D4.1: IoT-enabled Quality Controlled Logistics demonstration results

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Abbreviations

EMS	Environmental Monitoring Systems
EPS	Euro Pool System
GPRS	General Packet Radio Service
IoT	Internet of Things
ppb	parts per billion
ppm	parts per million
QCL	Quality Controlled Logistics
TNO	Nederlandse Organisatie voor Toegepast-Natuurwetenschappelijk Onderzoek
UC	Use Case
UMTS	Universal Mobile Telecommunications System
VOU	Van Oers United
WFBR	Wageningen Food & Biobased Research
WUR	Wageningen University & Research

Abstract

Food supply is a big challenge that our global society faces, and supply chain innovations are expected to contribute to a more secure, efficient and sustainable food supply. One of the promising innovations is to apply Internet of Things (IoT) to create the so-called data-driven food supply chain with quality-controlled logistics. To investigate the feasibility of this innovation, Wageningen Food & Biobased Research (WFBR) and TNO jointly developed a project within the NWO Dinalog financing framework to study IoT applications in the Fruits and Vegetable supply chains. The project includes 6 work packages:

- WP1 IoT enabled Quality Controlled Logistics (QCL), including a conceptual framework on IoT enabled QCL, the state-of-the-art supporting technologies, and a SWOT analysis of this QCL-concept.
- WP2 Business analysis, including the use cases for demonstration, the business case analysis and the business model analysis.
- WP3 Design and Solution Development, including the development work needed to demonstrate a proof of concept in a real-life setting.
- WP4 Demonstrations, covering a demonstration of the use cases in a maritime and a continental road trade lane.
- WP5 Evaluation and valorization, ensuring that the project knowledge is being disseminated among the target audience and support a broader valorization of the project insights.
- WP6 Project Management, assuring an overall efficient execution of the project and organizing and facilitating the cooperation between the consortium parties.

As part of WP 4, the aim of the research in this report is to proof the concept of quality controlled logistics in an integrated way. In order to demonstrate the proof of concept the overall comprehensive concept is split into 5 use cases as a basis for this demonstration. These use cases are:

- Use Case 1a: High quality ethylene monitoring during perishable shipment transport;
- Use Case 1b: Low-cost IoT solution for real-time perishable shipment status sensoring;
- Use Case 2: Optimal sensor positioning in perishable shipment;
- Use Case 3: Sensor-enabled quality decay predictions of a shipment;
- Use Case 4: Decision support for logistics interventions driven by quality decay predictions.

Thereafter these use cases are grouped into 3 practically feasible demonstrations, namely:

1. Real-life detection of ethylene (= UC 1a)
2. Optimal sensor positioning (= UC 2)
3. Real-time detection of the conditions that enable predictions of quality loss in order to achieve decision support for logistics interventions (= UC 1b, 3 & 4)

The three demonstrations can be divided into two categories, i.e., demonstrations 1 and 3 are carried out in practice whereby products are tracked and monitored during road transport. Demonstration 2 concerns a so-called 'theoretical demonstration'. Here it is investigated by means of models and mathematical comparisons whether it is possible to determine the optimal sensor positioning in perishable shipments.

In this report, the demonstrations are described in order to subsequently reflect the learnings and conclusions.

1 Introduction

1.1 Describing the concept to be proofed

In supply chains of fresh and perishable food products even minor disruptions in storage/transport conditions can have a considerable effect on product quality. A lack of insight in (changes of) product quality during storage and transport leads to challenges in managing the quality/shelf life of fresh produce, uncertainties in claim processes, food loss and waste throughout the supply chain, and difficulties to deliver according to agreed product quality standards.

The concept of quality controlled logistics (Vorst et al, 2007), addresses these challenges. Follow up research (Vorst et al., 2012) identifies the possibilities for making chain information directly and real-time available and usable to support decision making of all partners in the horticultural network but concludes that an integrated approach of quality-controlled logistics is still lacking.

The Internet of Things (IoT) offers promising opportunities for monitoring the quality of perishable cargo en-route and in real-time, which may be used to mitigate large amounts of product losses. Containers, pallets, crates or single products can be equipped with sensors and wireless communication devices to provide real-time product data. With quality- and shelf-life predictions available at any time, the supply chain can be adapted in order to reduce product losses. This is also recognised by the consortium partners. By capturing sensor data and using it as input for quality decay models, the aim is to proof the concept of quality controlled logistics in an integrated way.

In order to demonstrate the proof of concept the following 5 use cases have been defined as a basis for this demonstration:

1. Monitor international shipments and capture and disclose sensor data in real-time for quality decay modelling
   a. **High quality ethylene monitoring during perishable shipment transport**; Monitor international shipments with high quality ethylene sensors in order to use this as input data for quality decay modelling of the perishable cargo.
   b. **Low-cost IoT solution for real-time perishable shipment status sensoring**; Monitor international shipments with multiple low-cost sensors using novel IoT technology to capture and disclose the data in real-time for downstream processing.
2. **Optimal sensor positioning in perishable shipment**; Apply sensors on different locations within a truck or container and analyse the differences in sensor values in order to advise on the number and location of different sensors and to provide input for the feasibility of the business case of embedded sensors in pallets or crates.
3. **Sensor-enabled quality decay predictions of a shipment**; Provide quality decay predictions based on sensor values of relevant sensors attached to the international shipment(s) of perishables. Relevant sensors include sensors that can sense, log and measure environmental conditions in the reefer container or truck quality decay indicators such as ethylene, temperature, O_2, CO_2 and relative humidity that tell something about the effect these conditions have on product quality and/or are an indication of the fact that the quality of the product is deteriorating.
4. **Decision support for logistics interventions driven by quality decay predictions**; Configure possible logistics interventions and provide decision support on executing these interventions based on the quality decay predictions and remaining transport lead time of corresponding shipments.

The picture below (Figure 1) shows how the use cases link to the key concept building blocks.

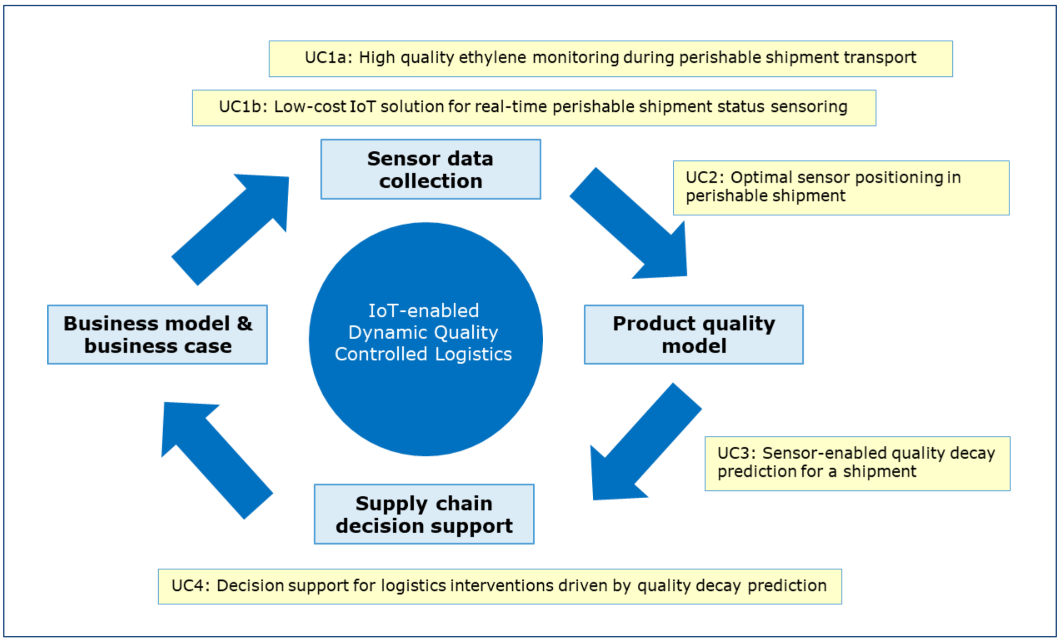

Figure 1 The link between the IoT4AGRI use cases and the conceptual building blocks of IoT-enabled dynamic quality controlled logistics. (Zomer, G., Bhoraskar, A., 2021)

1.2 How to proof the concept

In order to be able to operationalize, together with the project partners, the use cases in a real-life setting as pragmatically as possible it was subsequently decided to group them logically in so-called demonstrations.

1.2.1 Use Cases vs. Demonstrations

In the context of this project, these 5 use cases are grouped in 3 demonstrations. This means mainly that the use cases 1b, 3 and 4 have been merged into one logical demonstration to proof the concept of real-time detection of the conditions that enable predictions of quality loss in order to achieve decision support for logistics interventions. See Figure 2.

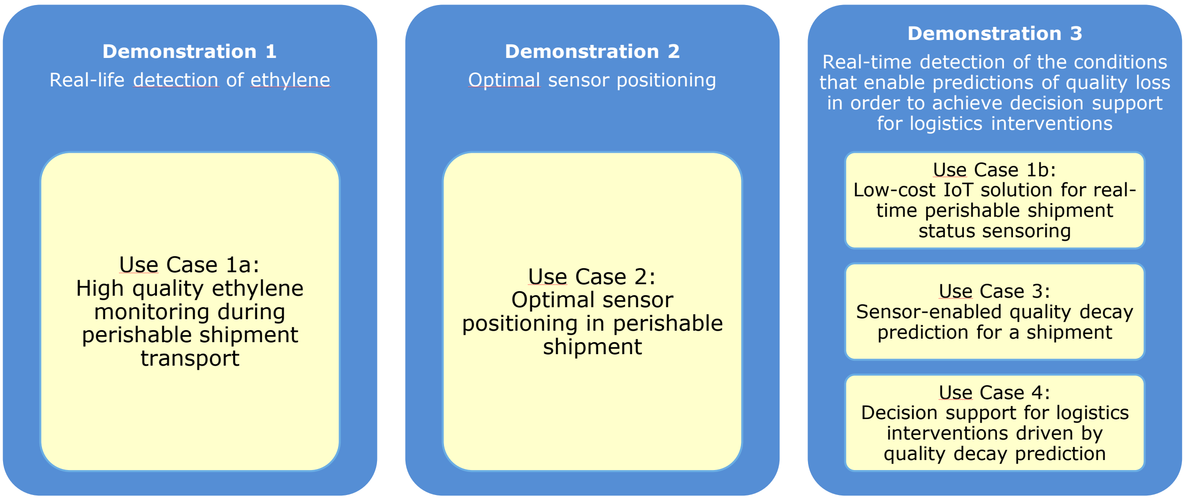

Figure 2 Relationship between Use Cases and project Demonstrations

By grouping the use cases into 3 demonstrations it is also possible to logically link the various partners within the project to a specific subject, i.e., demonstration. The breakdown is as follows:

- Demonstration 1: Van Oers United (VOU) and Environmental Monitoring Systems (EMS).
- Demonstration 2: Thermo King and Euro Pool System (EPS).
- Demonstration 3: Van Oers United (VOU) and Impact Smart Solutions[1].

1.2.2 Demonstration setup

The three demonstrations can be divided into two categories, i.e., demonstrations 1 and 3 are carried out in practice whereby products are followed during road transport. Demonstration 2 concerns a so-called 'theoretical demonstration'. Here it is investigated by means of models and mathematical comparisons whether it is possible to determine the optimal sensor positioning in perishable shipment.

In addition to indicating the objectives of the demonstrations, also the table template below will be filled to give a clear overview of the demonstration parameters and the consortium members involved.

Table 1 Demonstration parameters

Demonstration parameters	
Type of transport	
Condition settings	
Product	
Organizations	
Route	
When	
Number of transports	
Sensing and Logging	

[1] During the duration of the project, Het Internet Huis has changed its name to Impact Smart Solutions. In this report we will still refer to the name as formally included in the project proposal.

2 Demonstrations

2.1 Demo 1: Real-life detection of ethylene

2.1.1 Ethylene

As indicated in the State of the Art and SWOT-analysis work of this project (Finner & Zomer, 2020) ethylene or ethene is an organic gas with the chemical formula C2H4 that is naturally produced by plants. It is one of the substances released during the ripening process of fruit and vegetables. In addition, it triggers, stimulates and accelerates fruit ripening by acting as a ripening hormone and production by the fruit or vegetable can increase strongly (by a factor of up to 100) due to the presence of ethylene in ambient air or in response to physical damage to the fruit or vegetable. Ethylene plays a major role in the quality of fruit and vegetables. To retain the quality of fresh produce during transport, which is often needed in long supply chains, however, the goal is to not induce ripening, but to prevent it or slow it down. This can be done by removing ethylene gas through ventilation, by ethylene absorbing materials like potassium permanganate, or by adding ozone, which can destroy ethylene by oxidation. The effect of ethylene can also be reduced by lowering oxygen levels in combination with high CO_2, or by adding synthetic compounds (e.g., 1-MPC), whichblock ethylene receptors at the skin of fruit and vegetables. The gas 1-MCP is also often applied in the flower industry to maintain the freshness of cut flowers.

For this insight in the ripening of perishable cargo the levels of respiratory gases like oxygen, carbon dioxide and ethylene it should be monitored and tracked. While typical concentrations and concentration changes of oxygen and carbon dioxide lie between 0.1% – 20%, the sensitivity of an ethylene detector should be at a level of several parts per billion (ppb) to accurately monitor and predict the ripening status of the produce. That is why this demonstration focusses on high quality ethylene measuring. (Finner & Zomer, 2020).

2.1.2 Ethylene sensing device (SKID)

Environmental Monitoring Systems (EMS) developed a so-called SKID (see Figure 3). This SKID is a high-end device/sensor that senses, logs and transmits not only Ethylene but also O_2, and CO_2 levels via GPRS / UMTS. The concentration ranges to be detected are for Ethylene: 0 – 5.000 ppb, CO_2: 0 - 100.000 ppm (10%) and O_2: 0 – 25%. The SKID also logs Temperature and (Relative) Humidity. Besides sensing Ethylene, O_2, CO_2, Temperature and (Relative) Humidity also GPS-tracking is relevant. To make this possible the sensing device of EMS is also equipped with these functionalities, and thus able to monitor and transmit the Ethylene, O_2, and CO_2 data in real-time. This sensing device is placed as separate device/sensor between the cargo in the trailer.

Figure 3 ***Sensor for, among other things, sensing of Ethylene manufactured by EMS, so-called SKID (source: EMS)***

As mentioned also Temperature and (Relative) Humidity will be monitored and logged, but not real-time transmitted or uploaded to a dashboard. These logged and stored Temperature and (Relative) Humidity data from the SKID will be placed next to the other values (Ethylene, O_2, CO_2) after the shipment. The logged and stored Temperature and Humidity data are from the Xsense sensors owned by VOU (temperature from -35°C to +50°C and humidity from 20% to 95%)

2.1.3 Demonstration goal and setup

Goals:

- Proof-of-concept of real-life and real-time data communication with EMS cloud-solution.
- Proof-of-concept of real-life and real-time tracking of the transport and relevant transport conditions.
- Investigate what frequency of data-update is needed to get a good insight into the transport conditions.
- Investigate the connectivity between the ethylene sensor and the EMS cloud solution.

2.1.4 Demonstration activities and consortium members roles

Table 2 Parameters of demonstration 1

Demonstration parameters	
Type of transport	Mixed (vegetable) cooled transport by road
Condition settings	Temperature setting according to instruction is 0 degrees Celsius
Product	Mainly brussels sprouts
Organizations	Van Oers United (shipper), Kesko (client), EMS (producer ethylene sensor and platform provider)
Route	From the Netherlands to Finland
When	From October 15, 2021 till October 17, 2021
Number of transports	1
Sensing and Logging	- Oxygen (logging and real-time communication) via SKID - Carbon Dioxide (logging and real-time communication) via SKID - Ethylene (logging and real-time communication) via SKID - Temperature (logging) via SKID and Xsense - Relative Humidity (logging) via SKID and Xsense

For this demonstration the following activities were needed:

- drawing up procedure for operating and placement of ethylene sensing device and temperature logger by VOU and EMS;
- drawing up procedure for delivery and return of ethylene sensing device and temperature logger (both for personnel from VOU and Kesko) by VOU;
- drawing up communication (to the cloud) procedure and sharing real-time data by EMS.

2.1.5 Real-life shipments with high quality ethylene sensor results

The shipment from the Netherlands to Finland took place between October 15th, approximately 09.30 pm to October 17th, approximately 11 am by truck. The cargo was a mix of vegetable, but mainly brussels sprouts cooled transport.

2.1.5.1 Real-time transmitted information

The graphs below represent the sensor output from the SKID for Oxygen, Carbon Dioxide and Ethylene during shipment between October 15th, approximately 09.30 pm to October 17th, approximately 11 am. The data and the GPS coordinates were sent to the cloud of EMS in real-time.

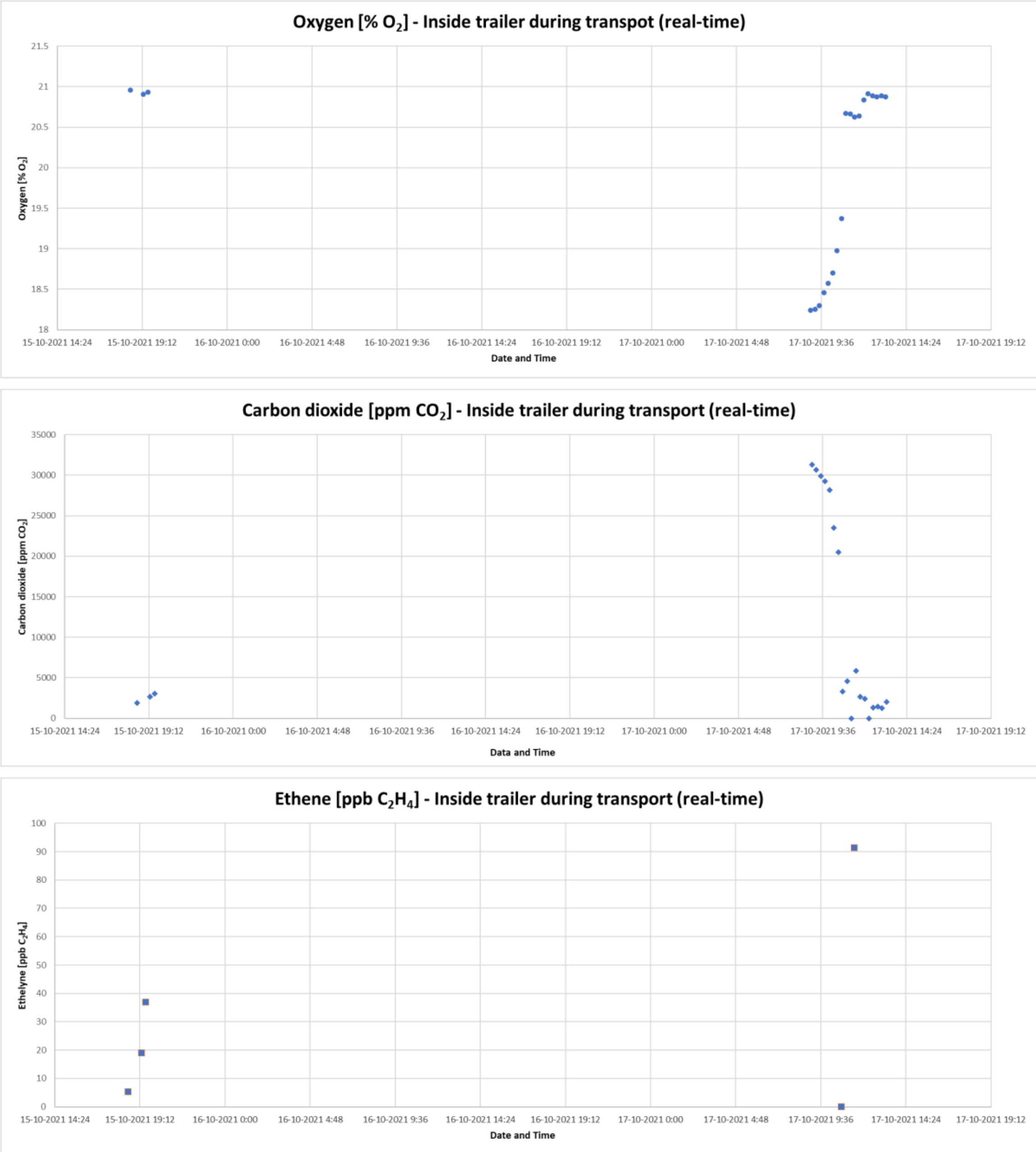

Figure 4 ***SKID registered real-time values of Oxygen, Carbon Dioxide and Ethylene during transport between October 15th, approximately 09.30 pm to October 17th, approximately 11 am (Source: SKID / EMS)***

Connectivity lost during transport

Figure 4 shows that there was a period of non-connectivity from the moment the SKID is put in the trailer. As soon as the SKID is unloaded, the connection is restored again, and that the data are visible via the EMS cloud service. Unfortunately, the cause for this connection loss could not be traced. However, it is suspected that by placing the SKID at the front of the trailer, the signal is blocked due to the presence of metal (back wall and corner profiles).

This thus demonstrates that the position of the logger is of the utmost importance for being able to connect to the GPRS / UMTS services operated by the public telecom providers. Alternatively, the logger/sensor inside could be connected to a transmitting device on the outside of the container/trailer.

2.1.5.2 Logged and stored information

Despite the loss of the connection, the data is logged and stored by the SKID and these data have been read after restoring the connection. This is visualized in Figure 5 below.

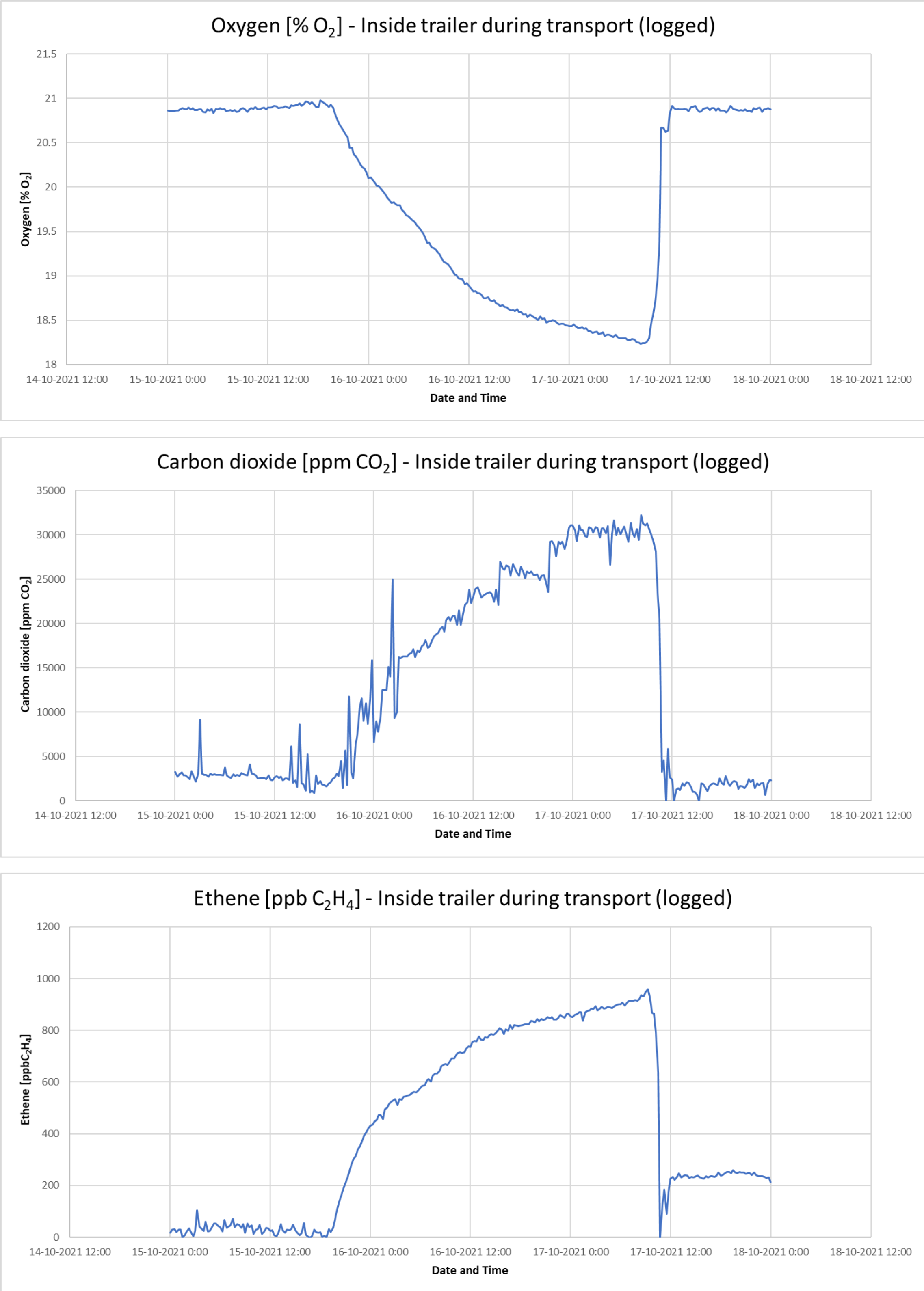

Figure 5 ***Logged values of Oxygen, Carbon Dioxide and Ethylene during transport between October 15th, approximately 09.30 pm to October 17th, approximately 11 am (Source: SKID / EMS)***

The SKID also includes a temperature and humidity logger. These data cannot be read in real-time but can be uploaded afterwards. These data are shown in the Figure 6 below.

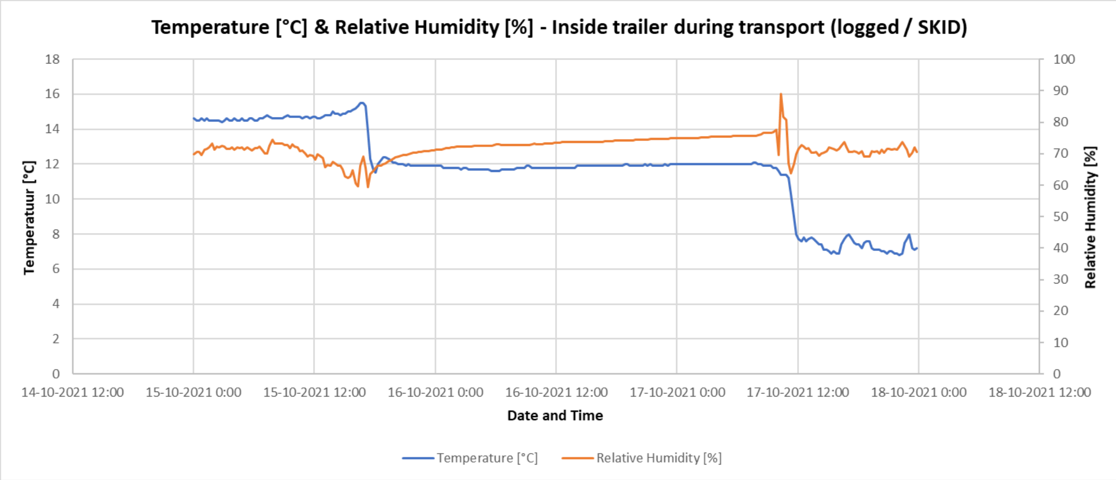

Figure 6 ***Logged values of Temperature and Relative Humidity during transport between October 15th, approximately 09.30 pm to October 17th, approximately 11 am (Source: SKID/EMS)***

The shipper, in this case Van Oers United, often also loads a temperature and relative humidity logger for each transport. The reason for this is to be able to relate the transport conditions afterwards, if necessary, to the determined product quality. This was also the case in this demonstration where VOU placed Xsense loggers between the loads. These data can be found in Figure 7.

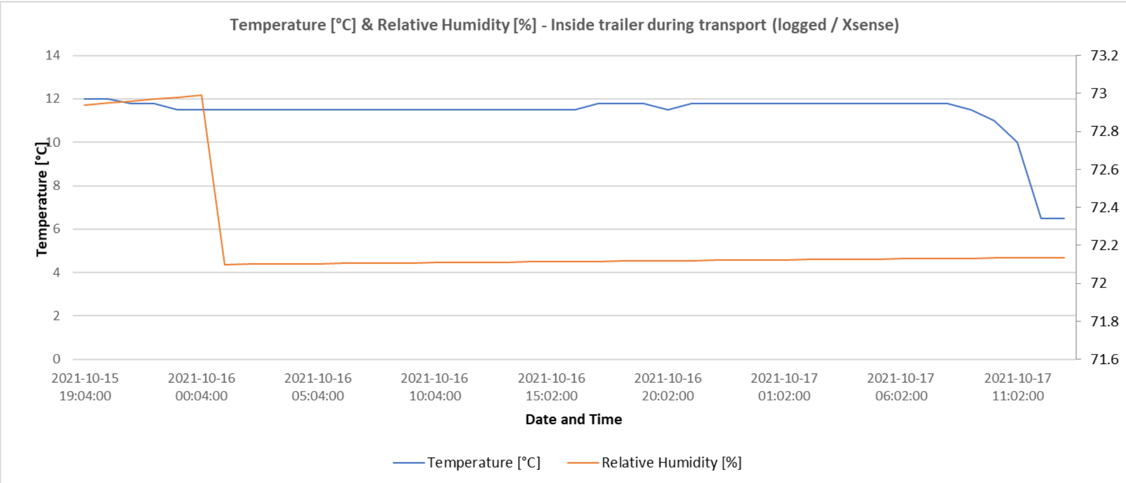

Figure 7 ***Logged values of Temperature and Relative Humidity during transport (Source: Xsense/VOU)***

It is striking that the loggers (SKID and Xsense) indicate comparable values for the registered temperature in the trailer. However, there is a difference in the relative humidity. Where the Xsense registered a value of around 72%, the SKID indicates that the relative humidity has increased to almost 80% at the end of the transport. The origin of this difference has not been further investigated within the demonstration, but it may be due to a difference in sensitivity and accuracy of the loggers or the position of the loggers. Again, this might demonstrate that the position of the logger is in all probability important.

Apart from this observed difference, it is also important whether the observed differences in relative humidity also have a possible influence on product quality. This depends on the product, shipping time and possibly other environmental conditions. There is no unambiguous answer to this within this demonstration (and was also not part of the demonstration).

2.1.5.3 Data-update frequency and connectivity

From the perspective of the shipper, in this case Van Oers United, an update frequency of at least 2 times per hour is required. At this frequency, based on experience, there is sufficient insight into changes in the conditions under which the products are transported. For this demonstration, a frequency of 4 times per hour was chosen, which means that the values of Oxygen, Carbon dioxide and Ethylene were measured every 15 minutes. The equipment used allows an even higher frequency, but for the insight to be obtained this has no added value for the transported products.

Connection was performed by GPRS / UMTS operated public telecom providers which in general, and certainly with continental transport, provides reliable and almost complete coverage. Experience of the parties involved also shows that it is possible to send signals from a closed trailer or container. Yet during this demonstration there was a period of non-connectivity from the moment the ethylene sensor is put in the trailer. Unfortunately, the cause could not be traced. However, it is suspected that by placing the SKID at the front of the trailer, the signal is blocked due to the presence of metal (back wall and corner profiles). The data has been logged and stored by the SKID and these have been read after restoring the connection.

2.1.6 Learnings and conclusion

The main goal of this demonstration was a proof-of-concept of real-life and real-time data communication with EMS cloud-solution and real-life and real-time tracking of the transport and relevant transport conditions. Despite experiences gained by EMS with the SKID in which connectivity during continental road transport had proven possible, this was not the case for this demonstration. Sometime after loading the so-called SKID, the connection was lost. Unfortunately, the cause could not be traced. However, it is suspected that by placing the SKID at the front of the trailer, the signal is blocked due to the presence of metal (back wall and corner profiles).

So, looking at the overall goal of this demonstration, it can be concluded that the proof-of-concept has not been achieved with the important lesson being that the positioning of the logger and checking the connectivity should be checked just after closing the trailer.

Other learnings
Planning:
Because it is not yet normal practice, sending a logger with this relatively large sized sensor requires very good planning and coordination. This is because the sensor requires the space of a pallet and thus less product can be transported, and this lower volume must match the demand of the end customer. It was even more true at the time of the COVID-19 pandemic, when schedules and preconditions were subject to significant change. So, planning is key.

Practical tips:
More practically, it would be helpful if the ethylene sensor could show:

- Connectivity level (see the above topic 'connectivity')
- And in case there is connectivity:
    - Low battery sign;
    - Hi level alert.

Cost and commercial usefulness:
In current practice, the parties see that the buyer of the products (i.e., the shipper's customer) does not yet ask for the sensing of ethylene during transport. The receiving party is not (yet) prepared to pay for the extra costs (not only using the service of the sensing device, but also the loss of volume for the place that the device takes / relative higher transport costs per transported product). And this is therefore (still) at the expense of the shipping party. During this demonstration this was even more true because the size of the ethylene sensor was at the expense of a full pallet location, so that either less product could be sent, and the receiving party is only willing to pay less for 1 pallet location.

In relation to the above, it has been shown that the desired conditions can be measured and recorded, but due to the current somewhat reticent position of the receiving party it is not yet undisputedly clear up to now for the participating parties, and mainly EMS, what the impact of data and commercial usefulness in continental transport is.

2.2 Demo 2: Optimal sensor positioning

In addition to this report, a separate report has been prepared by Leo Lukasse and Joost Snels from Wageningen Food & Biobased Research in which this demonstration is described and reported in more detail. In the current report only the relevant summarized description and findings are briefly presented. Further information can be found in the original report on this specific demonstration entitled "*Estimating temperatures in refrigerated containers and trailers. How many randomly-placed cargo temperature sensors are necessary?*" (Lukasse & Snels, 2022).

2.2.1 Demonstration goal and setup

The starting point for this demonstration is the fact that the project partners Thermo King and Euro Pool System (EPS) see a future development in which load carriers (think of crates, barrels, boxes, baskets, ...) will be equipped with embedded loggers and/or sensors. The assumption is that the loggers/sensors will be able to make a real-time connection via UMTS or GPRS via, for example, the available technology in (reefer) containers, trailers, cooling engines, trucks, etc. whereby the conditions, positioning, etc. of the load will be made available.

The starting point for this demonstration, and thus the research question, is that the embedded technology in the load carriers in a full truck or container load will not be available for all load carriers. In other words, probably only a (small) percentage of, for example, the number of EPS crates will be equipped with a sensor or logger (certainly in the start-up phase prior to a full rollout).

The next question that arises is how to deal with the crates that do have a logger or sensor. For example, these could be coloured and so be made recognizable in order to subsequently develop a loading instruction where to position these crates in order to obtain optimal insight into, for example, the temperature distribution. From a practical point of view, it may be more convenient not to mark the crates and thus not have to 'service' them separately, so that they can simply go along with the total flow. The latter does have the consequence that the crates will be distributed randomly over the entire load.

As indicated in the State of the Art and SWOT-analysis work of this project (Finner & Zomer, 2020) temperature is one of the most important influences on quality decay in fruits and vegetables, as it directly affects the respiration rate and the rate of chemical reactions. Therefore, in this demonstration, temperature has been chosen as the representative environmental condition.

2.2.1.1 Demonstrations research question and goal

And with this in mind, the following research question has been formulated for this demonstration: "How many randomly-placed cargo temperature sensors are necessary to gain a sufficiently accurate estimate of the temperatures of the complete cargo during refrigerated transport in reefer containers and (single compartment) refrigerated trailers?". Whereas the goal of this demonstration is to arrive at the theoretical finding of the optimal number of randomly placed cargo temperature sensors to gain a sufficiently accurate estimate of the temperatures of the complete cargo during refrigerated transport in reefer containers and (single compartment) refrigerated trailers.

Table 3 Parameters of demonstration 2

Demonstration parameters	
Type of transport	Cooled transport by road (reefer or trailer)
Condition settings	Temperature
Product	Perishables
Organizations	Thermo King and Euro Pool System
Route	n.a.
When	n.a.
Number of transports	n.a.
Sensing and Logging	Temperature (logging)

2.2.2 Demonstration set-up

To answer the above research question a physical model of the temperature dynamics in reefer containers and refrigerated trailers was constructed. The model has not been validated explicitly, but the simulation outcomes compare reasonably well to what experts on temperature management during refrigerated transport would expect.

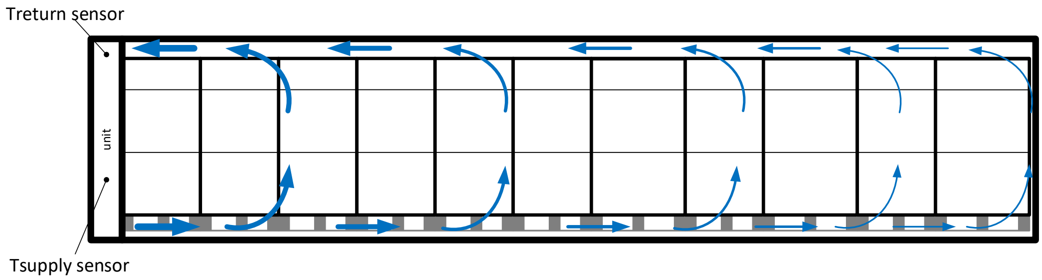

Figure 8 Schematic presentation of reefer container

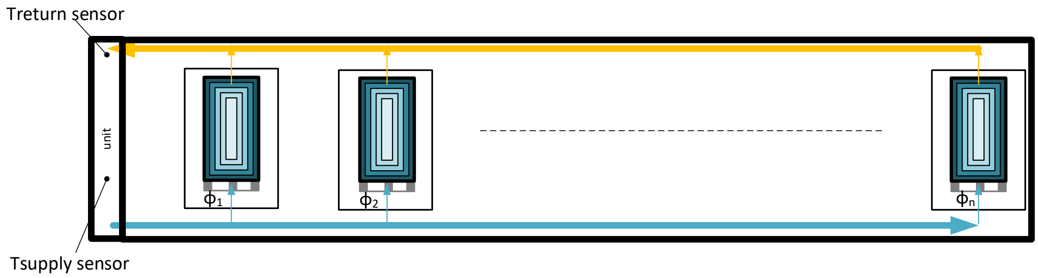

Figure 9 Schematic representation of zonal model, distinguishing between air and pallet load temperature, accounting for temperature gradients within pallet load

This physical model is then simulated for a reefer container shipment scenario. The scenario includes a pulldown phase because it assumes stuffing with a non-precooled cargo. Which means that after loading, at time zero (= 0 h.) the cargo will be warm (see Figure 10).

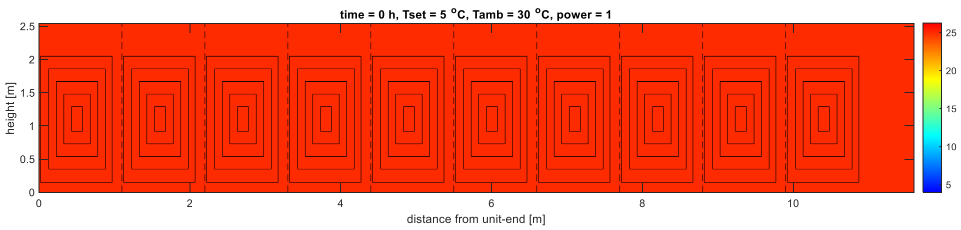

Figure 10 Contour plot of all simulated temperatures at initial time 0 h.

Over time, the temperature of the cargo will decrease as a result of the forced cooled air in the reefer. Figure 11 shows the temperature distribution in the pallet and in the trailer after 24 hours and Figure 12 after 240 hours respectively.

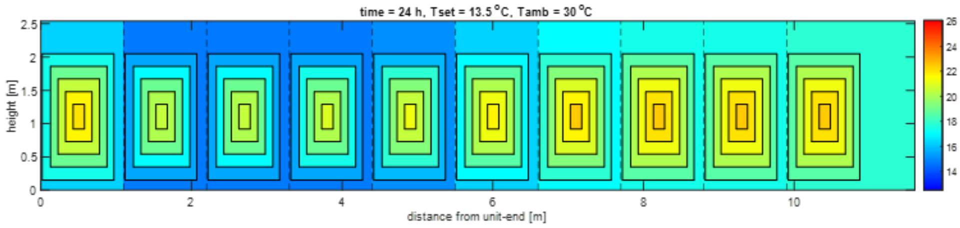

Figure 11 Contour plot of all simulated temperatures at time 24 h.

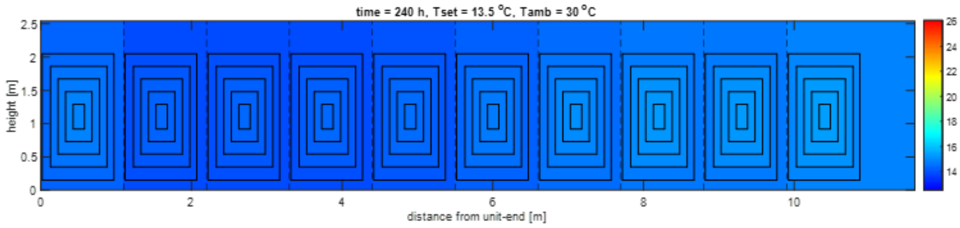

Figure 12 Contour plot of all simulated temperatures at final time 240 h.

Then a statistical model of the temperature distribution in a reefer container is defined. Inputs of the statistical model are any number of cargo temperature measurements collected at unknown locations in the cargo space. The difference between the statistical model output and the physical model output is analysed for a range of sensor numbers and different sensor-placement methods in order to gain a sufficiently accurate estimate of the temperatures of the complete cargo during refrigerated transport in reefer containers and (single compartment) refrigerated trailers.

2.2.3 Learnings and conclusions

The results indicate that there is little benefit in placing more than 30 randomly placed sensors per container load for the purpose of gaining a sufficiently accurate estimate of the temperatures of the complete cargo occurring during refrigerated transport in reefer containers, when using these recordings as inputs for a statistical model.
It is not to be expected that the situation will be a lot different for refrigerated trailers.
Care should be taken, as the above conclusions depend on many assumptions.

Random sensor placement is an ineffective sensor placement method, as two smartly placed sensors can be more informative than e.g. 40 randomly placed sensors. Smart sensor placement in a container is: one in the bottom of the coldest pallet (position 2 or 3 from unit-end) and one in the center of the warmest pallet (door-end).

The main research question in this study is very generic, and therefore hard to answer adequately. For future studies it is recommended to be more specific in formulating the purpose and application domain of temperature recording during transport. Further information can be found in the original report on this specific demonstration entitled "*Estimating temperatures in refrigerated containers and trailers. How many randomly-placed cargo temperature sensors are necessary?*" (Lukasse & Snels, 2022).

2.3 Demo 3: Real-time detection of the conditions that enable predictions of quality loss in order to achieve decision support for logistics interventions

2.3.1 Demonstration goal and setup

The goal of this demonstration is to carry out a trial shipment in a real-life business setting so that the feasibility of IoT-enabled quality-controlled logistics can be directly tested for proof of concept. Practical issues including data collection, timestamp alignment from different sensors, data transmission capacity, data translation and results demonstration have been closely monitored during the shipment.

2.3.2 Demonstration activities and consortium members roles

For this demonstration, two types of sensors were used:

- Low-cost ethylene sensor for real-time perishable shipment status sensoring. For this demonstration, two prototypes have been developed by Impact Smart Solutions (see Figure 13)
- TempTale® GEO LTE from Sensitech: real-time monitoring with 4G/5G coverage for sensing Temperature and Humidity (See Figure 14). For this demonstration in total 5 sensors are made available by Sensitech.

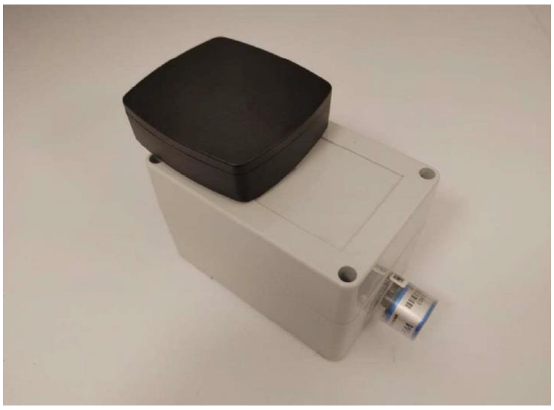

Figure 13 ***In house developed Printed Circuit Board (LxWxH = 157x80x100 cm., 250 gram) for detecting ethylene gasses in closed environments and determining location based on various GPS satellites (Source: Impact Smart Solution)***

Figure 14 ***TempTale® GEO LTE (LxWxH = 115.5x121.5x25.5 mm., 207 gram) for detecting Temperature, Humidity, Light and location (Source: Sensitech)***

Table 4 Parameters demonstration 3

Demonstration parameters	Location of the truck Humidity-measurements Temperature-measurements Predicted remaining shelf-life benchmarked with the expected remaining shelf-life
Type of transport	Road transport
Condition settings	Targeted relative humidity and temperature are 90% and 7 °C
Product	Green Beans
Organizations	Van Oers United
Route	From A1, 23000 Sindia, Senegal, Senegal to Handelsweg 120, 2988 BR Ridderkerk, Netherlands, Netherlands
When	From 02/02/2022 18:17 pm to 10/02/2022 06:32 am
Number of transports	1
Sensing and Logging	- Ethylene (logging and real-time communication) - Temperature (logging and real-time communication) - Relative Humidity (logging and real-time communication) - GPS coordinates (logging and real-time communication)

Departure Senegal (February 2, 2022)

Source: VOU


Arrival Netherlands (February 10, 2022)

Source: WUR

Figure 15 Impression of shipment at departure and arrival (Source: VOU & WUR)

The shipment started in the evening of Wednesday 2nd February when the transport departed from Senegal and ended in the morning Thursday 10th February. The quality-decay model was started to run on Thursday 3rd February. During the shipment the model was run three times a day; once in the morning, once in the mid afternoon and once in the late afternoon. This was except for:

- the weekend days, when it was not run;
- February the 10th, when it was only run in the morning, because the shipment had arrived in Ridderkerk at that point.

For each run, the following steps were carried out by WUR, TNO and Impact Smart Solutions:

1. Check if the Ethylene sensors had generated a measurement on the ethylene levels. If this was the case, the ethylene validation model had to be run. This model determined whether the maximum ppm concentration of ethylene exceeded 10 ppm. If this was the case another calculation would take place, which would reduce the shelf life by 40% (by WUR).

2. Log in to SensiWatch[2] and download the excel files containing location data and measurement data from the temperature and humidity sensors from the right time zone (GMT+01:00 CEST) (by WUR).
3. The downloaded files were checked whether the sensor had updated its measurements (by WUR).
4. The model would then be run on the sensors that had updated. The model will calculate a new estimate of the shelf life based on the temperature and humidity and provide 2 results files. One where per sensor per timestamp the humidity levels, temperature levels, predicted shelf life and expected shelf life is given. One where only the latest "predicted shelf life at arrival" is given per sensor (by WUR).
5. Send the generated files by the model to TNO to run the intervention model and to Impact Smart Solutions to use them for the dashboard (by WUR).
6. Run the intervention model and send the results to WUR and Impact Smart Solutions (by TNO).
7. Develop the dashboard to monitor the parameters (by Impact Smart Solutions).
8. Archive the files generated by the model and the model results received by TNO (by WUR).

2.3.3 Results

2.3.3.1 How is this sensor data being captured?

Unfortunately, the ethylene sensors were not able to send data during the shipment mainly because of energy management; the sensors are equipped with non-rechargeable batteries that should last long enough for the entire shipment. But due to some delay at the start of the demonstration and the fact that the sensor had limited or no GSM connection in Senegal, so that it tried to make continuous contact with the network ensured that the batteries were almost empty at the start of the shipment. Therefore, the ethylene levels were not considered for the calculation of the predicted shelf life for this shipment. Calculation of the shelf life was done based on temperature and humidity, which were to be measured by 5 sensors provided by Sensitech: JG69A001V4, JG69A001W4, JG69A001Y4, JG69A00204 and JG69A00254. However, before departure (on February 2nd) sensor JG69A001V4 and JG69A001Y4 were not able to send data. This is because the two sensors are put too deep in the pallets so that signals cannot be sent out. On February 4th, JG69A00254 was also not able to send the data anymore for some unclear reasons. Similarly, JG69A00204 stopped sending data during the evening of the 9th February. JG69A001W4 kept sending data through the whole shipment. It was decided that the model would still be run for the sensors JG69A001W4, JG69A00204 and JG69A00254 during the entire shipment.

2.3.3.2 How is the sensor data used as input for the quality decay model?

Excel-based senescence and chilling injury model

Table 5 shows the Excel implementation of the senescence and chilling injury model[3]. The green columns represent the input (which can be the output from time & temperature loggers attached to the cargo). The yellow column represents the output: the remaining shelf life after each time step. So, in the example as provided in Table 5**Fout! Verwijzingsbron niet gevonden.**: after one day at 280.15 K (= 7 °C), the remaining shelf life equals 19 days, while the initial shelf life equals 20 days (orange). After a subsequent timestep of 0.5 days at 280.15 K (= 7 °C), the remaining shelf life is reduced to 18.5 days. After a subsequent timestep of 1 day at 283.15 K (= 10 °C), the remaining shelf life is reduced to 17.3 days, etc.
Notice that at 10 °C, the shelf life decreases faster than at the (optimal) temperature of 7 °C, due to a higher senescence rate.

[2] SensiWatch is a platform from Sensitech providing users of their sensors a single, end-to-end view of their global supply chain with real-time insights on cargo location and condition.
[3] For the in-depth explanation the models we refer the interested reader to the original report created within this project entitled "D3.1 Design and Solutions Development report" (Bianco Martinez, J. et al, 2021), more specific; Chapter 3. Connecting sensor data to predict product quality, Page 14-31.

Table 5 ***Excel implementation of senescence and chilling injury model***

SL_T(d)	KQ_ref(d)	SL_opt(d)	T_opt(K)	k1_ref	Ea_1	R	T_ref(K)	T(K)	k2_ref	Ea_2	Loss_t_T(d)	t(d)	SL_fin_opt(d)
20.00055	17.74385	20	280.15	1	79	8.314	283.15	280.15	0.0549	-271.82	0.999972318	1	19.00002768
20.00055	17.74385	20	280.15	1	79	8.314	283.15	280.15	0.0549	-271.82	0.499986159	0.5	18.50004152
16.82041	17.74385	20	280.15	1	79	8.314	283.15	283.15	0.0549	-271.82	1.189031813	1	17.31100971
13.75698	17.74385	20	280.15	1	79	8.314	283.15	285.15	0.0549	-271.82	1.453807587	1	15.85720212

The remaining columns should not be modified. These columns just represent input and intermediate parameters of the model. An explanation of all columns is given in Table 6.

Table 6 ***Explanation of columns of Excel implementation of senescence and chilling injury model***

Excel column	Related variable	Explanation
SL_T (d)	$SL(T)$	Shelf life in days at temperature T
KQ_ref (d)	SL_{ref}	Keeping quality in days at T_{ref}
SL_opt (d)	SL_{opt}	(Optimal) shelf life in days at T_{opt}
T_opt (K)	T_{opt}	Optimal temperature in Kelvin
k1_ref	$k_{1,ref}$	Reaction rate chilling injury at T_{ref}
Ea_1	$Ea(1)$	Activation energy chilling injury
R	R	Universal gas constant
T_ref (K)	T_{ref}	Reference temperature in Kelvin
T (K)	T	Storage temperature in Kelvin
k2_ref	$K_{2,ref}$	Reaction rate senescence at T_{ref}
Ea_2	$Ea(2)$	Activation energy senescence
Loss_t_T (d)	$Loss(t,T)$	Loss of optimal shelf life SL_{opt} in days when stored at temperature T for time t
t (d)	t	Storage time in days
SL_fin_opt (d)	$SL_{fin,opt}$	Remaining shelf life in days at T_{opt}

The internal variable KQ_ref has been set in such a way that the optimal shelf life SL_opt equals 20 days for green beans from Senegal as indicated by VOU.

Excel-based weight loss model

Table 7 shows the Excel implementation of the weight loss model[4]. The green columns represent the input (which can be the output from time & temperature and time & relative humidity loggers). The yellow column represents the output: the remaining shelf life after each time step. So, in the example as provided in Table 7**Fout! Verwijzingsbron niet gevonden.**: after one day at 7 °C and 95% RH, the remaining shelf life equals 19.10 days, while the initial shelf life equals 20.10 days (column SL_0(T’,RH’)). After a subsequent timestep of 0.5 days at 6 °C and 94% RH, the remaining shelf life is reduced to 18.54 days. After a subsequent timestep of 1 day at 8 °C and 96%, the remaining shelf life is reduced to 17.68 days, etc. At higher temperatures and lower relative humidity, the shelf life decreases more, due to a higher weight loss.

Table 7 ***Excel implementation of weight loss model***

t (d)	T (˚C)	RH (%)		Weight loss (%)		SVP (Pa)	VPD (Pa)		T' (˚C)	RH'(%)	SVP'(Pa)	VPD'(Pa)		Loss'(t,T,RH) (d)	Acceptability limit(%)	SL_0(T',RH') (d)	SL_fin(T',RH') (d)
1	7	95		0.25		1001.68	50.08		7	95	1001.68	50.08		1.00	5	20.10	19.10
0.5	6	94		0.14		934.94	56.10		7	95	1001.68	50.08		0.56	5	19.10	18.54
1	8	96		0.21		1072.57	42.90		7	95	1001.68	50.08		0.86	5	18.54	17.68

The remaining columns should not be modified. These columns just represent input and intermediate parameters of the model. An explanation of all columns is given in Table 8.

[4] For the in-depth explanation the models we refer the interested reader to the original report created within this project entitled “D3.1 Design and Solutions Development report” (Bianco Martinez, J. et al, 2021), more specific; Chapter 3. Connecting sensor data to predict product quality, Page 14-31.

Table 8 ***Explanation of columns of Excel implementation of weight loss model***

Excel column	Related variable	Explanation
t (d)	*t*	Storage time in days
T (°C)	*T*	Storage temperature in Celsius
RH (%)	*RH*	Relative humidity during storage
Weight loss (%)	*WL(t, T, RH)*	Weight loss (as a percentage of the original weight) if stored at temperature *T* and relative humidity *RH* for time *t*
SVP (Pa)	*SVP*	Saturated vapour pressure in Pascal
VPD (Pa)	*VPD*	Vapour pressure deficit in Pascal
T' (°C)		Reference temperature in Celsius, i.e., temperature at which the shelf life is expressed
RH' (%)		Reference relative humidity, i.e., relative humidity at which the shelf life is expressed
SVP' (Pa)		Saturated vapour pressure in Pascal at T' and RH'
VPD' (Pa)		Vapour pressure deficit in Pascal at T' and RH'
Loss'(t,T,RH) (d)	*Loss'(t, T, RH)*	Loss of shelf life in days (as expressed at *T'* and *RH'*), if stored at *T* and *RH* for time *t*
Acceptability limit(%)		Shelf life ends if weight loss exceeds this acceptability limit as a percentage of the original weight
SL_0(T',RH') (d)		Initial shelf life in days (as expressed at *T'* and *RH'*) at the beginning of this time step
SL_0(T',RH') (d)	SL_{fin} *(T', RH')*	Remaining shelf life in days (as expressed at *T'* and *RH'*) at the end of this time step

The weight loss model is based on the calculation of the vapour pressure deficit (as a result of temperature and relative humidity) and the transpiration coefficient of green beans. The transpiration coefficient of green beans has been tweaked such that the initial shelf life SL_0(T',RH') equals (about) 20 days for green beans from Senegal. This turned out to be realized with a transpiration coefficient of 575 mg/(kg s mPa) which resulted into a weight loss per day per kPa VPD of 4.968% (Table 9).

Table 9 ***Second tab of Excel implementation of weight loss model***

Transpiration coefficient (mg/(kg s mPa)	Weight loss per day per kPa VPD (%)
575	*4.968*

R-Model

The R-model is a 'one on one' translation of the aforementioned two excel models. The predicted remaining shelf-life during the shipment is determined by the minimum value of the two shelf-life values determined by the senescence and chilling injury and weight loss models. The predicted remaining shelf-life is benchmarked with the expected remaining shelf-life under the targeted temperature and relative humidity.

Moreover, to take the ethylene into account, a simple rule of thumb (based on expert opinions) is applied in the model that whenever the ethylene concentration is above 1 ppm, an immediate one-off reduction of the remaining shelf-life by 40% is applied at the moment of violation. However, this module was never run during the shipment because of the failure of the ethylene sensor.

In addition to the predicted remaining shelf-life, to support the logistic decisions, the model also calculated the "predicted remaining shelf-life at arrival" which equals the current predicted remaining shelf-life minus the further decay predicted by the model during the remaining traveling time using the targeted temperature and relative humidity as the inputs. The "predicted remaining shelf-life at arrival" is the input to TNO's logistic intervention model.

To ease the inputs and output process, the R model contains the codes to automatically rearrange the dimensions of the raw data files from multiple sensors to the quality-decay model and output the results in the format that make them easily to be put into the intervention model and dashboard.

2.3.4 How is the output of the quality decay model used as input and converted by the logistics decision making models into intervention advice?

There are two input parameters for the logistics intervention model.

1. The “predicted remaining shelf-life at arrival”. Since the retailer requires a remaining shelf-life of at least 7 days, the model set the threshold triggering interventions to a “predicted remaining shelf-life at arrival” of 8 days.
2. The location of the truck (latitude and longitude). This is used to calculate the remaining lead time. It is also used to determine the location of the second driver, if there is a need for the second driver as an intervention.

The logistics intervention model works with the ‘predicted remaining shelf-life on arrival’. If, at any point in the journey, the remaining shelf-life on arrival is less than 8 days, the model advises to intervene. As mentioned in the previous report (Zomer G. et al., 2021), the decisions to intervene depend on the quality of the product in the shipment. If at any moment, the model predicts that the quality of the shipment is less than what is expected, the model advises to intervene.

The intervention model and the decision-making process
The intervention model advices on the possibility of intervening in the transport process in case the shipment is seen to be deteriorating. It advices to intervene based on the quality of the shipment alone. The model is designed in Python and requires a ‘.csv’ file as an input from the quality loss model and delivers a ‘.csv’ file with the intervention advice and the costs related to it.

In this demonstration two types of interventions are built into the model:

- Reducing the lead time by adding a truckdriver and drive and rest simultaneously. Moreover, the trailer could be swapped to another truck-trailer combination halfway, whereas another truckdriver just had his resting hours and is able to continue the journey. Thus the intervention model shows what the remaining lead-time to the final destination (in our case Ridderkerk in the Netherlands) is in relation to the shelf-life of the produce. If the lead-time is too long compared to the necessary shelf life, the model can propose to put a second driver on the truck in order to shorten the transport time and thus lead time. The locations where the second driver could be picked up are fixed at locations at the borders between countries. This was chosen because the truck usually needs to stop for border checks/customs at borders of countries and this could well facilitate the picking up of another driver. So, the intervention model also gives the location where the 2nd driver could be picked up as the location of the truck is known to the model.
- Re-routing to sell the produce on the local markets: This option is kept as a last resort for fast ripening shipments to re-direct the shipment to the local markets of Spain/France to save the shipment from rotting entirely before they reach the destination. The choice of the local market depends on the logistic possibility of selling the shipment in any of the local markets along the way.

The intervention model will also have to give insight in the financial gains from adopting such an intervention. The model considers the costs of deploying the sensor technology as ‘sunken costs’. These are one-time costs. On top of that, the model estimates the cost of the other interventions. For instance, the cost to deploy a second driver for a part of the journey or the costs involved to sell the shipment in a local market along the route. The estimates of these costs have been reported in the previous report (Zomer G. et al., 2021).

The intervention model can be illustrated in Figure 16.

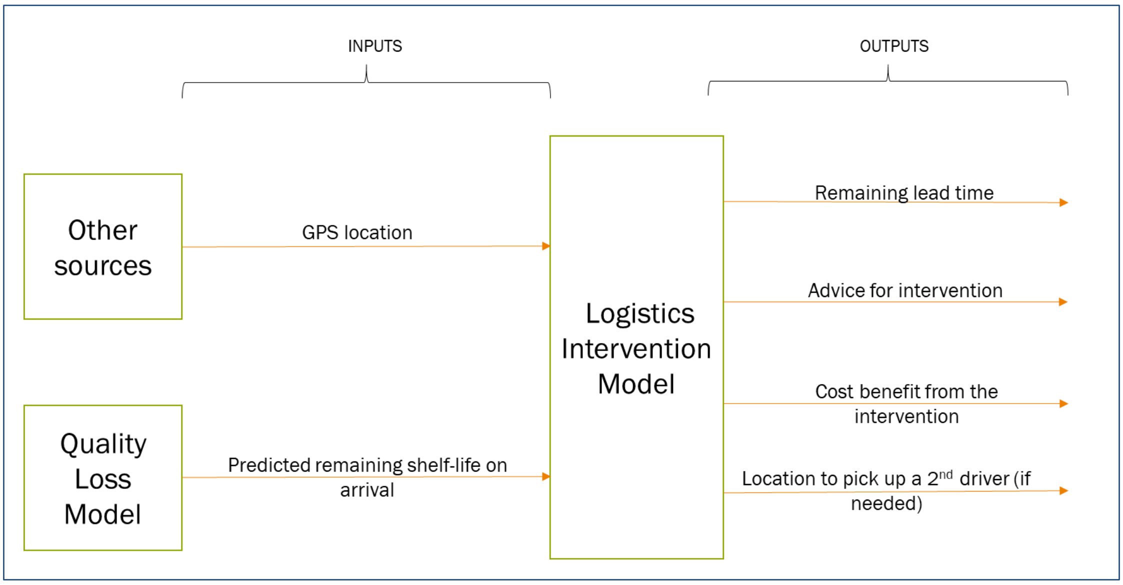

Figure 16 Illustration of the logistics intervention model

The decision-making process in the intervention model is as follows:

1. The shipment is already equipped with the sensor technology so the live updates about the quality of the shipment can be monitored.
2. Based on this quality, there are one of two interventions that can happen:
   a. Deploying a second driver on board.
   b. Selling the shipment in the local market.
3. If the 'predicted remaining shelf-life on arrival' is seen to be below 8 days, the model advices an intervention to put a second driver on board so the lead time to destination can be halved. This helps the shipment to reach the destination much before expected, thereby protecting the shipment from being rotten.
4. If the 'predicted remaining shelf-life on arrival', even after deploying the second driver indicates a time less than 8 days, thereby implying that the shipment is decaying much faster, the model advices the shipment to be sold in the local market.

The decision-making process can be illustrated in Figure 17.

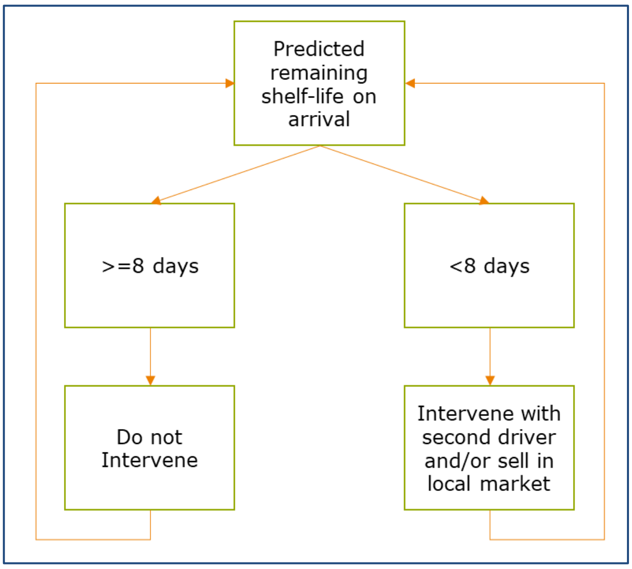

Figure 17 Illustration of the decision-making process of the logistics intervention model

2.3.4.1 How is sensor data and model results made visible for users?

The results of the sensor data and results during the shipment were demonstrated in the dashboard below (can be seen from Figure 18 to Figure 23). It presents the locations of the truck, temperature and relative humidity. It also gives the view of predicted remaining shelf-life with the benchmark together with the logistic intervention decision from TNO's logistic intervention model. Along with this, it also gives more insight into the financial gains from the intervention (if any) and the cost of applying the intervention. The column 'Intervention-cost' specifies what is cost of the intervention mentioned in the column 'Intervention-status' and the column 'Intervention-gain' specifies what is the net gain from applying the intervention (i.e., (total gain from applying the intervention – cost of applying the intervention)). This does not include the sunken costs of applying the sensor technology but only the net gain from applying the intervention.

The two rows in the dashboard (seen in Figure 18) are for the following reasons:

1. The first row was the actual shipment that was followed. It did not need any intervention and hence the 'Intervention-status' column reads no intervention. This also implies that the cost of the intervention and the net gain from the intervention are also zero.
2. The second row is a dummy output created to visualize how an intervention would look like. It shows that the column 'Intervention-status' column read Second Driver thereby implying that the intervention model advises that a second driver needs to be put on board. It also reads the total cost of applying such an intervention in column 'Intervention-cost' to be €200 and the net gain from applying this intervention in the column 'Intervention-gain' to be €300 (see Zomer G. et al., 2021). In this case, the dashboard also shows the location where the second driver could be picked up. This is shown in Figure 23. This way an informed decision can be made based on not just the intervention model advice but also keeping in mind the financial gains (if any) from applying such an intervention.
   Note: this is only a dummy and is only shown for demonstration representation purposes.

Name	Latitude	Longitude	Last Dropbox-update	Intervention-cost	Intervention-gain	Intervention-status
Truck #1	51.86250 °	4.55872 °	10-2-2022 9:54:27 CET			No Intervention
Truck #2 (Simulated)	44.71261 °	-0.74733 °	11-2-2022 9:44:13 CET	200	300	Second Driver

Figure 18 ***Dashboard showing the data of the location of the truck and the outputs of the intervention model including the intervention status, the cost of the intervention and the net gain from the intervention. Row 1 is the actual demonstration shipment followed whereas row 2 is the simulated shipment to show how an intervention would look (Source: print screen dashboard Impact Smart Solutions)***

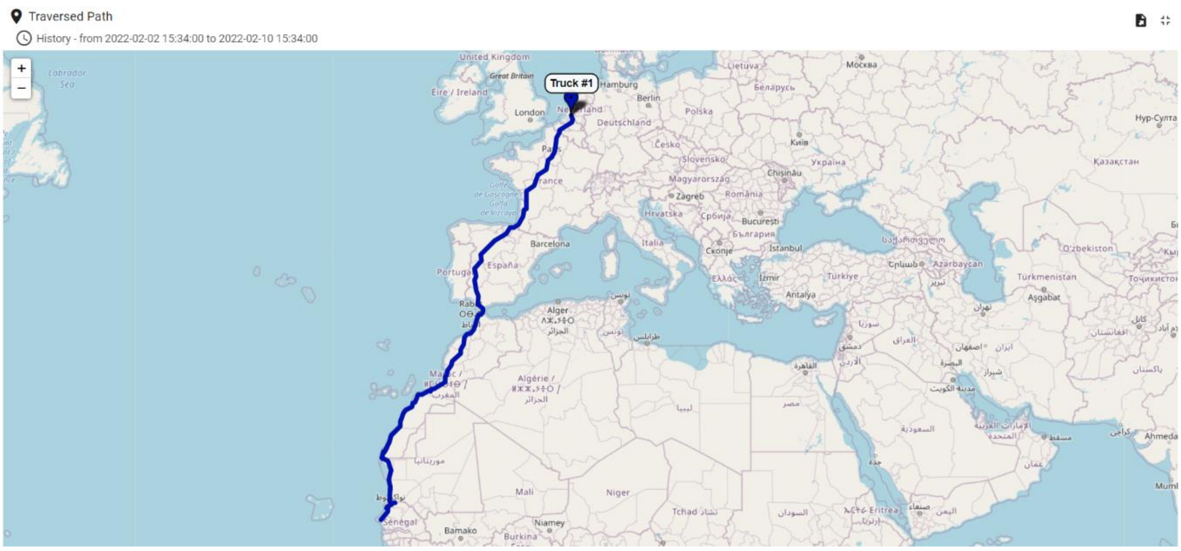

Figure 19 ***Dashboard showing the traversed path by the truck. This is made by mapping the GPS readings from the truck through the journey (Source: print screen dashboard Impact Smart Solutions)***

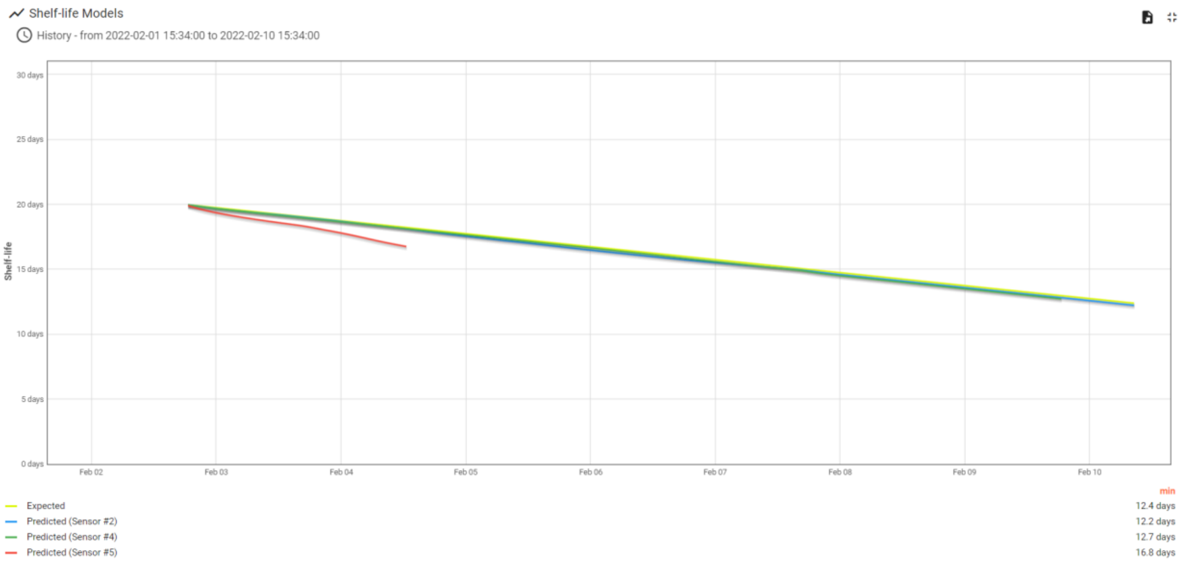

Figure 20 ***Dashboard showing the remaining predicted and expected shelf-life remaining. The yellow line shows the expected remaining shelf life and the blue, green and red show the predicted shelf life remaining from three sensor values in the truck (Source: print screen dashboard Impact Smart Solutions)***

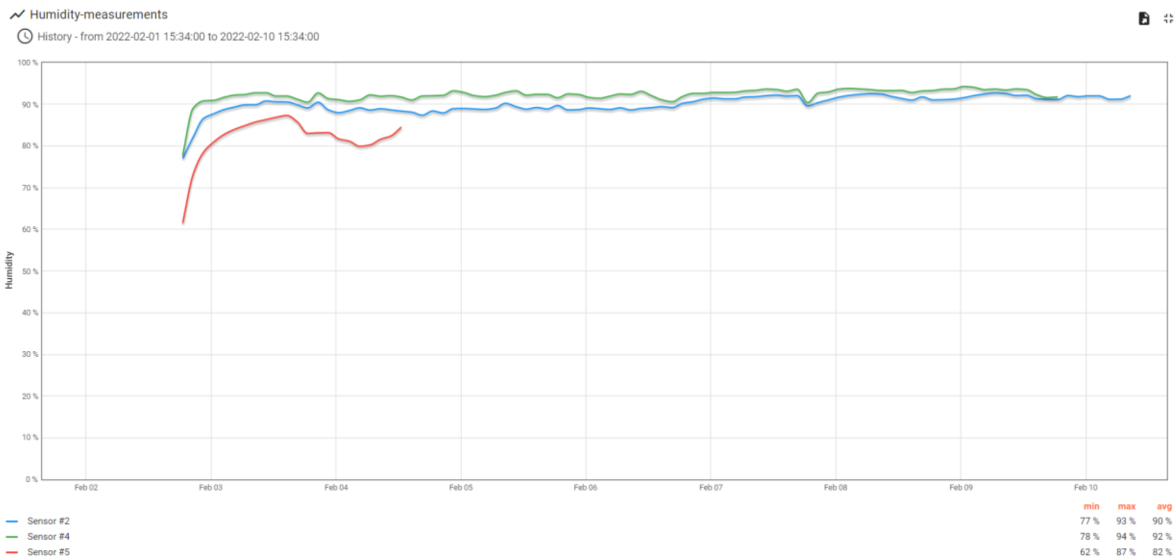

Figure 21 ***Dashboard showing the humidity measurements from the three different sensors throughout the journey (Source: print screen dashboard Impact Smart Solutions)***

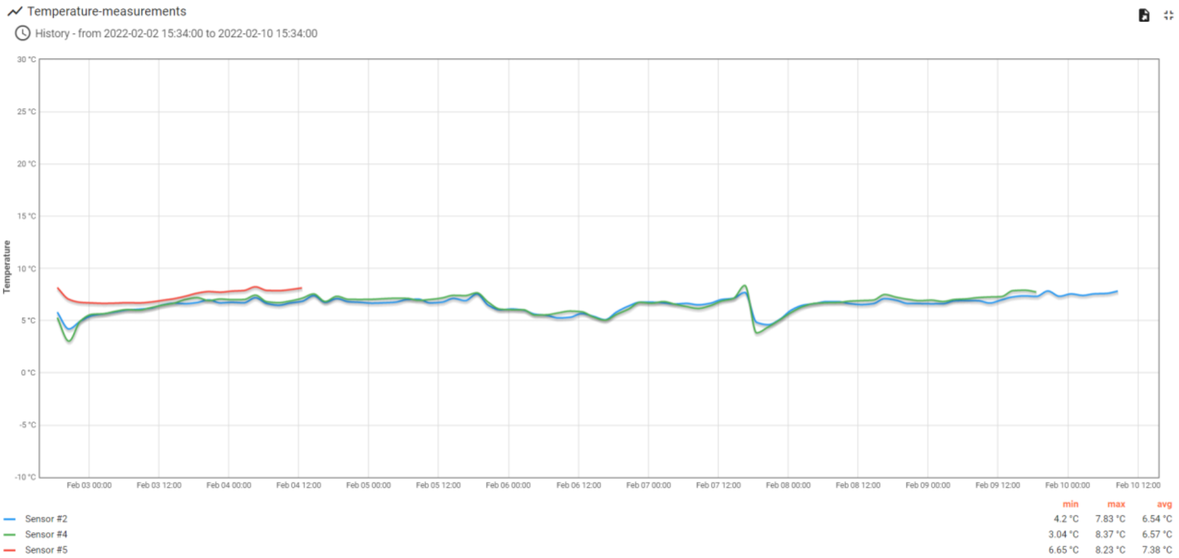

Figure 22 ***Dashboard showing the temperature measurements from the three sensors throughout the journey (Source: print screen dashboard Impact Smart Solutions)***

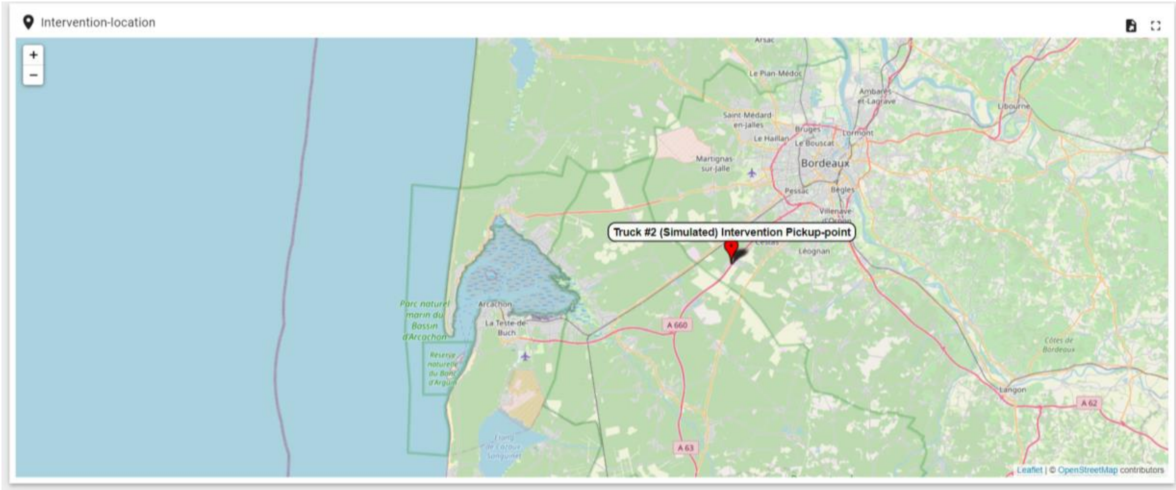

Figure 23 ***Location of the second driver as shown in the dashboard. This is a dummy output just simulated to show how the location of the second driver would be displayed in case there is a need for such an intervention (Source: print screen dashboard Impact Smart Solutions)***

As mentioned in sub-section 2.3.3.1, two of the five pairs of temperature and RH sensors did not work at all while the other two stopped working during the shipment at different time points. This is the reason why only the complete data history of one pair of sensors is shown in Figure 20, Figure 21 and Figure 22 and two incomplete data histories for the remaining two pairs.

2.3.5 Learnings and conclusions

The first learning from this project is that setting the sensors appropriately is very critical. To avoid data transmission failures, the sensors should not be placed too deep in the pallets and should have enough power. During the shipment, two sets of temperature and humidity sensors cannot transmit data from the very beginning on due to their location in the truck and the other two stopped data transmission during the trip. Only one set of sensors was able to send the information during the whole trip. The ethylene sensor did not work because of faulty energy management

The second learning is that it is quite difficult to set the reference relative humidity before-hand. The original model assumes the maximum shelf-life is 20 days at 95% relative humidity (see paragraph 2.3.3.2) based on the expert opinion. However, during the shipment, the relative humidity was around 90%. Therefore the transpiration coefficient (mg/(kg s mPa) was reset to 288 to make the maximum shelf-life still 20 days at a 90% relative humidity.

The third learning is that there was a big difference between the sensor temperature and the temperature measured after arrival. The sensor temperature was around 7 °C whereas the temperature measured after arrival is between 9.1 and 18.7 °C. The remaining shelf-life was only 5 days which was also deviating heavily from the model predication. It may be an indication of the incorrectness of the sensor temperature because if the sensor temperature is replaced with the measured temperature after arrival, the predicted remaining shelf-life is close to 5 days. Another explanation is the sensor temperature is correct, but the reference relative humidity set in the model (90%) is wrong. If 95% was use as the reference relative humidity, with the sensor temperature, the predicted remaining shelf-life by the model is also close to 5 days.

3 Conclusions and recommendations

The discussed learnings above demonstrate how complex the problem can be when implementing the IoT solutions in real-life quality-controlled logistics. It can be concluded that the available (IoT related) technology is not the biggest challenge and a high potential of IoT applications in the pilot shipment can be seen. However, to make it ready for real-life implementation, more pilots need to be conducted and more data needs to be accumulated.

Therefore the following recommendations can be made:

Loggers:

- Size of the loggers: The current high-end loggers (robust, high degree of accuracy and reliability of the measurements) are still relatively large in volume and therefore take up substantial space so that less product can be transported (between half and a whole pallet place). This makes it less easy to come to a positive cost benefit analysis. A further miniaturization of ethylene loggers in particular is therefore recommended;
- Quality of the loggers: the quality, including accuracy and reliability, must be tailored to the purpose. When small differences in the values of the transport conditions are important, the loggers must be able to handle this. For example, for the detection of ethylene during transport of fruit, sensors will probably need to have an accuracy of 10 ppb in the range of 40 ppb to 1000 ppb.
  Also often the temperature sum, that is the summation of the number of days that the products have been exposed to a certain temperature, important for product quality. When it is important for products to be able to register this over small-time intervals or temperature levels, the loggers must be able to measure, record and transmit with a (very) high frequency and accuracy. It is therefore recommended to have this clear in advance of the shipment and to invest in the right equipment (there is no 'one size fits all')
- Positioning of the loggers / connectivity: for real-time monitoring of the environmental conditions, a reliable and good connection via GPRS / UMTS is necessary. The demonstration shows that when the loggers are positioned 'deeper between the cargo' connection becomes very difficult. A solution can be found in:
  - drawing up good protocols with regard to the positioning of the loggers.
  - Using or developing loggers with an external sensor making it possible to place the sensor in the core of the load and at the same time keep the 'transmitting part' close to the wall of the trailer or reefer container
  - further research to determine whether the loggers between the cargo can connect to a kind of 'hotspot' in the reefer container or trailer, which is then connected to the 'outside world'.

Quality decay models:
For the demonstrations existing mathematical quality-loss models were used. These types of models require expert knowledge and experimentation to infer the relationship between a fix set of inputs (sensors) and output (quality). This also means that these models were adapted on the basis of the expert knowledge available from the various parties, but that there was no room for experiments to 'perfectly fit' them to the demonstrations. The demonstration shows that the output of the models used therefore deviates somewhat from what was observed in practice. Therefore, it is recommended to do more experiments to fit the models better, so that the predictions will be further improved (see also Bianco Martinez, J. et al, 2021).

Literature

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