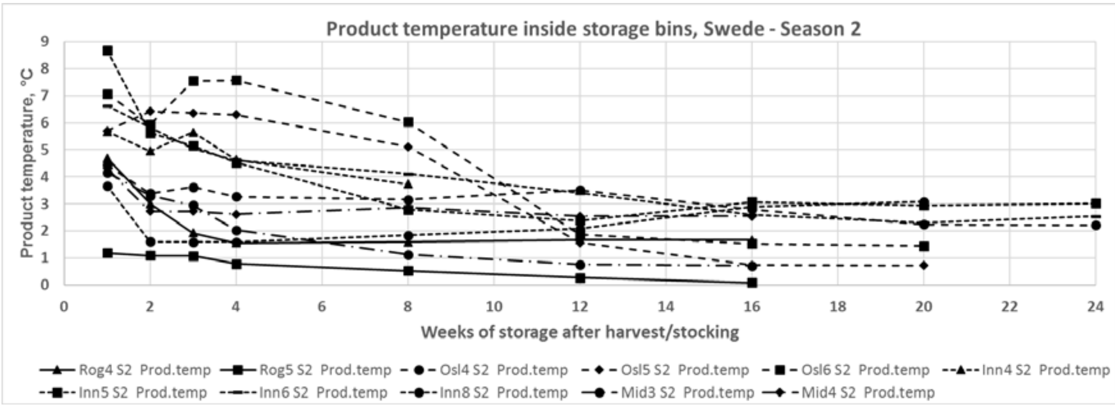

Figure 10: Swede, season 2: Product temperature (inside bins) during storage.

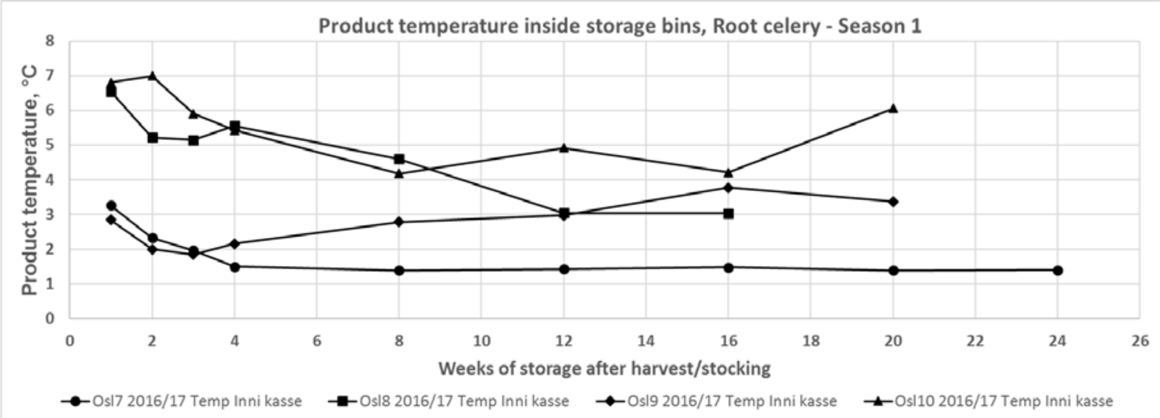

Figure 11: Celeriac, season 1: Product temperature (inside bins) during storage.

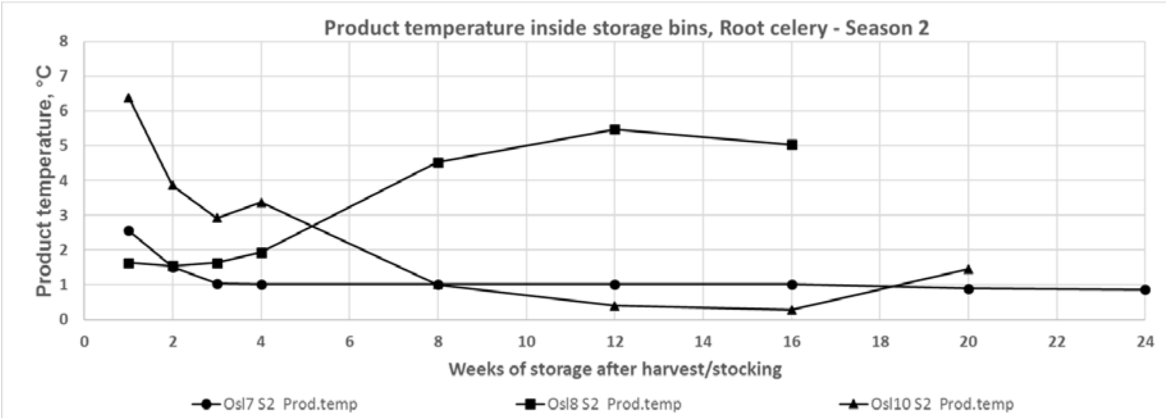

Figure 12: Celeriac, season 2: Product temperature (inside bins) during storage.

As seen in Fig. 1b earlier, the respiration loss due to conversion of sugar and O_2 to CO_2 and H_2O was very dependent on the product temperature. The influence of temperature over time is essential because the storage-life will dramatically reduce when the loss of weight from respiration is between 20-25 g per kg product (Hoftun, 1980). The products accumulated day-degree (average product temperature per day over x days) is presented in Fig. 13, together with the limits where the expected loss of 20-25g/kg occurs. There was an increase in storage-life from 15 to 30 weeks if the average product temperature was 1°C instead of 6°C. The average day-degree (red curve) for all products showed an expected storage-life of 18.5-24 weeks. If the cold-stores with the 50% highest product temperature lower their product temperature equal to the 50% with the lowest temperature (green curve), it is expected that the storage-life will increases to 21-27 weeks. The development of disease in the various cold-stores related to the storage parameters will be presented in a separate article.

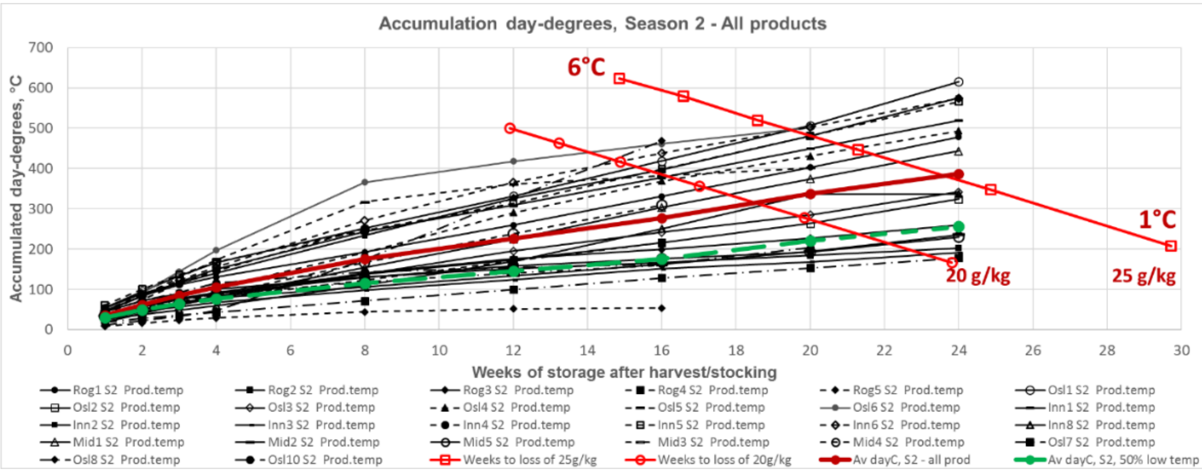

Figure 13: Accumulated day-degrees influenced the expected shelf-life of the products.

3.6 Weight loss related to temperature and relative humidity.

It was expected that the weight loss will increasing when the relative humidity was low in the cold-stores, but as seen from Fig. 14, this was not detected. The reason for this could be that the nets were placed the core of the bins where the relative humidity was close to 100% during the whole storage period.

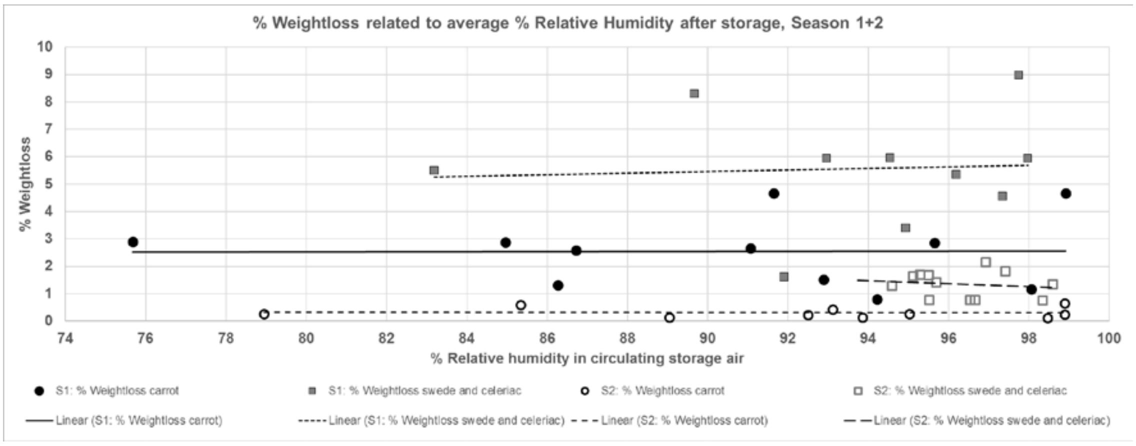

Figure 14: Weight loss of product related to relative humidity in the cold-store during storage.

There was a difference in the weight loss for the three products between the two seasons. It was not possible to conclude the reason for this, other than that the climate was different between these two seasons.

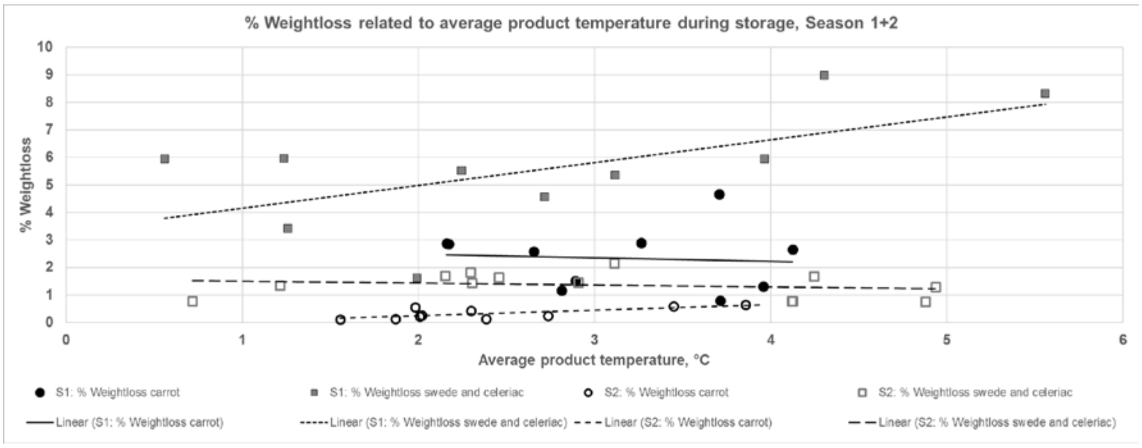

Figure 15: Weight loss of product related to product temperature during storage.

When the weight loss was correlated with average product temperature, there was a tendency that the weight loss increased when the temperature increased at least in season1 for Swede and Celeriac (Fig. 15). As mentioned, the analysed nets were placed inside the bins, so the circulating air did not have much influence. The increased weight loss was therefor likely due to increased respiration loss caused by increased temperature. As mentioned, have studies shown that storage conditions may play a significant role in creating conditions suitable for latent infections to develop and spread within the bins and packing houses.

4. CONCLUSION

Twenty-eight different commercial cold-stores for carrot, swede and celeriac located in four regions in Norway were studied regarding energy and quality aspects. The climate variation between the regions affected the indoor refrigerated air in cold-stores without humidifiers. Unsuitable storage condition negatively affects the respiration and quality of the root vegetables and storage-life, and influenced on the cooling capacity of the refrigeration systems. Quality of the products reflects on the storage parameters but is mostly related to disease brought into the storage with the products from the fields.

There was no difference in product temperature between the seven different principle of air distribution in the cold-stores, except for the Chimney heat rise (Findus) stored with carrot. A very limited amount of circulated air in this system affect the ability to remove the respiration heat. The Grae-principle is only suited in areas with very cold climate, because the storage air is sucked out to maintain negative pressure in the storage room.

The level of optimization and energy reduction of the existing refrigeration systems must affect the fact that there is a huge variation in age, cooling capacity and services between the systems. The cooling demand is highly variable during the season, and many systems do not have good regulation. Optimization must be done individually with various initiatives for each producer. A general way to improve the systems is to reduce the cooling capacity by energy storage. Respiration is the most significant factor regarding cooling demand, close to lowering the product temperature. The calculated worst-case scenarios resulted in a designed cooling capacity 20% lower for some regions in Norway, compared with the general worst-case scenarios used by refrigeration suppliers.

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