Traffic & Transport
Anna van Buerenplein 1
2595 DA Den Haag
P.O. Box 96800
2509 JE The Hague
The Netherlands

www.tno.nl

T +31 88 866 00 00

TNO report

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D1.1. State of the Art of IoT technology for quality-controlled logistics in the supply chain of perishable cargo

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Author(s)	Shari Finner, Gerwin Zomer
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Summary

Motivation
Fresh fruit and vegetables often undergo day- or week-long transport from their harvest location to the consumption location. Due to natural ripening and quality decay, about 4% of all fruit and vegetables is lost during transport alone (excluding storage). 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. Logistic interventions include, for instance, express treatment in ports to speed up the supply chain, a change of transport modality or dynamic pricing strategies depending on the product quality.

As shown in the schematic below, an IoT-enabled quality-controlled supply chain contains several steps and combines different knowledge areas. The goal of this report is to provide an overview of the existing knowledge and technologies in each of these areas, and to discuss how they may be combined in practice. In addition, a SWOT analysis is performed to identify the strengths, weaknesses, opportunities and threats of IoT-enabled supply chain monitoring.

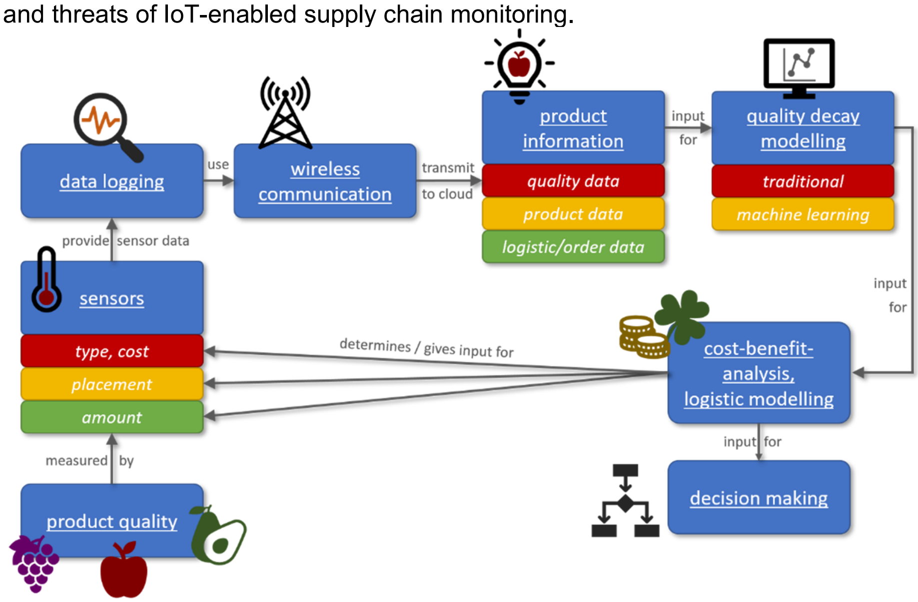


Figure 1 Schematic representation of IoT-based quality-controlled logistics of fruit and vegetables.

Results
The main quality parameters for fruit and vegetables are temperature, relative humidity, the atmospheric gas composition and *en-route* mechanical impacts. For a valid use case and business case, it is necessary that the respective sensors and communication devices be low-cost, sufficiently accurate and robust. While sensors for temperature, humidity and gases like O2 and CO2 are typically small, cheap and

widely available for use in IoT devices, sensors for the plant hormone ethylene are still rather costly and more complex. However, also ethylene sensors are recently undergoing promising developments, reducing their costs and complexity. Wireless communication technologies are rapidly developing due to rising interest and promising business cases of IoT-applications. In particular the technologies LPWAN and NB-IoT are developing fast. Several embedded or standalone IoT-devices are already available on the market, of which we provide a non-exhaustive overview. Also recent developments in quality-decay modelling are promising, with Big Data techniques like machine learning becoming more accurate and feasible. We identify the largest remaining challenges for IoT-enabled quality control to be the current lack of technology standardization, logistic decision making models and agreements for cost-benefit sharing. However, these challenges are likely to be overcome due to the large potential of mitigating food and financial losses.

This report aims to provide a knowledge base and guidance to the project “Quality controlled logistics in IOT enabled perishable supply chains”, which includes a pilot experiment as a proof of concept, as well as a business case analysis to explore the potential of IoT technology in perishable supply chains.

Contents

1 Introduction

1.1 Motivation

Despite the seasonal growth patterns of fruit and vegetables, fresh products are commonly available in our supermarkets throughout the entire year. The constant availability of fresh produce is warranted by production at the optimal production location and subsequent transport to the consumption location, which may well be on the other half of the planet. In particular in winter, most fruit and vegetables are produced at sunny and warm locations close to the equator or on the southern hemisphere, while being consumed on the northern hemisphere. Fresh food products therefore often undergo week-long transport, including overseas shipment, before arriving in supermarkets.
In view of marketability and food safety, the quality of the fresh produce ideally needs to be ensured for the entire transport duration and duration of storage. However, global food losses during transport are high, as the perishable cargo undergoes mechanical stress as well as natural quality decay due to ripening and aging *en-route*. If transport conditions like temperature and humidity are not well-controlled, the natural quality decay is accelerated, leading to large amounts of wasted food and financial losses.

In 2016, roughly 14% of food was lost between post-harvest and the distribution stage according to the FAO (Food and Agriculture Organization of the United Nations). This is shown in Figure 2. For fruits and vegetables, postharvest food losses are typically higher than for cereals and pulses and for animal products, as visualized in Figure 2. The damage or quality-decay is often only discovered at intermediate stopovers in the supply chain, or at the final destination of the produce.

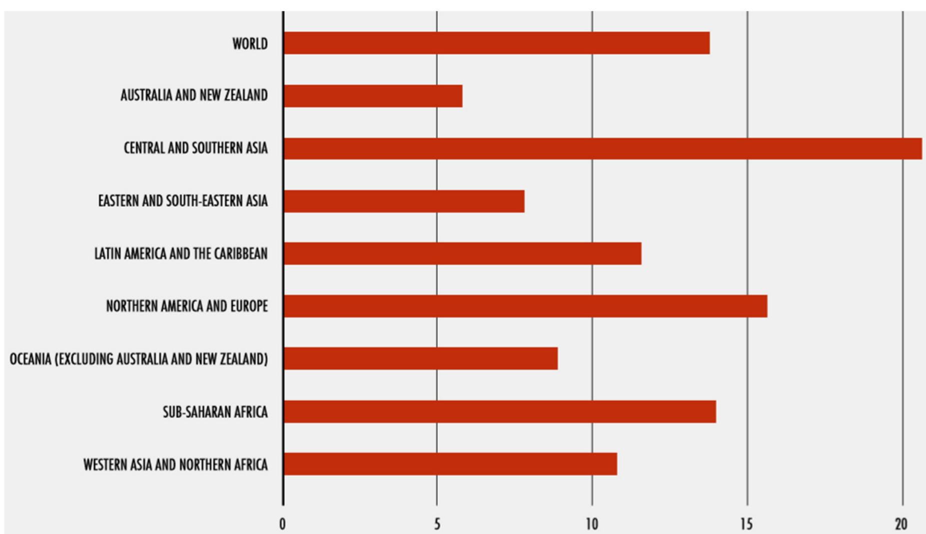


Figure 2: Estimated percentage of food waste from post-harvest to distribution in 2016 in different regions of the world. Note that it is in some cases unclear whether losses occur in the *production* or the *consumption* region. Estimates Source: FAO 2019 [1].

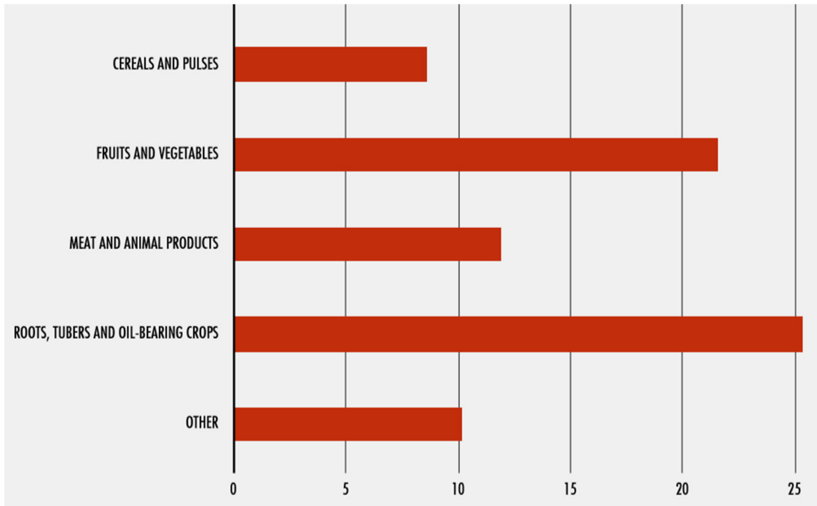


Figure 3: Percentage of global food loss in the year 2016 for different crop categories. In the fruit and vegetable sector, more than 21% of food was lost between post-harvest and distribution. Source: FAO 2019 [1].

According to Wageningen University of Research, transport alone accounts for a loss of 3.84% of all fruit and vegetables. [2] The financial consequences of quality decay of fruit and vegetables are therefore significant. For a large company like Van Oers United, with a revenue of 245 million Euro in the year 2014, about 9.1 million Euros of value loss may potentially be mitigated. Looking at the total of extra-European imports to the EU, with a worth of 20.1 billion Euros, [3] the fruit and vegetable loss during transport is equivalent to 772 million Euro. Globally, the fruit and vegetable sector amounted to nearly 1,300 billion US dollars in 2018, with around 50 billion USD worth of fruit and vegetable losses.
However, food waste is not only relevant due to its financial impact. Also, scarce resources like water or fertile land are being wasted in producing large amounts of fruit and vegetables in the first place. This is a problem in particular in developing countries. Reducing postharvest losses therefore has great potential to improve the sustainability of fresh supply chains.

The question that arises is: Could the large amount of food waste and financial losses be mitigated if the ripening and decay status of perishable cargo during transport were available in real time?

Possible adaptations of the supply chain, depending on the decay status of the product, include:
- speeding up or relaxing the supply chain;
- selling the product to different markets;
- dynamic pricing strategies (e.g. decreasing the price of a lower-quality product batch instead of having it rejected by the buyer);
- avoiding transport of already perished cargo;
- identifying points of failure and holding the responsible parties accountable.

Recent developments in IoT technologies provide an opportunity to estimate and track the status of perishable cargo in real-time. IoT stands for the *Internet of Things*, meaning that communication devices – in this case smart sensors in the

storage location or in transported containers, pallets or crates – are interconnected and form a network without requiring human interaction. If sensor data about the product quality can be communicated in real-time to logistic providers, the hypothesis is that large postharvest losses could potentially be mitigated.
While several solutions to reduce large amounts of food waste have been proposed in the literature, many of them focus on a quality-control perspective without taking into account logistic decision-making processes, or *vice versa*. The effective interplay of quality control and real-time logistic adaptations in an overarching conceptual framework has, to our knowledge, not yet been sufficiently addressed in the literature. In this report, we therefore aim to summarize the current state of the art of IoT-enabled quality-controlled logistics from an overarching point of view. This way, we intend to provide a general overview and some in-depth knowledge to both:

- the scientific community;
- businesses that aim to digitalize their supply chain.

The report describes the present knowledge on environmental parameters that drive product quality decay, as well as existing sensing-, data logging- and communication technologies. Furthermore, the most common quality-decay models for fruit and vegetables are discussed, as well as methods for decision making processes. In the end, we explore advantages and possibilities for the smart integral use of IoT-technology in digitalized supply chains and name the major weaknesses and bottlenecks for implementing the technology. While we mainly focus on mitigating losses in fruit and vegetable supply chains, some concepts may also be translated to other quality-controlled supply chains like those of flowers, medicine, chemicals or fragile goods.

In addition to this report, an overarching conceptual framework for the deployment of IoT devices in fresh produce chains has recently been put forward by Xuezhen Guo, Joost Snels and Seth Tromp from Wageningen Food & Biobased Research. Here, we highlight main concepts in the chapters 5 and 6. For further information on the conceptual framework, we refer the interested reader to the original research article, which has been recently submitted to a peer-reviewed journal. [4]

1.2 Approach and Sources

We have performed desk research and interviews with TNO in-house as well as external experts on the topic. The desk research involved widespread internet search as well as a scan of relevant studies, among which:

- Guo. X, Snels. J, Tromp. S.O (2020). Quality-Controlled Logistics with Internet of Things: A conceptual framework to analyze quality-sensor based fruit and vegetable supply chains. Wageningen University & Research. [4]
- TNO report "Inventory of technologies for monitoring, tracking and identification of maritime containers and their cargo" | TNO 2019 R11022v2 | 9 September 2019 [5]
- S. Janssen, K. Schmitt, M. Blanke, M. L. Bauersfeld, J. Wöllenstein and W. Lang (2014). Ethylene detection in fruit supply chains. Phil.Trans. R. Soc. A 372: 20130311 [6]

Interviews were performed with the following TNO experts and external stakeholders:

- Kees Koopal (TNO - EMSA);

- Evert van den Akker (TNO - ICT);
- Johan Kruysse (Van Oers United);
- Joris Tenhagen (Pharox);
- Marco Snikkers (OneThird / Ocean Insight);
- Joyce Boezaard-Klapwijk (Purfresh).

1.3 Content and structure of this report

The concept of IoT-enabled quality-controlled logistics of perishable supply chains is visualized in Figure 4. The product quality is measured by electronic sensors. Subsequently, the digital sensor data need to be logged and communicated to the internet using wireless communication devices. Complete product information, including quality product and order data, can be used for quality-decay modelling. After a quality- or shelf life prediction, a cost-benefit analysis needs to be performed in order to take the most beneficial logistic decision. A cost-benefit analysis can also be used to determine the required type, ideal placement and number of sensors during transport.

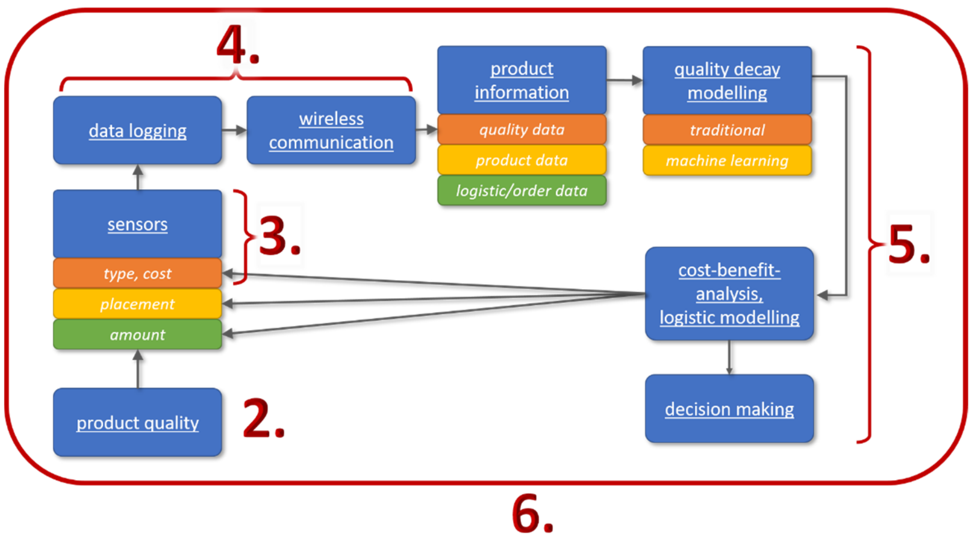


Figure 4: Concept of IoT-based cargo monitoring of perishables. Red numbers indicate the chapter of this report, in which the subject is discussed.

Also the structure of this report is illustrated in Figure 4 above by red numbers: In chapter 2, we first outline the ripening process of fruit and vegetables and identify the main parameters influencing the quality decay of perishable cargo.
Chapter 3, describes the state of the art of current sensing and scanning technologies to monitor quality-decay parameters. Chapter 4 focuses on the logging and wireless communication of sensor data and provides examples of existing commercial IoT-devices. In chapter 5, we discuss common quality-decay models and possible methods for data-based decision making.
We explore the role of IoT technologies in quality-controlled logistics chains, and discuss how newly developed technologies may be integrated into the existing application domain in chapter 6. Lastly, in chapter 7, we perform a SWOT analysis of IoT technologies for perishables and conclude our main findings.

2 The product quality of perishables

To monitor the quality decay of fresh produce and be able to mitigate product losses, we first aim to understand which factors influence product quality. Fruit and vegetable quality decay typically occurs by ripening, senescence (biological aging), physical damage or diseases such as mold and bacterial infections. In this chapter, we describe the ripening process of fruit and vegetables and the influences on their quality-decay in detail.

2.1 The quality decay of fruit and vegetables

Fruits and vegetables accumulate water and nutrients from their host plant. In fruits, these nutrients are used to grow seeds, and the flesh surrounding the seeds initially acts as a protective layer. The flesh of immature fruit is therefore typically hard and unattractive. This changes with seed development, after which the flesh ripens and changes its properties. Ripening can change the color or firmness, but also the sweetness of the fruit. In contrast to fruit, (leafy) vegetables typically don't *ripen*. However, they do undergo senescence, which affects their quality and taste.

In fruit ripening, a change in color typically takes place by the breakdown of green chlorophyll, as well as the accumulation of other violet or orange pigments. The firmness of the produce is mainly determined by the state of the cell walls, which are broken down by enzymes during the ripening process. This leads to softening of the flesh. Also, the fluid content has a strong influence on the fruit firmness. After maturation and harvest, the produce loses water by evaporation, which decreases the internal pressure and can make the fruits shrivel. Sweetness increase during ripening is related to a breakdown of complex sugars into simple sugars like glucose, fructose and sucrose. The content of simple sugars in pineapples, for instance, increases from approx. 4% to 15% in the last two weeks of the ripening process. In addition, ripening fruits undergo a decrease in acidity and a decrease in bitter substances like alkaloids.

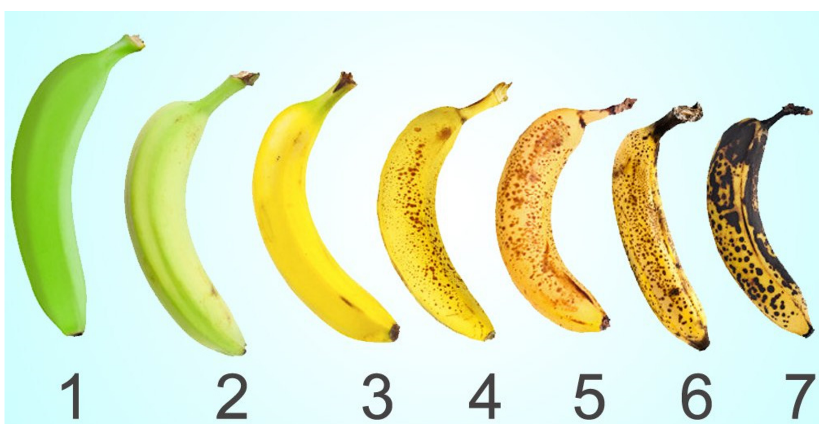


Figure 5: Demonstration of fruit ripening and senescence for a banana. Source: ScienceABC [7].

From a consumer's point of view, ripening initially increases the quality of the fruit, leading to a more pleasant aroma, taste and texture. However, ripening negatively affects the flesh quality, and ripe fruits tend to deteriorate more rapidly. In addition, both the increase in sugar content and the softening of cell tissue can make a ripe fruit more susceptible to diseases like molds or bacterial infections.

Fruit ripening is caused by the produce undergoing respiration ("breathing") after harvest. This not only includes the loss of moisture, but also the intake of gases like oxygen from ambient air and the release of CO_2. Also, ethylene and other volatile compounds that give ripe fruit its characteristic aroma are emitted. The gaseous atmosphere has a great impact on the ripening process and product quality. In the following section, we focus on the production of the plant hormone ethylene in fruit, as well as ethylene-induced ripening and aging. Subsequently, we describe the influence of other atmospheric gases on the fruit ripening process.

2.2 Climacteric and non-climacteric fruit: the effect of ethylene

Ethylene or *ethene* is an organic gas with the chemical formula C_2H_4 that is naturally produced by plants. It is one of the substances released during the ripening process of fruit. In addition, it triggers, stimulates and accelerates ripening or senescence by acting as a plant hormone. Ethylene plays a major role in the development, growth and spoilage of fruit and vegetables, and also affects resistance against pathogens.

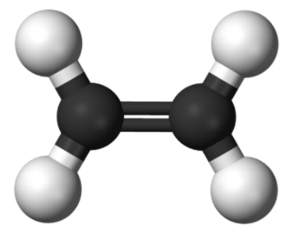


Figure 6: Structure of the ethylene molecule C_2H_4

Every fruit exhibits a certain level of ethylene production at some point in its ripening process. However, for certain types of fruit the ethylene levels strongly increase at the onset of ripening. These are called **climacteric fruit** and include, for instance, tomatoes, avocados, mangos, apples, melons, peaches, pears, kiwis and bananas. Often, climacteric fruits types don't only produce large amounts of ethylene, but also react very sensitively to ethylene levels present in ambient air. In contrast, **non-climacteric fruits** like strawberries, grapes and citrus fruits do not exhibit a boost in ethylene production during ripening. Also, many vegetables like Brussel sprouts, cabbage, beans and spring onions exhibit a low ethylene production and are in principle non-climacteric. However, they may still very sensitively react to ethylene present in ambient air by temporarily increasing their respiration rate and undergoing aging processes more rapidly. In contrast to climacteric fruits, non-climacteric fruits do not change much in composition after ethylene exposure and typically do not perish as rapidly. [8]

Figure 7 visualizes the ripening process of climacteric fruits. In the pre-climacteric ripening stage, the ethylene level increases with time, which accelerates the ripening process. As a result, also the levels of simple sugars and volatile compounds increase, and more ethylene is produced. At the same time, the pH increases, indicating a drop-in fruit flesh acidity. Also, due to an enhancements of the fruit's respiration rate, the levels of emitted CO_2 increase sharply. [9] Ethylene production increases until a peak is reached in the so-called climacteric phase. In this phase, the fruit is not only mature, but also ripe. Its firmness and green color (indicated by the chlorophyll content) decrease.

In the post-climacteric phase, fermentation of simple sugars to alcohols and the dismantling of cell walls starts to take place. This results in a sharp decrease in sugar content and firmness and an increase in acidity, as shown in Figure 7.

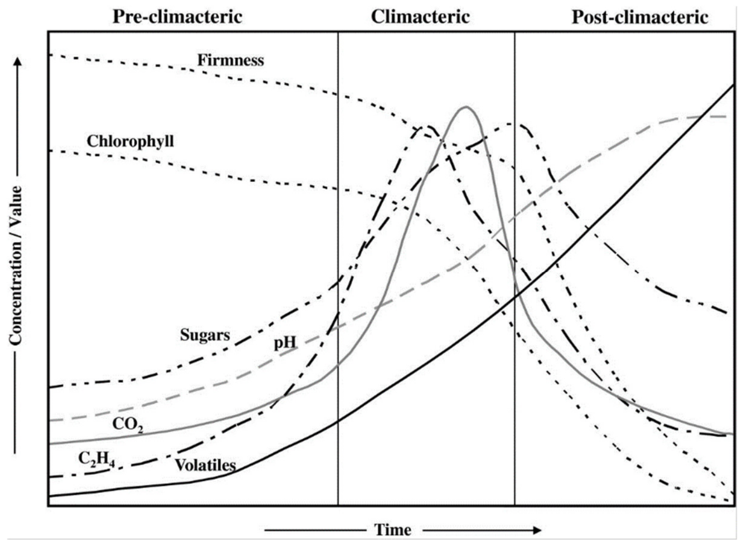


Figure 7: Visualization of the ripening process of climacteric fruits. The development of firmness, chlorophyll content, sugar content, pH, CO_2 emission, ethylene emission and emission of other volatile gases is plotted against time. Source: (Nath 2006) [10].

The effect of ethylene on fruit ripening depends on several factors. Classic climacteric species show a clear increase of respiration and a dramatic increase in ethylene production at the onset of ripening. Some types of climacteric melons, however, can exhibit a substantial rise in ethylene levels already *before* the onset of ripening. Avocados are another untypical species in that they are strongly climacteric, but do *not* ripen when still connected to the tree – not even if exposed to great amounts of ethylene. They only start ripening after harvest, after which they gradually increase their ethylene production and sensitivity.

Table 1: Ethylene production and sensitivity of several commodities. Source: [6]

commodity	commodity classification	ethylene efflux	ethylene sensitivity
apple	climacteric	++	+
avocado	climacteric	+	+
banana	climacteric	0	+
carrot	non-climacteric	− − −	+ + +
citrus	non-climacteric	− − −	0
kiwi	climacteric	−	+ + +
pear	climacteric	+	+
passion fruit	climacteric	+ + +	+
tomato	climacteric	0	+
onion	non-climacteric	− − −	−

Also, ethylene sensitivities of different fruit and vegetable species differ greatly, as shown in Table 1. Some climacteric species like kiwis are very sensitive to ethylene stimulation, while tomatoes or apples are only moderately sensitive. For the latter, ethylene presence mainly shortens the time before the ripening process starts. In general, immature fruit requires greater concentrations of ethylene to stimulate ripening than mature fruit, and the sensitivity to ethylene progressively increases with the ripening process. Some products need to pass a certain ripeness threshold to respond to ethylene presence in the first place. Typically, the lower bounds for ethylene levels to stimulate ripening are very low. They lie between 50 ppb (parts per billion) and 1 ppm (part per million).

2.2.1 *Controlling ethylene levels*

Ethylene production 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 (for instance a wound). Historically, Egyptians used to cut figs in order to speed up their ripening process. In addition, ethylene can be produced externally as a by-product of incomplete combustion of fuels. The ancient Chinese therefore used to burn incense in closed storage rooms to induce faster ripening of pears. Also, today, fruits like tomatoes, bananas and pears are harvested in the mature stage *before* the ripening process. Subsequently, ethylene gas is commonly used in distribution centres close to the final destination in order to ripen the products.

To retain the quality of fresh produce during transport, which is often needed in long supply chains, however, the goal is not to *induce* ripening, but to *prevent* it or slow it down. This can be done by removing the gas through ventilation, by ethylene absorbing materials like potassium permanganate, or by catalytic converters, which are commonly applied on an industrial scale in fruit storage facilities. In catalytic converters, ethylene is oxidized at the surface of a catalyst material following the reaction:

ethylene + oxygen -------> water + carbon dioxide.

In addition, the gas may also be removed by ozone through oxidation.

If ethylene is not removed, its *effect* on both climacteric and non-climacteric commodities can be reduced by lowering oxygen levels in combination with an increased amount of CO_2, or by adding synthetic compounds, which block ethylene receptors at the skin of fruit and vegetables. An example is the gas 1-MCP, which is also often applied in the flower industry to maintain the freshness of cut flowers.

While ethylene is a major controlling factor of the ripening and decay of fruit and vegetables, it is not the only one. Next to several alternative ripening hormones, the ripening- and quality decay process are greatly influenced by the ambient air temperature, moisture levels, and the presence of other respiratory gases such as oxygen and carbon dioxide.

2.3 Other quality decay parameters

Most factors affecting the ripening of fresh produce are related to respiratory activity – the breathing of fruit. Lowering the respiration rate of fruit and vegetables therefore provides great opportunities to slow down quality decay. The main influences on the respiration rate are temperature and humidity of the ambient air, as well as the presence of respiratory gases like O_2 and CO_2.

2.3.1 *Temperature and transpiration*

Temperature is an important factor in the ripening process. All physical diffusion mechanisms and chemical reactions inside of the cell tissue take place faster with increasing temperature, and slower at low temperatures. Typically, ripening products also generate heat, which in turn accelerates ripening. To enhance the shelf-life, fruit and vegetables are typically subjected to cold temperatures above freezing. Also ethylene production is lowered at low temperatures. However, the feasibility of this approach is limited, as some commodities such as bananas, cucumbers and green mature tomatoes may be damaged by chilling. Also, cooling fruit below the freezing point is often not a viable option, as this often leads to flavor loss and texture decay due to ice crystals in the fruit flesh.

Another important process in fruit ripening is moisture loss. While water is the major component in plant tissue, fruit and vegetables that are detached from their plant have no renewable water source available to compensate loss by transpiration. This so-called *water stress* affects the weight, appearance, texture, juiciness and nutrition quality of the fruit. From a weight loss of 5% onwards, the fresh produce exhibits increased respiration by approx. 70% and increased ethylene production by approx. 50%. It also suffers from decay of its outer appearance, making it unacceptable to sell. Also, it has been found that water stress decreases induces earlier ripening in fruits like bananas, avocados and pears. The water transpiration rate typically depends on temperature, the condition of the fruit surface, relative humidity level, air movement and the surface-to-volume ratio of the fruit. [9]

While a high ambient moisture level can prevent water loss, it also increases the chance of pathological or physiological disorders. High relative humidity and temperature fluctuations can lead to condensation and accumulation of water in the package. The excess moisture then enhances leaf sprouting as well as fungal and bacterial decay. Also, physiological disorders such as tissue discoloration and peel blemishes may take place if the fruit is in contact with the condensed water. How sensitive the produce is to excess moisture levels is strongly commodity-dependent.

2.3.2 *Oxygen and carbon dioxide*

Another factor affecting respiration are the ambient levels of oxygen and carbon dioxide. Harvested fruit needs oxygen to ripen and emits carbon dioxide. Ripening can therefore, in principle, be slowed down by reducing oxygen and increasing carbon dioxide levels. However, low oxygen levels may at the same time cause anaerobic respiration and fermentation of sugar to alcohols. Therefore, the oxygen level must be balanced between minimizing the normal (aerobic) respiration rate, while anaerobic respiration is completely avoided. The optimum oxygen level depends on the fruit, the variety of fruit, its maturity level as well as the storage temperature. [9]

An additional effect of oxygen reduction is that oxygen is involved in the production of ethylene. A reduction of oxygen to approx. 1% may reduce ethylene synthesis by up to 50%, and has been reported to reduce the breakdown of cell walls. Also, the fruit tissue appears to be less sensitive to ethylene presence in a low-oxygen environment.

Turning to carbon dioxide, we note that also high CO_2 levels can slow down the respiration and metabolism of the fruit, and enzymatic activity. In addition, high CO_2

concentrations are reported to inhibit the effect of ethylene by occupying the relevant active receptor sites. However, high CO_2 levels may also negatively affect respiration by increasing fruit acidity. At very low carbon dioxide concentrations of ca 1%, ethylene production is accelerated. A well-known commodity that requires excessive CO_2 levels for ripening-delay are blueberries.

2.3.3 *Nitric oxide (NO), ozone (O3), and other gases*

Nitric oxide is often emitted simultaneously with ethylene and has a regulatory effect on ethylene production. Its presence typically delays aging effects (senescence) in fruits, vegetables and also flowers and extends postharvest life. Applying NO to tomatoes above a certain concentration has been shown to decrease biomass conversion and delay the ethylene production peak and colour development, at least in the early postharvest stages when the fruit is still green mature.
In addition to nitric oxide, gases like carbon monoxide (CO), nitrous oxide (N_2O), nitrogen (N_2), sulfur dioxide (SO_2) and chlorine dioxide (ClO_2) are used in storage environments to reduce infestation with microbes or insects. Besides that, also ozone (O_3) is known to delay ripening and prevent microbial contamination. It destroys remaining pesticides and microbiology such as fungi by oxidation. Also, ethylene can be destroyed by oxidation, thereby reducing the overall ethylene levels in the environment and within the fruit flesh. [9]

2.3.4 *Diseases, vibrations and shocks*

Diseases of fruit and vegetables can include fungal or bacterial infections. While these infections are unlikely to occur in the unripe stages, ripening and aging create more favorable conditions for diseases. Moisture loss, for instance, is one of the main drivers of changes in the internal flesh structure. The physical breakdown of the cells is supported by enzymatic activities, which further softens the fruit flesh. Also, the skin-surface condition in terms of moisture, temperature, nutrient availability and possible wounds influences the vulnerability to diseases. Typically, bacterial infections take place first. Mold then forms in soft and rotten areas that are already infiltrated by bacteria. [11]
Infections of the fresh produce can be controlled by reducing the temperature, controlling the ambient moisture level, and by certain chemicals or pesticides that eliminate fungal spores and bacteria before infestation can occur. In addition, CO_2 can be added to prevent fungal growth.

Next to diseases, mechanical bruises and vibrations can influence quality decay of the fresh produce. As mentioned above, physical cuts and bruises do not only accelerate infestation with diseases, but can also boost ethylene production. In addition, vibrations during transportation can increase water loss by disintegrating a thin layer of high-humidity air called the “diffusion shell”, which typically forms close to individual fruits and vegetables.

2.3.5 *Sugar content*

Except for providing nutrients for bacterial or fungal infections, the internal sugar content of fruit does not strongly *influence* the ripening process and quality decay. However, it is a good and measurable *indicator* for the sweetness, firmness and overall ripeness of climacteric fruit, as demonstrated in Figure 7 on page 11.

2.4 Quality control mechanisms

In the previous section, we have summarized the main influences on the product quality of perishables and demonstrated that the product quality can be influenced by changing and controlling the environment of the freshly harvested product. Here, we outline the most common methods to control product quality and mitigate food waste and financial losses in the supply chain.

2.4.1 Selective harvesting and pre-sorting

Commodities like avocados or mangos exhibit a large biological variation in their ripening status and speed. However, a great ripeness variety in a batch of fruit influences the surrounding atmosphere and thereby the respiration rates. Due to their enhanced ethylene production, a few ripe mangos or avocados can make the entire pallet ripen and decay faster, unless low temperatures or controlled atmosphere are applied. Similarly, it is well-known that the presence of one rotten apple can spoil the whole basket.

A mechanism to control the product quality is therefore to harvest the produce homogeneously, i.e., with all products in the same ripening state. However, a pre-harvest estimation of the ripening status in the orchard is often challenging. At this point in time, ripeness is often estimated according to firmness and color. Recent developments show that also optical scanners are more and more used in the field to measure fruit and vegetable ripeness pre-harvest. However, the use of this technology can slow down the harvesting process, and is not widely applied yet.

Another option to ensure batch homogeneity is to do *post-harvest* sorting according to maturity and ripening status. This may, again, be done by hand, or by optical grading lines. Industrial grading and packaging lines are large machines that automatically classify the products by ripeness and sort them into separate batches. These lines are automated to a large extent, but have the downside of significant investment costs. In Chapter 3, we further discuss the sensor technologies behind pre- and post-harvest optical ripeness sorting.

2.4.2 Temperature control and cold chains

As mentioned above, the temperature is one of the most important influences on quality decay in fruit and vegetables, as it directly controls the respiration rate and the rate of chemical reactions. Also, ripening fruit produces heat, which further accelerates the ripening process. With lower temperature, also the ethylene production decreases. Bananas at 13ºC, for instance, emit only about a quarter of the ethylene that they produce at 20ºC. [12]

Figure 8: Reefer containers by Maersk and Hamburg Süd.
Source: Wikipedia [30].

A widely applied remedy for quality decay is therefore to cool the product throughout the entire supply chain in so-called cold chains. For this purpose, refrigerated container (reefers) are widely used for transporting perishable cargo like food, flowers and medicine. The temperature can typically be controlled in a range from -30°C to 40°C, and down to -65°C in special cases. To provide the energy for cooling, reefers are connected to power sockets on the ship, train or truck.

Reefers are essential for current cold chains and the main reason why grocery stores can offer fresh products all year round. The postharvest life of bananas, for instance, can be increased by cooling from 2-4 weeks to 4-6 weeks. [12] Reefer containers are standardized and constitute roughly 6-7% of the global container fleet. [12] The terminals in the Port of Rotterdam, for instance, have 18.500 reefer power connections available. [13] However, reefers can be vulnerable to failures of the refrigeration units or to power-off events. Containers for very valuable, temperature-sensitive or hazardous products therefore often contain a second (redundant) refrigeration system that takes over if the primary system malfunctions. In addition, reefers for sensitive cargo are often equipped with one or more diesel generator sets to provide reliable power in cases of external power outage. In some cases, in addition to the temperature, also the gaseous atmosphere can be controlled.

2.4.3 *Modified atmosphere (MA) and controlled atmosphere (CA)*

Modified atmosphere and controlled atmosphere packaging are terms for packaging in which the gas composition surrounding the products, including the humidity, is adjusted in order to decrease the respiration rate and extend shelf-life. We distinguish between passive MA, active MA and CA applications.

Passive MA-packaging is widely used for fresh respiring produce. The atmosphere in passive MA-bags depends on the respiration rate of the product as well as the type and permeability of the packaging film. As a result of respiration of the product, high CO_2 and low O_2 levels build up inside the package over time as shown in Figure 9. Due to transpiration, also the relative humidity increases. The desired atmosphere is achieved by fine-tuning the oxygen, carbon dioxide and water vapour transmission rates of the polymeric packaging film. The film composition and amount and size of micro perforations need to be adjusted to the weight, anticipated temperature fluctuations and the expected respiratory activity of the product. Therefore, film packaging that is adequate for *transport* and *bulk* packages is not always equally suitable for *consumer* product packaging, and *vice versa*.

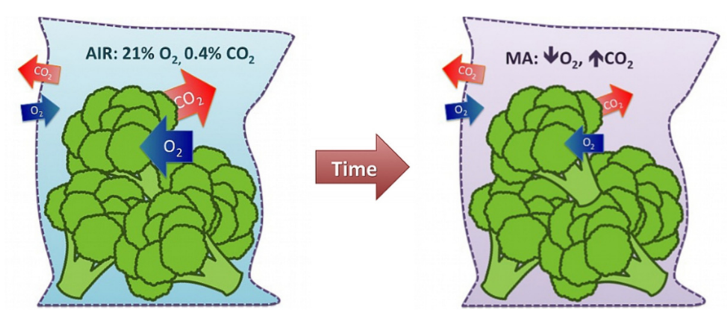


Figure 9: Schematic representation of modified atmosphere (MA) packaging of broccoli. Source: [14].

Undesirable consequences of incompatible film design or excessive temperatures can result in damage to the product. A lack of oxygen, for instance, can result in anaerobic respiration or fermentation in fruit and vegetables, which leads to the production of alcohols and gives the product a characteristic off-smell and off-taste. Excessive CO_2 levels can result in tissue damage. In apples, high CO_2 concentrations lead to the core tissue turning brown (“brown heart”). In bananas, excessive CO_2 levels may result in a black blotchy outside appearance. A combination of elevated temperature and CO_2 levels above 5% for a prolonged amount of time may in some cases kill the fruit. [15] [16]. The optimal oxygen and CO_2 levels for fruit and vegetables typically lie between 3-5%, while the optimal nitrogen concentration is around 85 – 95%. [17]. In active MA packaging, ventilation, active moisture absorbers, CO_2 or O_2 scavengers or emitters, as well as ethylene absorbers or ethanol emitters can be added to the product package.

A more advanced technique than MA packaging to ensure product quality is controlled atmosphere (CA), in which the gas composition inside large packages, whole containers or storage rooms is monitored and controlled during (part of) the supply chain. The atmosphere is actively manipulated if deviations from the desired gas composition occur. With close monitoring, the product atmosphere can be kept constant, or be scheduled to trigger ripening at desired milestones in the chain.

CA containers are typically reefers with additional atmosphere control systems. They commonly include humidity control, oxygen and CO_2 - sensors, active N_2 and CO_2 injection systems and mechanisms for automatic ventilation. In some cases, also ethylene scrubbers can be applied. [16] The PurFresh CA system, for instance, adds ozone to the container to destroy airborne and surface pathogens, and to remove any ethylene present in the container.

Examples of controlled atmosphere containers are:

- Maersk StarCool CA and CA+
- CMA CGM CLIMACTIVE
- Thermoking AFAM+
- eAutoFresh
- Transfresh
- Maxtend
- PurFresh

The use of controlled atmosphere containers plays a major role in mitigating food losses during transport in the supply chain of perishable cargo.

2.5 Summary of quality parameters

In the following table, we summarize the main parameters affecting fruit and vegetable quality decay:

Table 2: Summary of parameters affecting the quality-decay of fruit and vegetables.

Parameter	Origin	Effect on quality decay	Importance	Mitigation
Temperature	Ambient air; fruit metabolism	Respiration rate -> affects CO_2 and O_2, Metabolism: sugar content, fungal/bacterial growth, Ethylene production	very high	Cooling/reefer

Humidity/ moisture	Ambient air; fruit transpiration	Moisture loss, Fungal/bacterial growth, physiological disorders, Ethylene production	medium	Ventilation, MA-packaging, humidity absorbers, CA
Oxygen	Ambient air; Fruit takes in oxygen during respiration	Respiration rate, Production of bad-tasting substances like acids	medium	MA-packaging, CA, O_2 absorbers
CO2	Ambient air; Fruit releases CO_2 during respiration	Respiration rate, Production of bad-tasting substances like acids	medium	MA-packaging, CA
Ethylene	Produced during ripening; Present in ambient air due to surrounding fruit	Accelerates ripening and senescence	Low to very high, depending on the sensitivity of the commodity	Ventilation, ethylene absorber, synthetic compounds (gases), pre-sorting for homogeneous batches with similar ethylene emission
Sugar content	Fruit metabolism breaks down cell walls and builds up sugar in tissue	Cell wall integrity (firmness), Provides nutrients for fungal/bacterial growth	Low to medium	Mainly cooling

In principle, all quality-decay parameters mentioned in the table above can be *measured* or even *controlled* in order to predict/prolong the shelf-life of the fresh produce. In order to effectively monitor the ambient atmosphere or the sugar content in the flesh, however, sufficiently accurate temperature, humidity, gas and sugar sensors are required. For the application in IoT-based quality-controlled logistics, additional requirements for sensors are their small size and weight, as well as a low energy consumption. It can also turn out useful to track the location of the container, or to optically estimate the fruit ripeness at certain milestones in the supply chain. There are several sensing and scanning technologies available to monitor and ensure the product quality of fresh produce. They are described in detail in the following chapter.

3 Sensing and scanning technologies

3.1 Sensor technologies for fruit quality monitoring

A wide range of electronic sensing and scanning technologies is available to measure and predict the ripening status and quality of perishable cargo. The main considerations and sensor requirements depend strongly on the application and corresponding business case.

However, some *typical* considerations for sensors used in embedded or standalone IoT devices for cargo monitoring are: [18]

- Long battery life (in the absence of container power supply)
- Sufficient accuracy for the monitored commodity
- Small volume/weight
- Low cost
- Robustness against mechanical impact, water or temperature fluctuations (in order to work remotely and survive different transport scenarios)
- Mass production possible.

Due to their importance for quality control in the supply chain and their low costs, some electronic sensors are already commonly used in IoT-devices. Examples that fulfil these requirements are sensors for relative humidity, temperature, CO2, shocks and vibrations, as well as GPS. In the case of expensive cargo, also sensors to detect door openings or tampering are in use. Other types of sensor are not yet widely applied in real-time food quality tracking. Reasons for this include insufficient gas detection accuracies, high investment costs and insufficient support of the business case. In this chapter, we discuss the most relevant types of gas sensors, optical scanners, as well as temperature, humidity and shock sensors for IoT-applications in quality-controlled logistics.

3.1.1 Common sensors used in IoT devices

3.1.1.1 Relative humidity

The relative humidity indicates the current humidity at the sensor site relative to a fixed maximum humidity at the same temperature. It is typically expressed in percent. As relative humidity is a function of both the temperature and the absolute moisture content, common humidity sensors (hygrometers) need to be combined with temperature sensors for accurate predictions. To measure humidity below the frost point, heated sensors are used and widely available. Relative humidity sensors are very important in the context of dewpoint detection, to prevent condensation and outbreak of fungi, mold, and bacteria on fresh products. They can also measure the relative breathing of the fruit, so that unwanted interferences in storage can be detected. Two common humidity sensors are the so-called gravimetric hygrometer and the chilled mirror hygrometer. Both methods are very accurate with an accuracy of ±1.2%RH, but rather complex in use. In addition, they are very susceptible to air impurities and baseline drift, meaning that they need frequent recalibration.

For application in IoT devices, where cost, volume, simplicity and robustness are strongly relevant parameters, alternative hygrometers are often used, albeit with a slightly lower measurement accuracy. The most frequently used type is the **capacitive hygrometer**, in which humidity present in the air changes the dielectric constant of a polymer- or metal oxide layer. This change can be measured electronically. If calibrated well, capacitive sensors have an accuracy of ±2% RH in the range of 5–95% RH. They are usually robust against temperature shocks and condensation.

In the other common type, the **resistive hygrometer**, the electrical resistance of a material changes due to the presence of humidity. Commonly used materials in these sensors include salts or conductive polymers. Resistive sensors are slightly more complex and are less sensitive than capacitive sensors. They exhibit accuracies of approx. ±3% RH.

The main advantages of capacitive and resistive hygrometers are their small size and low power consumption, with currents of 0.5 µA and a power consumption below 5 µW. Also, their low cost of 1-2€ (including a temperature sensor), makes these humidity sensors very attractive for atmosphere-monitoring. Disadvantages of both the capacitive and the resistive hygrometer are that they can be subject to some extent of baseline drift and may require regular recalibration. Their high sensitivity to dust and other contaminants is typically solved by using miniature dust covers. Both capacitive and resistive hygrometers are very well suited for IoT-applications, and in fact already frequently being used in this context.

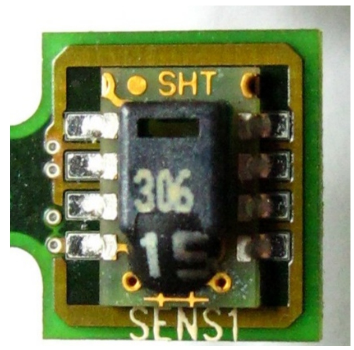


Figure 10: Example of a capacitive humidity sensor with a sixe of approx. 7mm x 7mm. Source: [35].

3.1.1.2 *Temperature*

As indicated above, temperature sensors are often combined with relative humidity sensors and are typically very inexpensive, with prices of a few euros or less per sensor. Historically, the most widely used type of temperature sensor is the thermocouple. It consists of two different wires connected by an electrical junction, which produces a temperature-dependent voltage. Thermocouples are inexpensive, can measure a wide temperature range and are self-powered. In some cases, accuracies higher than ±1°C are challenging to achieve, and the devices need to be frequently recalibrated. Other types with good wiring can achieve accuracies of ±0.1°C and provide a reliable and robust signal. At this point in time, **resistive temperature devices (RTDs)** and **thermistors** are therefore replacing thermocouples for most applications below 600°C.

In IoT-devices, RTDs and thermistors are in fact the most commonly used temperature sensors. Both of these sensors measure the temperature by a change in the resistance of the material used. RDTs often contain a fine platinum, nickel, or copper wire wrapped around a ceramic or glass core. The resistance of the wire goes up as the temperature increases. This way, temperature changes can be accurately measured between -270°C and 600°C. In contrast, the thermistor-based thermometer is a resistor which *decreases* in resistance with rising temperature.

Thermistors are made from semiconducting materials like metal oxides, doped ceramics or silicon, and in some cases from polymer composites.

Great advantages of RTDs and thermistors are that they have a high accuracy and wide operating range. They exhibit a low baseline drift, meaning that they can remain accurate for many years without recalibration. In addition, they are typically small, exhibit a low power consumption and are available at very low cost. Sensors commonly used in IoT devices typically cost less than a euro, have an accuracy of ±0.2°C and their size is less than a few millimeters per dimension. More elaborate temperature sensors can, in principle, achieve precisions of ±0.001°C, at the cost of becoming significantly larger and more expensive. However, such high accuracies are not required for the monitoring of fresh cargo.

3.1.1.3 *Shock and vibration sensors*

Shock and impact detectors are useful to check where in the supply chain physical damage occurs to the cargo. They can in principle be cheap single-use items that signal force overload or high impact by breaking above a certain threshold. However, these devices only provide binary information on whether or not a shock has occurred, without the time, location or strength of the impact. In addition, also vibrations can cause damage that would not always trigger a single-use shock detector.

Shock and vibration data loggers, in contrast, are battery-powered devices that measure the product’s acceleration over time, often expressed in terms of g-forces.
This information is relevant, as not only the maximum acceleration is relevant for product damage, but also the duration of the shock or vibrations. While a short shock of 300g amplitude during a time of 1 ms may result in very little damage, the same impact during 20ms may cause severe damage to the product. In addition, time stamps from data loggers can help identify the time and location of any mechanical damage and hold the responsible parties accountable.

Figure 11: MSR electronics shock and vibration logger with a digital 3-axis accelerometer and a lithium-ion battery. Source: [36].

In commercial shock and vibration loggers, piezoelectric, piezoresistive and capacitive elements are often used to convert motion information into an electrical signal. **Piezoelectric sensors** rely on so-called “piezoelectric materials” that accumulate charge when a mechanical stress is present. These materials are often quartz crystals or polycrystalline ceramics. Advantages of piezoelectric accelerometers are their high detection frequency, low weight and wide temperature range. **Piezoresistive** or **capacitive accelerometers** are mostly used in high-impact applications. Their output is measured as a change in electrical resistance, instead of a change in accumulated charge. These sensors are typically made from silicon or other semiconducting materials. Compared to the piezoelectric devices, the performance of piezoresistive accelerometers is superior in the *low* vibrational frequency range.

Most modern accelerometers are designed as **micro-electro-mechanical systems** (**MEMS**) as an alternative to piezoelectric or piezoresistive sensors. They are typically simple, inexpensive and reliable. Often, MEMS-based shock sensors consist of cantilever beams and a proof mass. If external accelerations are present, the mass moves away from its equilibrium position. This can either be measured optically, or by changes in capacitance.

MEMS-based accelerometers are very small and can fit inside smartphones and smartwatches. They weigh on the order of 2g and consume little power, with typical currents between 1 and 20µA. These accelerometers can also be very affordable, with prices starting from as low as 1€, and typical costs of roughly 30€, depending on their sensitivity and desired application. With shock sensors, however, a compromise must be made between the sensitivity and maximum acceleration. A 50g- sensor for typical shipping applications can have a sensitivity that is about 10 times higher than that of a 500g-sensor.

To accurately determine both the magnitude and the direction of the motion, 3-dimensional information is required. However, a single sensor measures the acceleration along one axis only. Common accelerometers therefore typically contain three different sensors with different orientations. The measured information can then be stored as the entire waveform, as summarized data, or only as events in which a threshold value was surpassed. Also, the mounting location affects the response of the shock detector. Large or long items, for instance, may benefit from shock loggers at both ends of the shipping container instead of a single sensor.

3.1.1.4 *GPS (Global Positioning System)*

GPS sensors are, by now, very commonly known and used in many consumer applications. They draw information about their position coordinates from a satellite communication system owned by the US government and operated by the US Space Force.

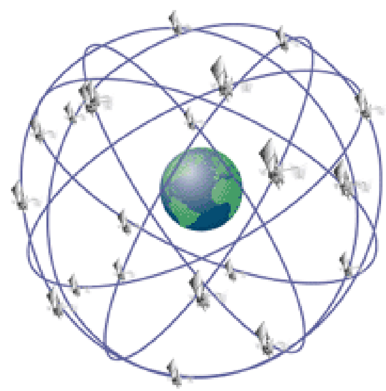


Figure 12: A schematic representation of the GPS satellite constellation.

GPS tracking is based on the GPS satellite system, which continuously broadcasts signals with very exact time stamps. The GPS sensor receives these signals with an integrated or external antenna. It then calculates its position based on the time it takes for these signals to travel from the respective satellite to the receiver. In order to determine its position, the GPS receiver requires four or more satellites to be visible. If only three satellite signals can be received, a smart sensor may estimate its position by assuming, for instance, the last known altitude. Location accuracies are often in the range of approx. 1-5m.

With a current of ca 25 mA, GPS modules during measurement consume about a thousand times more power for a measurement than MEMS-based shock sensors, and roughly 40,000 times more power than the simplest temperature and relative humidity sensors. However, data about the physical containers locations are typically not required every second or every minute. Instead, depending on the application, location updates once per hour or less may be sufficient for cargo monitoring. As a result, the overall power consumption of GPS trackers can still be considered low. Typical GPS modules that update their location 2 to 7 times per day usually exhibit battery lifetimes of about 2-6 years.

GPS sensors are small, with dimensions of ca 1cm x 1cm x 2mm, and are relatively low-cost. Prices for GPS receivers often lie around 30-40€, while some variants may be purchased for under 20€. This makes these sensors well-suited for use in IoT tracking devices.

3.1.2 *Gas detectors and e-noses*

As shown in the previous chapter, not only the temperature and humidity have a large impact on the quality of fruit and vegetables. The ripening of perishable cargo can also be monitored by tracking the levels of respiratory gases like oxygen, carbon dioxide and ethylene. 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. However, the accuracy again depends on the fruit to be monitored. Ethylene levels as low as 20 to 100 ppb can in some cases be sufficient to induce ripening in climacteric fruit. Kiwifruit, for instance, are said to be rather sensitive. In banana ripening, in contrast, ethylene levels are typically brought up to 150ppm for 24 hours in order to induce ripening – a factor more than 1000 higher. Next to accuracy, gas sensors for IoT-use need to be reliable, portable (i.e., small in size) and exhibit a low power consumption in order to be suitable for real-time cargo monitoring in the supply chain. In the following, we describe several common types of gas sensors, with a focus on O_2, CO_2 and ethylene detection.

3.1.2.1 *Summary of relevant gas detectors*

For the purpose of monitoring the quality of fruit and vegetables, it is most important to measure the oxygen content, the carbon dioxide concentration, and ethylene levels. In Table 3 below, we list the most feasible types of sensors for the respective gases. The different sensor types are subsequently described in more detail in the remainder of this section.

For oxygen detection, the most widely used detectors are electrochemical sensors and fluorescence sensors. Both of these technologies are inexpensive, easy to apply and provide sufficiently accurate sensor data for ripeness monitoring in IoT devices. In principle, it is also possible to use NDIR sensors for oxygen detection. However, due to the lower price and complexity, electrochemical and fluorescence sensors appear to be much more commonly used.

For measurements of carbon dioxide levels, in contrast, NDIR sensors are by far the most common type due to their manageable cost and high accuracy.
The second option, metal oxide sensors, is slightly cheaper, but less CO_2-selective than the NDIR method.

Table 3: Most feasible multi-use gas sensor types for oxygen, carbon dioxide and ethylene detection in smart IoT-devices.

Oxygen (O_2) – relevant for all commodities		
	cost	**practicability aspects**
Electrochemical	approx. 80€	• Self-powered • Lifetime 3-5 years
Optical/Fluorescence	50-100€	• Low cost • Good accuracy • Lifetime: several years to tens of years
Carbon dioxide (CO_2) – relevant for all commodities		
	cost	**practicability aspects**
NDIR	30 – 80€	• Low cost • Low power • small size • very good accuracy, -> most common CO_2 sensor • Some cross-selectivity
Metal oxide sensors	6 – 20€	• relatively high-power consumption • cross-selectivity to other gases
Ethylene (C_2H_4) – relevant for climacteric or ethylene-sensitive commodities		
	cost	**practicability aspects**
Electrochemical	7,000 – 8,000€	• High power • acceptable accuracy • some cross-selectivity to other gases
(miniature) gas chromatography - uGC	2,000 – 20,000€	• high power • short battery lifetime • Complex devices • acceptable accuracy
NDIR	>1500€	• Moderate size and power consumption • Detection limit too high, but promising development in lowering detection limit with pre-concentrator. • Otherwise acceptable accuracy
Photoacoustic	25,000 – 30,000€	• Excellent accuracy, • Some sensitivity towards noise/ vibrations • High cost
Chemoresistive	still unknown	• Self-powered • Long lifetime • Low cost • Cross-sensitivity and lack of accuracy
Arrays of metal oxide sensors	approx. 7,000, varies strongly	• Several sensors embedded • high power consumption • in principle high cross-selectivity. Accuracy depends on pattern recognition algorithm. • high computation power required

With ethylene playing a significant role in the ripening process, it is highly desirable to also measure ethylene levels during perishable transport. However, ethylene sensors need to be much more accurate than oxygen and CO_2 sensors, as less than 1 part per million of ethylene gas is sufficient to trigger the ripening process of climacteric fruit (compared to 1%-20% of O_2 or CO_2).

In this low concentration range, also other organic gas compounds are present, so that any potential sensing method requires both a high sensitivity and selectivity to ethylene. As a result, portable, reliable and robust ethylene detectors are still widely lacking. In addition, current ethylene detectors are still exceedingly costly and exhibit a high-power consumption. It can therefore be concluded that no low-cost ethylene sensors are currently available for widespread application within IoT-devices.

However, recent developments show that progress is being made in miniaturizing accurate ethylene gas detectors. A recent (2014) article reviewed five ethylene detection techniques shown in the table above as promising candidates for quality-tracking in fruit and vegetable supply chains. In their paper, chemoresistive ethylene sensors are still deemed too unspecific and inaccurate for ripeness tracking, while the method of photoacoustic spectroscopy exhibits excellent accuracy, but also a high price between 20,000€ and 30,000€.

The remaining methods are NDIR, miniaturized gas chromatography and the electrochemical sensor, as well as sensor arrays/e-noses. They show good overall performances with accuracies in the parts-per-billion range, and are promising candidates for further development of mobile IoT tracking units. With a price ranging from 1,500 to 10,000€, however, the investment cost is high and thereby currently inhibits widespread use in IoT applications of ethylene sensing. Also, the sensors require significant maintenance, and their high-power consumption limits the battery lifetime of mobile devices to approx. 8h. It is therefore expected that reefers will be the first containers equipped with ethylene sensors in the future, as refrigeration units are by default fitted with an external power supply. It remains to be seen whether data from ethylene or other gas sensors in combination with a quality-controlled supply chain could be used to transport perishable cargo also in *non-refrigerated* units without increasing product losses.

3.1.2.2 Gas chromatography

An accurate and one of the most commonly known gas detection techniques is gas chromatography. Most gas chromatographs use flame ionization detectors or thermal conductivity detectors. As a result, they are often large with a high-power consumption. In addition, these systems are typically expensive and require an additional carrier gas. They are therefore not the preferred candidates for mobile IoT application in containers. In recent years, however, gas chromatography systems with an improved size and power consumption have been developed [19]. An example of a commercial gas chromatograph is the multi-gas analyser Photovac Explorer, which is roughly 40cm x 30cm x 15cm large and costs approx. 19,000€. The device has a battery lifetime of approx. 8 hours and makes use of a refillable cylinder for the required carrier gas. Its sensitivity to ethylene is approx. 100 ppb [6]. Other prototypes of miniature gas chromatographs have been developed that do not require a specific carrier gas, with the disadvantage of reacting to changes in ambient air humidity as well. These systems allow for a measurement roughly once per hour. The ethylene detection limit is estimated at 50ppb, and the costs are expected just below 2,000€ [6].

While gas chromatography has undergone large improvements in recent years, their price and complexity remain high, make these systems unfavourable for large scale mobile use in IoT applications.

3.1.2.3 *Electrochemical detectors*

In electrochemical gas detectors, a gas reacts with an electrode inside the detector cell. This electrochemical reaction results in an electric current that depends on the gas concentration. Electrochemical sensors are standard sensors for gases like molecular oxygen, sulfur dioxide or carbon monoxide. However, the detection mechanism requires a chemical reaction with the gas, and can therefore not easily be used to measure the concentration of inert gases like CO_2.

An advantage of electrochemical sensors is that their measured concentration range can be customized by changing several design parameters such as the type of porous membrane between electrodes, type of electrodes, type of ionic liquid etc. Electrochemical oxygen sensors can generate their own analog current and can therefore be self-powered, similarly to the working principle of a fuel cell.
The downside of some electrochemical sensors for IoT-devices is their short lifetime. As the electrodes become oxidized by chemical reactions, such detectors only work for 3-5 years before a replacement is required. However, due to their otherwise robust design and low cost of around 80€ or below (excluding electronics), these sensors are still widely used, predominantly for oxygen detection.

Also the detection of *ethylene* with electrochemical sensors is possible. However, external power supply is needed in this case. In a recent prototype, the ethylene dissolves in a liquid covering a gold electrode. A voltage between two electrodes then causes the oxidization of ethylene with oxygen to CO_2 and water. While some electrochemical ethylene sensors have been shown to exhibit very high accuracy and low cross-selectivity, a common disadvantage of electrochemical ethylene sensors can be cross-selectivity to common gases such as CO, NOx, water vapour, ethanol, SO2, H2S, amines etc. The influence of temperature and relative humidity can sometimes result in a continuous baseline disturbance and range interference, which can prevent low concentrations of ethylene to be accurately detected.

In the following, we give two examples of devices that detect ethylene with the electrochemical method. The first one is the portable MacView® device by EMS shown in Figure 13, which is designed for postharvest and transport applications. It contains a solid state electrochemical ethylene sensor as well as an optical CO_2 and O_2 sensor. The integrated device includes a data logger, data communication by GPRS / UMTS as well as a display. The MacView® ethylene sensor exhibits very low cross sensitivity to other gases. It has a low detection limit of 0.1 ppb in volume, with a standard deviation of 0.09 ppb. [20] The analyser is semi-portable and can be fed by an internal battery or by an external power plug for transport [20].

The second example of an electrochemical ethylene sensor is the Fluid Analytics postharvest gas sensor ETH-1010 shown in Figure 14. It has similar dimensions as the EMS device, has an integrated CO2 sensor and provides the option of adding additional O2 and 1-MCP sensors. The ETH-1010 exhibits low cross-selectivity to other gases and humidity. With an accuracy of ca. 10ppb, the device is less sensitive than the EMS MacView®. A downside of the ETH-1010 and other electrochemical ethylene sensors is that they exhibit rather high costs on the order of ca. 7,000€ [6].

Figure 13: Ethylene gas measurement sensor with O_2 and CO_2 sensors, MACView® post-harvest gas analyser from Environmental Monitoring Systems (EMS). The device is based on an electrochemical ethylene gas sensor with an accuracy down to 0.1 ppb [20]. Picture: courtesy of EMS.

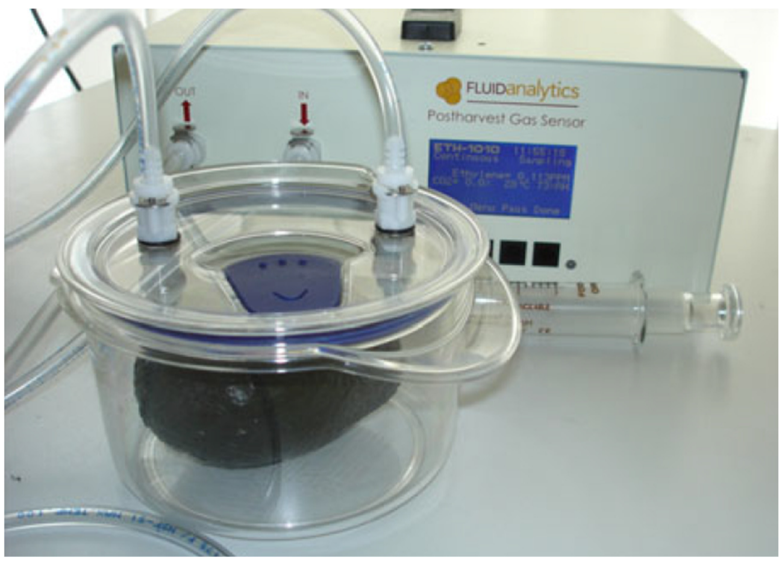


Figure 14: Ethylene gas sensor ETH-1010 by Fluid Analytics. The sensor is based on electrochemical gas detection and exhibits an accuracy of approx. 10ppb. Costs lie at about 7,000€. Picture reproduced from [6].

3.1.2.4 *Nondispersive Infrared (NDIR) sensors*

NDIR sensors are simple optical devices that detect gases by illuminating them with infrared light and measuring their absorption intensity. Each gas absorbs light at a characteristic wavelength, and the intensity of absorbed light depends on the gas concentration. NDIR sensors are most commonly used for measuring CO_2, for instance in heating, ventilation and climate control units, but also in smart IoT-devices. They are very widely available in the price range of 30-80€ and can exhibit sensitivities in the range of 20-50 ppm (parts per million).

Advantages of the NDIR technology for CO_2 detection are the very small size and high accuracy of the detector. Also, their low cost and low power consumption makes these devices well-suited for IoT applications in quality-controlled logistics.

NDIR sensors are in principle gas-specific, as other gas molecules do not absorb light at the same wavelength as CO_2. However, cross-sensitivity of CO_2 NDIR measurements with water, sulfur dioxide or nitrogen dioxide may arise at very low CO_2 concentrations.

Another advantage of NDIR sensors is that this type of sensor only requires an optical path between the light source and the detector. It does not necessarily need to be placed *inside* the gas to detect it, which allows for average measurements of large air volumes. Also, simultaneous measurements of more than one gas at several different wavelengths are possible.

For the measurement of *ethylene* with NDIR sensors, it needs to be noted that ethylene is optically active at a wavelength of approx. 10.6 µm, but available infrared sources for this wavelength either have a relatively low intensity or are rather expensive, making them currently unfeasible for *en-route* ripeness tracking in IoT-devices. Also, the detection limit of commercially available NDIR ethylene sensors lies around 20 ppm, which is roughly a factor 1,000 too high for our intended application. While current systems are not sensitive enough, tests to improve the ethylene sensitivity by use of a pre-concentrator show very promising results for future developments.

3.1.2.5 *Photoacoustic spectroscopy (PAS)*

In photoacoustic spectroscopy, the gas to be measured is irradiated with short light pulses. As a result, the gas molecules are periodically heated. These temperature changes induce pressure changes, which can be measured with a microphone. A PAS sensor thus measures the "sound" emitted by the gas molecules. In analogy to the NDIR technique, every gas has a characteristic wavelength at which it absorbs light. The intensity of the sound which is emitted after radiation with this wavelength depends on the gas concentration

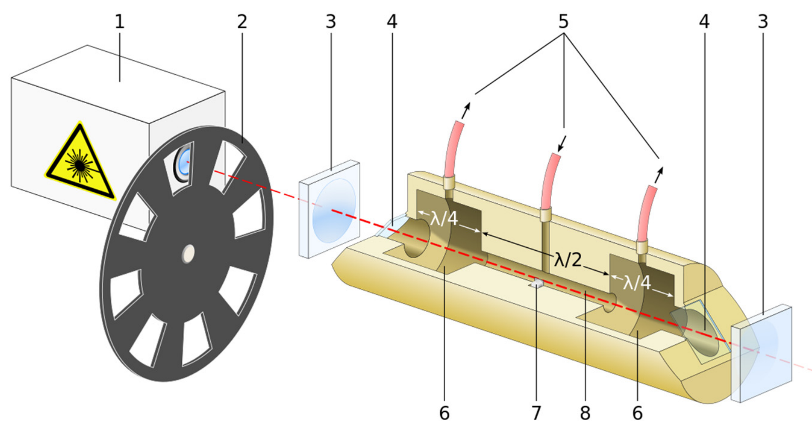


Figure 15: Assembly of a photoacoustic spectroscope for gas analysis with an acoustic cell with 1. laser, 2. chopper wheel, 3. optics, 4. cell windows, 5. gas in- and outlet, 6. buffer gas volume, 7. microphone, 8. resonator. Source: Wikipedia [21].

The PAS-method exhibits an exceptionally high sensitivity. For ethylene, measurable concentrations can be as low as 0.3 ppb, which is certainly sufficient for ripening control and predictions. Also, PAS-sensors with a total size of 50cm×50cm×14cm can be relatively mobile and could in principle be included in containers. However, these devices are sensitive towards vibrations and ambient noise. In addition, they are rather expensive, with prices in the range of 25,000 to 30,000€. This makes them economically unfeasible for the intended IoT-application in quality-controlled logistics.

3.1.2.6 Holographic, fluorescence and color sensors

Holographic sensors are devices based on light reflection at a hologram, which typically consist of a thin polymeric film. In the presence of gas molecules, this holographic film undergoes a change in the color of the reflection by changing its refractive index or the spacing between the holographic fringes. If the hologram gets illuminated with white light or a laser, these changes can be measured with a light detector. The light source and light detector need not necessarily be physically close to the hologram.
Instead, a hologram can be read out from a distance, given that the optical path to the light source and detector is free. Holographic sensors are commonly used to detect hydrocarbon gases and volatile organic compounds with an accuracy of about 1% in the concentration range between 5% up to 100% . However, they have the disadvantage of being rather cross-selective between different hydrocarbon gases, meaning that several different gases will trigger a similar response [15].

A conceptually similar type of sensor are fluorescence sensors. Fluorescent materials emit light of a specific wavelength following exposure to light. These sensors are based on a fluorescent film that changes the intensity of the emitted light with the gas concentration. Fluorescence sensors are widely used for the detection of molecular oxygen by so-called *oxygen fluorescence quenching*. Oxygen fluorescence sensors can be read out contactless from a distance. They typically have a resolution of approx. 0.01 to 0.1% O_2 and their lifetime ranges from several years to an unlimited lifetime, at least if they are not continuously exposed to light. Oxygen fluorescence sensors are often made from transition metal complexes and do not exhibit cross-selectivity with other gases. This is because other gases present in ambient air are not able to lower the fluorescence intensity, and because an additional silicon layer is sometimes used, which acts as a protective shield against all other gases [22].

Both the holographic and the fluorescence sensor have the advantage that they do not irreversibly react with the gas to be detected. As a result, they do not get contaminated and have an extensive lifespan compared to electrochemical (oxygen) sensors. Also, fluorescent and holographic films can be used in small digital scanning devices with integrated optics. In the case of fluorescent oxygen sensing, these integrated sensors are about as small as a thimble and have a price of the order of 50-100€. As holographic sensors seem to be less commonly used than fluorescence sensors, their size and price could not be determined.

A simplified optical detection technology is the color indicator. An ethylene color indicator can show selective color change based on chemical reactions of ethylene gas with ammonium molybdate. Photosensors that detect the color change can be used to determine the ethylene concentration. A great disadvantage is the single use due to the irreversible color change. However, the color indicator can be a good choice for single-use fresh cargo applications [23].

3.1.2.7 *Chemoresistive Sensors*

In chemoresistive sensors, a resistance change due to the presence of gas molecules is measured. Here, we describe the most common types of chemoresistive gas detectors: metal oxide sensors and chemoresistive polymer or nanoparticle sensors.

3.1.2.7.1 *Metal oxide sensors*

Metal oxide semiconductor (MOS) sensors are also known as MOX (metal oxide) or MOSFET (metal oxide semiconducting field-effect transistor) sensors. Their detector material consists of a semiconducting metal oxide, which decreases in resistance when it comes in contact with the gas to be measured. The most common material in these sensors is tin oxide, but also zinc nanorods may be used. Tin oxide typically has a resistance of about 50-200 kΩ in normal air, but its resistance drops to around 1-5 kΩ in the presence of 1% methane.
MOS sensors are typically very inexpensive, with prices between 6€ and 20€ without electronics. Common gases to be measures with this technology are hydrogen, oxygen, ethanol (in breathalyzers), carbon monoxide, sulfur dioxide, hydrogen sulfide, and ammonia. Also, the plant hormone ethylene can, in principle, be measured by such devices containing a sensor made of silicon carbide (which is not a metal oxide, but exhibits similar semiconducting properties).

The downside of some types of metal oxide and silicon carbide sensors is that they can require high temperatures to operate, and therefore may exhibit a relatively high-power consumption. For ethylene detection, the sensor temperature needs to be between 150 and 350 degrees Celsius. Depending on the type of sensor, and whether a “pulsed temperature scheme” is used, power consumption can vary between ~180 µW to more than 100 mW, with typical battery lifetimes on the order of weeks or months. [24] Also, these devices are rather cross-selective to several gases and therefore often not sufficiently accurate. To achieve better selectivity, a number of modified MOS sensors may be used in a so-called *sensor array.* The reaction pattern of these different sensors can then be analyzed with a pattern recognition system to determine the concentrations of different gases and reduce cross-selectivity. However, pattern recognition can be quite computationally involved. For low-power applications, it should therefore not be conducted within the IoT device, but on a larger computer or in the cloud, at least if simplicity of the device and a long battery lifetime are required.

3.1.2.7.2 *Polymer (composite) and nanoparticle sensors*

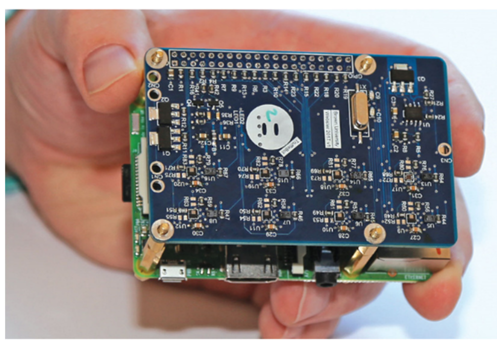
In polymer sensors, the resistance of a conductive polymer film changes depending on the gas concentration. However, conductive polymers exhibit poor processability and high manufacturing costs. As an alternative to conducting polymers, nanofibers like carbon nanotubes or zinc nanorods may be used. Also, polymer nanocomposites, which contain conductive nanoparticles like carbon black, react to adsorbed gas molecules by a drop-in resistance and can be used in gas sensing applications. An advantage of these types of sensor is that they have a very low energy consumption, are rather inexpensive and can be very small in size. As a result, they could easily be incorporated into IoT devices. A disadvantage is that they have a rather short lifetime and need to be frequently recalibrated. A promising type of nanoparticle sensor is built from a copper complex and carbon nanotubes. The design is based on the same principle as ethylene receptors in fruit: the copper complex binds ethylene to start the reaction mechanism of ripening. This sensor does not consume any power and exhibits a long lifetime, but its disadvantages are low reproducibility and cross-sensitivity to other gas like CO [25].

In analogy to metal oxide sensors, detectors based on polymers, polymer composites or nanorods are also not selective to a single gas. Again, a solution to improve gas selectivity is to incorporate several differently doped polymer sensors or nanoparticle sensors into a *sensor array*, which computationally identifies different gas components by comparing the sensing pattern to a growing database of known gas mixtures. An exception is a recently developed sensor based on a mixture of a copper complex and carbon nanotubes, which can selectively bind ethylene gas.

This sensor, however, can only detect ethylene concentrations with an accuracy between 0.5 and 50 ppm, [6] which is a factor 10 – 1,000 to low for our desired application in ripeness monitoring.

3.1.2.8 *Sensor Arrays / E-noses*

E-noses are usually sensor arrays based on a number of slightly different metal oxide or polymer sensors. All embedded sensors are in principle sensitive to all volatile compounds at the same time, but each one to a different extent. The data recorded by e-noses subsequently needs to be treated with statistical models and compared to known data sets in order to make sensible estimations of gas concentrations.



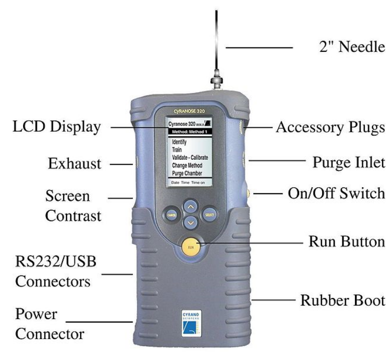


Figure 16: Examples of e-nose systems. Left: Sensor array of an e-nose device [33]. Right: handheld e-nose device Cyranose 320 [31].

At this point in time, most e-nose systems are rather bulky and make use of a large amount of sensors that require high power input. However, recent developments show that more and more hand-held e-nose devices are deployed. In addition, e-noses require significant computing power for the postprocessing and data analysis, as well as the training of the pattern recognition system. To avoid extensive data processing in mobile and low-power devices, the data analysis may be outsourced to a remote computer or the cloud in order to keep the complexity and power consumption of IoT-devices low.

3.1.3 *Optical ripeness scanners*

Next to temperature, relative humidity, shock, GPS and gas sensors in IoT-devices, the product quality of fruit and vegetables can be estimated with optical ripeness scanners using near infrared (NIR) refractometry or NIR spectroscopy. While fruit is often not optically visible due to packaging, stacking and palletizing during storage and transport, this technology can be valuable if applied at specific quality-control points or other milestones in the supply chain, for instance in distribution centers or at arrival in a certain port.

In NIR scanners, the product is directly radiated with near-infrared light in the wavelength range between 780 and 2,500nm. Light reflection and scattering at the skin or within the flesh of the product takes place wherever there are changes of refractive index. Most NIR scanners are *refractometers,* which measure changes of refractive index in the fruit flesh. NIR *spectrometers,* in contrast, are much more elaborate devices that provide an entire reflection- and absorption spectrum. Most optical ripeness scanners for fruit or vegetables are based on NIR refractometry. They are often used in fixed installations or hand-held scanning devices. These refractometers, often called “Brix meters”, measure the amount of Total Soluble Solids (TSS) in the cell juice. As soluble solids consist mainly of sugars, the TSS content is a valid estimation for the sweetness, and therefore ripeness, of the produce. The TSS value is typically measured in degrees Brix (°Bx), where 1°Bx is equivalent to 1% sugar content (in mass) of the cell tissue. Common refractometers have an accuracy of approx. 0.1 °Bx.

The optimal Brix value varies with the type of fruit, but also varieties of the same fruit.

Consumers appear to have a preference for Brix values of:
- 13 for apples
- 12 for avocados
- 16 for banana
- 14 for mango
- 12 for tomatoes
- 20 for kiwis
- 20 for grapes [2].

While sugars are the major soluble solids in fruit juice, it needs to be noted that other soluble solids like acids may in principle influence Brix measurements. However, the concentration of acids is usually considerably smaller than that of sugars and therefore does not significantly affect the optical spectrum. Also, alcohols have a higher refractive index than water. Once fermentation has begun and alcohols are being produced in the fruit tissue, the measured Brix value will therefore be substantially higher than the actual sugar content suggests. While this is a disadvantage for explicit sugar measurements, it can still provide useful knowledge about the quality and ripeness of the produce.

3.1.3.1 Stage of the technology

At this point in time, several industrial sorting and grading lines equipped with NIR-scanners are commercially available from the companies *Aweta*, *Greefa*, Unitec, Mafroda, TOMRA, *Mitsui-Kinzoku*, *Sacmi*, *TasteMark*, *Color Vision Systems, Ocean Insight,* amongst others. These large and complex grading lines, however, are typically installed in large warehouses for post-harvest sorting on an industrial scale.

Figure 17: Picture of an optical grading line by Aweta (aweta.com).

Recent developments in the availability of affordable miniature refractometers have now also opened up promising possibilities for portable, hand-held devices. These devices may be used as scanners in the orchard for a quick pre-harvest analysis, but also for taking samples of fruit ripeness at certain milestones of the supply chain or in the supermarket for quality control by the end consumer. While not yet industrially applied, there have been successful initiatives to embed miniaturized NIR scanners into smartphones [26].

3.1.3.2 *Advantages, disadvantages and challenges*

The main advantage of NIR scanners is that they provide a non-destructive measurement of quality parameters inside the tissue of the fresh produce. If calibrated well, they additionally be used to verify the ‘organic’ classification of the product. Due to the non-destructive character of the measurement, it is possible to scan every single item without quality loss. With recent developments in miniature devices, it is also possible to perform scans pre-harvesting, or *en-route*. The small devices have potential to be embedded into mobile phones for use by the end-consumer.

A major disadvantage of NIR refractometry lies in the fact that a scanner only provides a point measurement, while there may be significant variations of 5-10°Bx across the cross section of a fruit. While automated grading lines can take several data points per item, the limited sampling is an issue in particular for handheld scanners.

Another challenge of NIR refractometers and spectrometers is their calibration. For spectrometers, the measured optical spectra are typically convoluted and not straightforward to interpret. This is due to a mixture of light scattering and absorption processes, and a variety of different chemical compounds present in fruit and vegetable juice. To extract the required maturity information, *chemometrics* software needs to be applied, that is, complex and advanced statistical techniques for model calibration. The pattern-recognition in chemometrics software works in a similar way to the interpretation of data measured by sensor-arrays and e-noses, as discussed in the previous section. It can (and needs to) be optimized depending on the required application.

The optical response also appears to be rather sensitive to interference with ambient light and temperature fluctuations. As a result, influences of the environment should either be minimized during the measurement, or accounted for with suitable data processing and modelling. It turns out to be beneficial to combine optical information with more elaborate data on environmental conditions and the type and race of the measured produce, as well as a history of the origin, harvest time and *en-route* weather. This approach requires large datasets and adds complexity on the modelling side, but may be tackled in the near future with growing technologies such as artificial neural networks or other machine learning techniques. This is the vision of startup OneThird, which applies cloud-based artificial intelligence algorithms in combination with a small-scale or even hand-held NIR scanner.

3.1.3.3 *Applications of hand-held NIR devices*

The **SCiO-device** by consumer physics is a hand-held NIR refractometer combined with a materials database and several chemometrics models in the cloud.
The device connects to a smartphone via Bluetooth, and its scanning and analysis results are communicated via a mobile app. According to the manufacturer, the device has a low power consumption allowing for more than a hundred scans before recharging the battery. It is roughly 7cm x 4cm x 2cm large, weighs 35g, and currently costs around 150€. For a scan, the device can be in contact with the product, or at up to 2cm distance. As mentioned above, NIR scanners do rely on elaborate chemometric models. How accurately the sensor can measure the Brix value or other parameters depends on details of the chemometrics software. The software by SCiO, for instance, has mainly been optimized for measuring the water content of animal feedstock. If applied to a wider set of products, its predictions strongly rely on a simplification of the problem by the user, who needs to identify a category or provide further information about the scanned item. This makes the device most suitable for large farms producing a limited number of commodities.

Figure 18: (left) Example of a NIR-scanner and the corresponding mobile application, predicting the shelf life of a Roma Tomato. Picture courtesy: Marco Snikkers (OneThird). (right) example of a small SCiO -scanner used in the testing of pineapples. Picture reproduced from [27].

Similarly, the Halma plc startup **OneThird** aims to use NIR scanners to measure the quality of fresh produce and reduce food waste. In combination with the scanner, their mobile app provides shelf-life estimations and suggests actions on how to handle the product. The cloud-based artificial intelligence software also analyses trends and includes external parameters such as seasonal changes, sourcing details and logistical data.

3.2 Suitable sensors for IoT-applications

In this chapter, we have discussed several sensor technologies that are relevant for quality-tracking in the supply chain of fruit and vegetables. A summary is shown in Table 4.

Table 4: Overview of the main sensor and scanning technologies discussed in this chapter. The background colour of the fields indicates a rating scale for different sensor requirements. Green represents "good", yellow "moderate" and orange "challenging, but possible".

	Battery lifetime	Accuracy	Size	Cost	Robust-ness	Mass production possible	Conclusion
Temperature sensors	long (>10y)	good	small (pinhead)	<1€	good	yes	well-suited
Relative humidity sensors	long (>10y)	good	small (pinhead)	1 – 2€	good	yes	well-suited
Shock sensors	long (>10y)	good	small (fingernail)	1 – 30€	good	yes	well-suited,
GPS sensors	moderate (2-6 y)	good	small (fingernail)	20 – 40€	good	yes	well-suited
O_2 gas sensors	long (>10y)	good	small (fingernail)	50–100€	good	yes	well-suited
CO_2 gas sensors	long (>10y)	good	small (fingernail)	6 – 80€	good	yes	well-suited
Ethylene gas sensors	Short (≤8h), or external power required	Very high to low (depends on type)	Large, but feasible (~shoebox)	1,500 – 30,000€. (≥7000 for sufficient accuracy)	Very high to low (depends on type)	not on large scale	costly -> often not feasible yet
Optical ripeness scanners	moderate (~hundreds of measure-ments)	depends on type and software	moderate (hand-held)	~150€ (hand-held device)	good	yes	Best suited for quality-checks at milestones, not cargo monitoring

We conclude that temperature plays a very important role in quality decay, and that temperature sensors and reefer containers are already very widely used.
Next to temperature, also relative humidity, shock and GPS sensors are very suitable to be used in small IoT devices placed in containers with perishable cargo. In fact, they are already commonly applied for this purpose. Also, the integration of gas sensors for oxygen or carbon dioxide during transport is feasible. While at this point in time, gas atmosphere monitoring is mainly applied in controlled atmosphere reefer containers, oxygen and carbon dioxide can in principle be measured in any type of (dry) container if the sensors are properly placed.

For the plant hormone ethylene, however, it seems that no gas sensor is currently on the market that fulfils the requirements for mass application mentioned above. Common ethylene sensors are still too costly for standard integration into IoT

devices, with prices starting from 1,500€ and heading up to 30,000€. Some types of ethylene sensor exhibit very good accuracy, while others are still too inaccurate to correctly monitor and predict the ripening process. With their high-power consumption, ethylene sensors cannot easily run on battery. In the future, they may therefore be applied in reefer containers first, as these have access to external power supply.
While ethylene is known to be a very important quality parameter for climacteric fruit, it is not yet clear how strongly the current challenge to develop low-cost ethylene sensors will impact the overall performance of a digitalized and quality-controlled supply chain. The necessity and usefulness of an ethylene detector largely depends on the exact use case and is influenced by the transported commodity, other types of sensors applied in the supply chain, the type and accuracy of the employed quality-decay model and the corresponding business case.

Optical ripeness scanners or Brix meters that make use of NIR technology turn out to be feasible for application in quality-controlled supply chains of fruit and vegetables. However, these scanners can only probe the sugar content at one single point on a single product, and need to have a distance to the product of less than two centimeters. The method in its current form is therefore not particularly suited to predict the average shelf-life of a whole product batch during transport in a container. However, NIR scanners have great potential in determining the ripeness in the orchard to enable selective harvesting, or in sorting the products according to their color or sugar content in industrial grading and packaging lines. The latter can be applied to freshly harvested produce, or at certain milestones in the supply chain like distribution centers. In this way, NIR scanners can be complementary to other common IoT sensors: the grading and sorting by ripeness leads to the transport of more homogeneous batches, whose quality can subsequently be monitored with temperature, humidity and gas sensors. As handheld scanners and grading lines require a significant investment, however, they will only be widely applied when food loss can be mitigated on a large scale, or when consumers are ready to pay premium prices for, e.g., extra sweet and juicy fruit.

In this chapter we have discussed the feasibility of the most relevant sensing and scanning technologies for the quality control of perishables in a digitalized supply chain. How the costs of sensors for quality-monitoring compares to *potential benefits* of sensor data availability and the resulting logistics adaptations, however, is still largely unknown and needs to be discussed in a separate business case analysis, as mentioned above. In the next chapter, we address the additional technological challenge of recording, storing and communicating potentially large amounts of sensor data.

4 Logging, wireless communication and IoT-devices

Here, we discuss the technological requirements and challenges associated with storing and communicating large amounts of sensor data. At the end of this chapter, we give a non-exhaustive list of examples for existing IoT-devices on the market.

4.1 Data logging

For quality-tracking in the perishable supply chain, not only the availability of sensors is crucial. Sensor data must also automatically be measured in certain time intervals and stored without human interaction. For this purpose, data loggers are required. Data loggers are electronic devices that automatically record and store data over time. In most cases, loggers contain a standard set of embedded sensors in one single device. However, these devices can include additional channels for the input of external sensor signals, like in the case of the Pharox Bell Rock or the TRAXENS devices, which we explain in more detail at the end of this chapter.

There are several types of data loggers, for instance: [28] [29] [30]

1. **standalone loggers**, to be activated once and read out manually after the measurement cycle;
2. **PC-based loggers** that require a connection to a computer;
3. **web-based loggers**, requiring an internet connection;
4. **wireless (web-based)** loggers, using wireless technology for data communication.

As a logger needs to collect data independently and is typically left unattended to measure, it needs to be self-sufficient regarding data collection and power. Loggers therefore typically contain the following elements: [28] [29]

- digital microprocessor (typically 16 or 32 bit);
- low-power storage medium;
- clock;
- internal or external sensor(s);
- battery;
- communication device.

The microprocessor is programmed to control all processes within the logger.
For data storage, a non-volatile storage medium is required, meaning that the data is kept without power supply. Common storage media used in this context are low-power Flash or FeRAM (ferroelectric random access memory) drives.
A real-time clock is used for date- and time-stamping the data collected by internal or external sensor(s). The battery acts as an independent power source, and the communication device is needed to share (and possibly analyze) the collected data. Wired or wireless data readout via the communication device can take place either continuously, or at the end of the measuring cycle.

Data loggers have already extensively been used in *cold chains* of food or medicine in combination with temperature sensors, to monitor whether or not the cold chain was broken during transport.

For some products such as pharma products, regulations and contracts even make temperature monitoring mandatory. Simple single channel data loggers with integrated temperature sensors are therefore very affordable. They cost as little as 10 or 15€ for single-trip throwaway items, and 20-25€ for multi-use items. However, the price of data loggers depends strongly on their application and requirements. More sophisticated loggers that allow for cross-channel computations and alarms based on predetermined conditions may costs hundreds or thousands of euros, and are therefore not dispatched as single-use items. Also, precise and selective gas sensors can be very large, expensive and complex, which greatly increases the complexity of the required corresponding data logger.

In general, for the application of independent data collection, loggers need to be reliable and power-efficient, *i.e.*, have a long battery life. Manufacturers go to great length (and cost) to ensure these requirements are met. Other influences on the price and complexity of data loggers are:

- reusability;
- number of measurements stored;
- response time;
- shock and vibration resistance;
- water resistance (humidity, condensation, …);
- size, weight, and mounting options;
- ease of use;
- certifications, calibrations, …
- software;
- data accessibility and integration with other systems.

While the original model of data loggers was based on wired connections, by now many loggers have access to wireless communication and serve web pages or applications. Use cases then include automatic data reporting, remote control access and alarms for certain events. Due to the growing industrial IoT-market, the development of newer-generation data logging equipment is accelerating. Also, the standardization level of protocols and data formats is growing in the industry, and file formats like XML, JSON, and YAML are increasingly being adopted for data exchange. However, the data standardization level in IoT-applications is still relatively low, and one of the most critical hurdles for the technology in the near future. [31] With billions of connected things, common data storage standards are required to operate with an acceptable, manageable and scalable level of complexity.

Another challenge is that the measured sensor data needs to be communicated all over the world. For the IoT application of data-driven logistics in the transport of perishable cargo, we are therefore facing a large interest in wireless communication technologies. These are required for offering real-time connectivity from trucks or ships throughout the entire supply chain. The most relevant communication technologies and standards used in container tracking are summarized in the following section.

4.2 Communication technologies for cargo monitoring

For the purpose of monitoring the ripening state of perishable container cargo, existing container tracking technologies can be used. Most of these technologies make use of wireless satellite or radio communication. They can be divided into six technology subgroups exhibiting different bandwidth- and range characteristics. These subgroups are visualized in Figure 1 in different colors [5]:

1. *green* Wireless Local Area Networks (WLAN), such as Wi-Fi (the 802.11 range)
2. *blue* Short range wireless technologies, such as Bluetooth and Zigbee
3. *purple* Radio-Frequency Identification (RFID) and Near Field Communication (NFC)
4. *yellow* Cellular communication networks, such as 2G, 3G, 4G-LTE and 5G
5. *red* Low Power Wide Area Networks (LPWAN), such as LoRa and Sigfox
6. *grey* Satellite communication, such as VSAT.

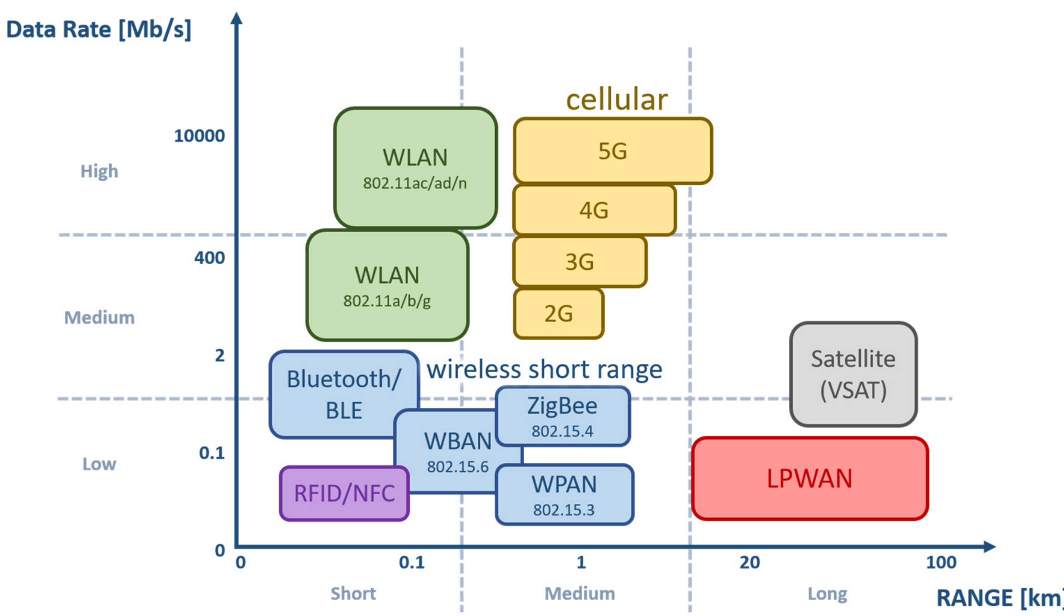


Figure 19: Overview of wireless communication technologies. Picture re-designed from [3]

Typically, a high data rate corresponds to the fast communication of large amounts of data, but also to high energy consumption. This increases the operational costs of high-data-rate applications. For the purpose of monitoring (perishable) cargo, however, the amount of relevant sensor data may be rather small, depending on the exact application: In some cases it is not required to monitor the cargo status in real time, and a limited amount of measurements per hour would suffice. As a result, large data rates are not essential for cargo monitoring purposes. This can strongly reduce the cost of the relevant communication technologies.

In this section, we briefly outline the main advantages and disadvantages of the six subgroups of technologies in the context of perishable cargo monitoring, and finish with concluding remarks. Our information is mainly based on the TNO report "Inventory of technologies for monitoring, tracking and identification of maritime containers and their cargo" (TNO 2019 R11022v2), with additions from an interview with Joris Tenhagen (founder of Pharox).

4.2.1 *Wireless Local Area Network (WLAN, Wi-Fi)*

A Wireless Local Area Network, typically called Wi-Fi, is used to link two or more devices. This connection is usually local, i.e., within a limited area (home, school, office building). Through a gateway, a WLAN can provide a connection to the internet. Wi-Fi offers high bandwidths (>100Mb/s) and a reach up to a few hundred meters. The configuration of hard-and software is typically simple, and large numbers of devices are supported.

For the application of perishable cargo monitoring, containers may be equipped with Wi-Fi-devices, having the vessel act as a gateway to the internet. A disadvantage of Wi-Fi is its high energy consumption, increasing the cost of use and maintenance.

Cargo monitoring: optimizing this technology for cargo monitoring is possible, however, specific and complex configuration is needed.

4.2.2 *Short range wireless communication*

Short range wireless communication includes technologies such as Bluetooth, Bluetooth Low Energy (BLE), Zigbee, infrared communication, Wireless Body Area Networks (WBAN) and Wireless Person Area Networks (WPAN). These technologies communicate over short distances on the order of 10 meters.

Cargo monitoring: For the purpose of (perishable) cargo monitoring, short-range networks (for instance on a container ship) need to be combined with long-range communication technologies (e.g. from the ship to the internet).

Bluetooth/BLE operates with ultra-high-frequency radio waves, has a low data rate and a reach of up to 10 meters. Due to limitations in the number of devices (up to eight), it seems practically unfeasible as a technology for large-scale short-range container networks.

ZigBee is a low-power and low-data technology, with a long battery life and a reach of 10-100 meters. ZigBee uses high-level secure communication protocols and can connect many devices, which makes it a suitable candidate for large-scale cargo monitoring.

Infrared (IR) communication is a technology used most commonly in remote controls with a low data rate. IR light does not penetrate walls and requires line-of-sight communication. While reducing signal interference, this makes IR communication rather impractical for cargo monitoring.

WBAN/WPAN technologies are used for devices close to the human body. For the purpose of quality-sensing and cargo monitoring, they are therefore not relevant. WBAN/WPAN often use short range communication technologies such as Wi-Fi, Bluetooth or IR communication.

4.2.3 *Radio-Frequency Identification (RFID) and Near Field Communication (NFC)*

The **RFID technology** uses so-called “tags” attached to cargo, which store electronical information. These tags can be active or passive.
Active tags contain a local power source (e.g. battery) and require a low signal strength. They have a range of around 100 meters, but are rather expensive ($15-$100). There are two types of active tags: transponders and beacons. A beacon broadcasts constantly, reducing its battery life, while transponders only communicate in the immediate vicinity of a reader.

Passive tags, in contrast, have a very low price, starting from 5-20 cents per tag. They are powered exclusively by the electromagnetic energy transmitted by the RFID reader. While cheap, a passive RFID tag has a very short range of a few centimeters to a few meters.

<u>Cargo monitoring:</u> Active RFID is a feasible technology for short-range read-out of sensor data and could be used for IoT-enabled cargo monitoring if combined with a long-range communication technology. Passive RFID appears less feasible for the use-case of continuous perishable monitoring, as it requires a very short distance for read-out. However, it could be used to obtain sensor data in distribution centers or at other milestones in the supply chain.

Near Field communication (NFC) is a technology for connecting two devices at a distance of less than 4cm of each other.
<u>Cargo monitoring:</u> With its very short range and limited connectivity, NFC is not a favorable option for the monitoring of perishable cargo.

4.2.4 *Cellular communication networks*

Cellular communication networks (2-5G) are typically characterized by a high data rate and a corresponding high energy use, which often results in high operating costs and makes them unattractive for widespread cargo monitoring. In optimized cellular solutions like Narrowband-IoT or LTE-M, the data rate and power consumption are lowered. This makes them attractive to the IoT sector and to the use-case of cargo-monitoring. In addition, it gives them some overlap with our fifth category: LPWAN (Low Power Wide Area Networks).

Narrowband-Internet of Things (NB-IoT) is a 4G-LTE cellular technology with a reduced communication bandwidth (200kHz), which is designed specifically for low cost, long battery life (10 years) and a high connection density. The network is licensed by a network operator. For (perishable) cargo monitoring, NB-IoT devices, including a battery and sensors, can be attached to single containers. An advantage of NB-IoT is that all signals are guaranteed to get delivered, at least within the connection range of 1-10km.

The alternative 4G-based IoT solution **LTE-M** (Long Term Evolution for Machines) provides a higher data rate than NB-IoT. It is fast and offers data exchange in real time, while NB-IoT is near real-time. Disadvantages of the higher bandwidth are increased costs and reduced battery life.

<u>Cargo monitoring:</u> Both technologies are in principle suited for long-range communication of sensor data for cargo-monitoring. However, an issue arising for all cellular IoT solutions appears to be the lack of practical agreements between

cellular communication providers regarding the handling, rules and costs of data roaming. Despite the rapid development of cellular technologies in the field of IoT, it is not yet clear when practical IoT roaming agreements with be in place.
Until then, tracking is either limited to a single country, or the manufacturer needs to include multiple sim-cards and employ complex software solutions.

In cellular communication, two recent and promising developments are the eSIM (embedded SIM) and iSIM (integrated SIM) technologies. Integrated SIMs and the required temperature-, humidity or GPS sensors are typically printed on product packaging or labels, and are specifically designed for low-power IoT solutions.
The SIMs automatically connect to mobile networks. As they are embedded in the product packaging and do not form a separate chip, they cannot be removed without losing their functionality, providing additional anti-tamper and anti-theft protection. [32] For the purpose of monitoring perishable cargo, however, it remains to be seen whether single-item or single-package tagging can have a favorable business case.

4.2.5 Low Power Wide Area Networks (LPWAN)

Low Power Wide Area Networks allow for sending small amounts of data with limited battery capacity. On land, these networks use radio masts, while at open sea or in peripheral regions more expensive satellite communication is needed. LPWAN technologies are inexpensive, with costs of a radio chipset around 2€, and operating costs of roughly 1€/year. The LPWAN domain is rapidly developing, with a number of competing standards and vendors. For simplicity, we focus on the two market leaders LoRa and Sigfox, as well as the cellular standard Narrowband-IoT.

The LPWAN technology **LoRa** is a proprietary long-range IoT technology and has a range of 1.5-15km per radio tower. It operates on an unlicensed frequency band with a fair use policy. The advantage is that no deals with network providers are required, but the network does not provide any guarantee of signal delivery.
In addition, the fair-use policy restricts the transfer of data to ten times per hour, making this technology only suitable for *near real-time* monitoring. Another issue with LoRa may be that noise and interference can be caused by other parties using the open network. The latter is expected to be a problem in port regions, but not on the open sea. To apply LoRa for maritime cargo monitoring, the ship needs its own radio masts and server, and each container is equipped with a LoRa-sensor. While LoRa technology is well-tested and applied in practice, it does employ three different protocols and frequencies in Europe, the US and Asia, which slightly adds to the complexity of the required devices and software.

The French LPWAN operator **Sigfox** works in a similar manner as LoRa. It uses a narrower bandwidth, making it less susceptible to interference. While the costs for the single sensors are lower than those of LoRa, the network provides a smaller range and data rate and has limited availability. Also, network authentication and encryption are not supported. Sigfox uses two different frequencies: for Europe and the US, respectively.

A LPWAN technology using *cellular* networks is the already mentioned **Narrowband-IoT**.
While SigFox and LoRa are advantageous in battery life, capacity and cost, NB-IoT turns out to have a shorter latency and provide better data quality [33]. NB-IoT is not suitable for suburban or rural areas that do not benefit from 4G-LTE connectivity. For a comparison of LoRa, Sigfox and NB-IoT, see Figure 20 and Table 5.

Figure 20: Performance of Sigfox, LoRa, and NB-IoT in terms of IoT factors.

QoS: Quality of Service. [23]

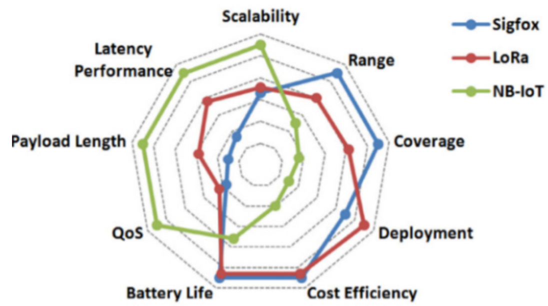


Table 5: Different costs of Sigfox, LoRa, and NB-IoT. [33]

	Spectrum cost	Deployment cost	End-device cost
Sigfox	Free	>4000€/base station	<2€
LoRa	Free	>100€/gateway >1000€/base station	3–5€
NB-IoT	>500 M€ /MHz	>15 000€/base station	>20€

4.2.6 *Satellite communication*

Satellite communication makes use of a broad frequency range to transmit and receive signals (1-50GHz). Very small aperture terminals (VSATs) are used to transmit both narrowband and broadband data, with data rates ranging from 0.5kb/s to 2Mb/s. They consist of a two-way satellite ground station with a dish antenna (1 meter). Maritime VSATs can be operated on sea.
Satellite communication typically has high costs of operation due to the high-power consumption. It therefore does not seem preferable as a mass container monitoring application, but might be necessary in cases where other technologies are unavailable.

4.2.7 *Network integration technologies*

The technologies described in this section may be combined to achieve the desired performance. Examples are Wireless Mesh Networks or Wi-Fi Radio Frequency Identification.

A **Wireless Mesh Network (WMN)** consists of interconnected radio nodes in a mesh-topology. These nodes work together to create a network, thereby offering a wide coverage area (the so-called mesh cloud). It also provides redundancy: if one node fails, the rest of the network remains interconnected. WMNs are not restricted to specific technologies or protocols and work well with the aforementioned short range wireless communication technologies or cellular technologies.

Wi-Fi Radio Frequency Identification combines active RFID tags in a network with a special communication protocol. It is often used to effectively track location-based information. While the traditional RFID system provides a location only in relation to the RFID reader, a WLAN-based network provides much more precise location coordinates by triangulation, similarly to GPS. For our purpose of monitoring sensor data, in which high location accuracy might not always be required, WLAN may still be used for data backhaul of the RFID-network.

4.3 Conclusions on communication technologies

In conclusion, we find that it is indeed technically possible to communicate real-time sensor data in any digitalized supply chain from any location on the globe using satellite technology. Depending on the precise commodity and application, however, satellite communication can be relatively expensive and may not always have a valid business case. To reduce communication costs, other wireless technologies based on Bluetooth, Zigbee, RFID, LPWAN or cellular technologies have been developed. At this point in time, these technologies mainly provide data coverage at land, while satellite communication remains the only reliable option at open sea. Our main considerations from the inventory of existing communication technologies are summarized in Table 6 and explained below.

Table 6: Overview of wireless communication technologies and their estimated feasibility for IoT-enabled cargo monitoring, based on a comparison of advantages and disadvantages.

		Rating	(Dis-) advantages	Comment
Short range	**WLAN/Wi-Fi**	+	high energy consumption, complex configuration needed	Needs to be combined with long-range comm. tech.
	Bluetooth/BLE	-	limitations the number of devices	Needs to be combined with long-range comm. tech.
	Zigbee	+	low cost, scalability issue for many devices	Needs to be combined with long-range comm. tech.
	Passive RFID	-	cheap, very short range	Mainly useful at milestones
	Active RFID	o	medium cost	Needs to be combined with long-range comm. Tech.
Long range	**Cellular (NB-IoT, LTE-M)**	++	medium to low cost, lack of standardization/ agreements (e.g. roaming), not reliable at open sea	Promising low-cost technology
	LPWAN (LoRa, SigFox)	++	low cost, not reliable at open sea LoRa: proprietary	Promising low-cost technology
	Satellite	+	high cost, not always economically feasible	Only reliable option at open sea

Passive RFID tags are cheap and may be easily used to read (accumulated) sensor data on crate- or pallet-level in warehouses. Due to its short range, however, RFID does not seem suitable for cargo monitoring in containers. Active RFID is often too costly to be applied on large-scale.
A very cost-effective communication solution is the short-range technology Zigbee, however, it faces scalability problems with many devices in a small range. While cellular technologies are typically rather expensive, optimized solutions such as Narrowband-IoT and LTE-M are developing fast and are very promising candidates for the monitoring of perishable cargo. The lack of practical data-roaming agreements in the field of cellular networks is still a practical issue, but is expected to be resolved by telecommunication providers in the near future. Also, LPWAN technologies are becoming very inexpensive and might cause a breakthrough in low-cost tracking and monitoring solutions, as recent developments in technological standards like LoRa and Sigfox show.

Both for cellular IoT and LPWAN solutions, connectivity at open sea is a challenge due to their limited range (<10km for NB-IoT, 22km for LoRa). Research shows that "it can be assumed that [the] maximum achievable distance is significantly longer" than 22km. [34] This might aid the use of mesh-technologies in the future, in which ships communicate with each other and serve as nodes for the network. However, until this day, the only technology that allows for independent cross-ocean cargo monitoring is satellite communication such as VSAT.

4.4 Examples of smart IoT devices on a pallet or container level

For the purpose of (near) real-time cargo monitoring, it is important that IoT devices be reliable, well-connected and energy-efficient, while their volume or weight typically does not play a dominant role. One class of IoT devices are single-use throwaway items. These are very inexpensive, but exhibit a low battery lifetime and therefore need to be disposed of after a single trip. Disposable devices are usually basic temperature- or humidity loggers. More elaborate IoT devices are also more expensive and may be temporarily attached to a container or pallet, or mounted to the container permanently.

In this section, we describe a few prominent examples of multi-use commercial smart container devices and the communication technologies they employ. Often, the devices are not acquired by the customer on a per-piece basis, but rented out on a contractual basis in combination with the services of data connectivity, an online dashboard and customer support. Depending on the contract period, volume and services, prices for a single device can range from 50-60€ per month to 1,400€ per trip.

4.4.1 Traxens (traxens.com)

An example for a commercial smart container device is the one by Traxens, which is permanently attached to the container, avoiding the problem of reverse logistics that may arise for temporary attachment. The Traxens device uses Tri-band cellular technology (433MHz, 868MHz, 920MHz) and can adapt to its location in order to meet the local telecom regulations. A mesh network, which was specifically designed to function in metallic and humid environments and also reaches also levels of large container vessels, offers connectivity throughout the vessel and inside container terminals. The smart device can monitor GPS position, temperature fluctuations, shocks and container door openings. It is also equipped with a GPS sensor, which is only activated if the mesh network is dysfunctional. In addition to the embedded sensors mentioned above, up to sixteen remote sensors can be integrated with the device (parent-box) using Near Field Communication (NFC). In May 2019, the large shipping groups CMA-CGM, MSC and Maersk each ordered 50,000 trackers from Traxens, and all obtained an equal share in the company.

4.4.2 Globe Tracker (globetracker.com)

The Danish firm Globe Tracker offers cellular, Bluetooth and LoRa-based container tracking solutions to ports and container carriers. Their sensors provide data on location, temperature, humidity, shock, motion, tamper, and light. Additional sensor nodes that are connected with the main node of the container can be placed anywhere inside the container. Hapag-Lloyd plans to outfit its entire fleet of 100,000 reefer containers with Globe Tracker IoT devices. Also, the companies Samskip and Dole decided in 2019 to equip their container fleets with the Globe Tracker technology.

4.4.3 *Maersk & Hamburg Süd Remote Container Management (hamburgsud-line.com, maersk.com)*

The German transport company Hamburg Süd, recently acquired by Maersk, offers Remote Container Management (RCM) to monitor temperature, O_2, CO_2, relative humidity and power-off events.

The IoT-device is built into the container control panel and communicates via 3G cellular networks on land and via satellite communication on sea. The measured data is visualized with a user interface called ‘Captain Peter’, and the costs amount to 10$ per container [35].

By 2020, the entire Maersk and Hamburg Süd fleet of 380,000 reefer containers has been equipped with the technology, and customers like Dole, Safir Fruits and Jana Fresh use this service. The RCM solution is currently only available for *reefers*, presumably because of their standard power supply, eliminating the need for low-power IoT devices. [36]

4.4.4 *Purfresh (purfresh.com)*

The smart container devices by Purfresh are not permanently attached to the container, but are built in and -out after each trip, leaving the reverse logistics to the company. Purfresh devices mainly use satellite communication, as well as a mesh technology for containers on the same vessel, so that also containers below deck remain connected. Measured and tracked parameters include the temperature, relative humidity, CO_2, O_2, ozone (O_3), GPS and door breach. In addition, ozone can be produced in real-time and added to the inside of the container for desterilization and the removal of ethylene. The Purfresh panel requires energy input (for instance for generating ozone), making it – similarly to the solution by Hamburg Süd - only suitable to reefer containers.

4.4.5 *ThermoKing (europe.thermoking.com)*

Thermoking offers smart IoT devices and data loggers for truck, rail and maritime fleet management that can track, amongst others, the location, temperature, relative humidity, fuel level and door status of refrigerated containers. In addition, it allows for adjustments to the reefer atmosphere, and its interface offers alarm notifications via SMA or email.

4.4.6 *Orbcomm (orbcomm.com)*

With its AG40, the company Orbcomm offers a smart device and data logger for trucks and maritime applications that tracks temperature and door openings independently from the container refrigeration unit. It can additionally act as a gateway for eight external sensors, which may both be wireless or wired.

4.4.7 *Pharox (pharox.io)*

Another example for a smart container device is the “Diamond Lady” device by Pharox, which can be either temporarily or permanently attached to containers and monitors the container’s geolocation with GPS, as well as temperature, relative humidity, motion and light. The Diamond Lady uses LPWAN for data communication, as well as Wi-fi/WLAN (802.11; 2,4 GHz) for localization support.

Bluetooth Low Energy (BLE) is used for beaconing (performing actions with nearby electronic devices) as well as device management and readout.
The newly developed Pharox device “Bell Rock”, which will be released in the course of 2020, additionally offers the option to connect several external sensors. In addition to Wi-Fi and BLE, the Bell Rock uses cellular NB-IoT/LTE-M or 2G networks for data communication. Its rechargeable battery is expected to last up to 10 years.

4.5 Examples of smart labels on a single-item level

At this point in time, smart single-item labels can be used to crudely monitor an item’s location, movement, the humidity or temperature. Accurate ripeness and quality decay monitoring of perishable cargo, however, is expected to require more elaborate gas sensors and does not yet seem to be economically and practically feasible on a single-item level. Nonetheless, we here give two examples of recent developments in single-item IoT labels that future technology may build upon.

4.5.1 Bayer & vodafone iSIM technology (vodafone.com)

Bayer, a large health care and agriculture business, has created smart product labels with a low-power iSIM technology in collaboration with Vodafone Business, Arm, Altair Semiconductor and Murata. Their label is specifically designed for IoT-purposes, which decreases cost and power requirement and increases the device security. The smart label contains a battery, microprocessor, iSIM, modem and antenna. It automatically connects to cellular networks and works for up to three years. Data can be sent regularly, or after certain triggers like cutting the package or the package being in motion, as shown in Figure 21 below. According to Vodafone, the communication module cannot be removed without affecting its functionality, which increases anti-tamper protection. [32]

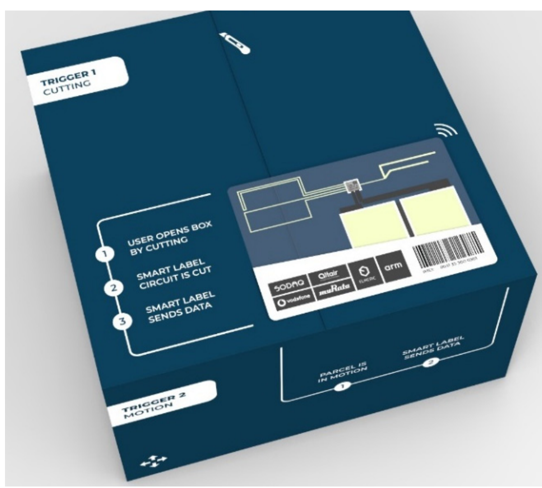


Figure 21: Representation of a smart label developed by Bayer, Vodafone Business, Arm, Altair Semiconductor and Murata. Source: Vodafone 2020 [20].

4.5.2 ThinFilm and Xerox printed sensor labels (xerox.com, thinfilmsystems.com)

Together with the Norwegian printed electronics company Thin Film Electronics, Xerox is planning on mass-producing printed smart labels for food packaging. The thin printed sensors can give information about location, temperature, movement or humidity. In contrast to larger IoT-devices mentioned in the last section that may use big data techniques for quality-decay predictions, smart labels at a single-item level are limited by their internal memory and can only store a small amount of data, which may be visually read out or communicated, for instance, with RFID of NFC technology. The labels currently cost a few cents per piece, with prices expected to decrease in the near future. [37] They are not deemed feasible for quality monitoring during transport. Instead, these labels can be used to check for failures like mechanical or temperature shocks, which may render the item unsafe to eat. [38]

5 Quality-decay modelling and decision-making

In the last two chapters, we discussed different types of sensors as well as data logging and communication technologies. While high-quality sensor data and real-time communication are essential for quality monitoring, the sole accumulation of large amounts of sensor data is not sufficient for setting up a quality-controlled supply chain. Instead, sensors and sensor data need to be translated into quality classifications and used to predict the remaining shelf-life of the product.

The questions that we intend to answer in this chapter are:

1) If sensor data on temperature, relative humidity and gas composition are known, how can the shelf-life of the transported commodity be predicted?
2) If the shelf-life is known, how can suitable logistical decisions be taken?

We therefore discuss current quality decay models as well as common methods of data-driven decision making. The content of this chapter is based on the book “Postharvest Physiology and Pathology of Vegetables” edited by Jerry A. Bartz, Jeffrey K. Brecht [39], and on the recently submitted article “Integration of IoT with quality-controlled logistics: A conceptual framework to analyze the quality-sensor based fruit and vegetable supply chains” by Xuezhen Guo, Joost Snels and Seth A. Tromp from Wageningen University of Research [4].

5.1 Perishable classification and quality decay models

Classifying the quality or shelf-life of perishable products is a rather challenging task. The reason is that the current level of quality standardization is low, meaning that different parties often have different views on acceptable or required standards. As a result, the choice of quality estimation parameters often seems arbitrary, and miscommunications about the product quality may arise between different parties in the supply chain. Also, for the development of mathematical or computational quality decay models, the lack of standardization is a challenge. Concepts that are often used in quality decay models to estimate the product quality are 1. the remaining shelf-life and 2. the probability of marketability, *i.e.*, the estimated probability of the product to be sold to a customer with profit.

5.1.1 The temperature quotient of respiration: Q_{10}

One of the simplest shelf-life estimations is based on the value of Q_{10}, the so-called temperature quotient of respiration. It characterizes the changes in reaction- and respiration rates inside the product as a result of a temperature change, and is defined as

$$Q_{10} = \frac{\text{Rate of reaction at temperature T} + 10°\text{C}}{\text{Rate of reaction at temperature T}}.$$

The Q_{10} value is a good measure to predict the increase of the respiration rate with the temperature, and can serve to predict the loss of quality and the remaining shelf-life of the product. For many commodities, it lies between 2.0 and 2.5, at least in the temperature range from 5°C to 25°C. This means that the respiration rate increases by a factor of 2 or 2.5 if the temperature is increased by ten degrees Celsius.

Within a normal temperature range, the remaining shelf life is assumed to be inversely proportional to the respiratory activity. However, the Q_{10} value cannot be applied in late ripening stages, as the composition of the fruit flesh then changes drastically. Also, it is not suitable to describe the shelf-life of chill-sensitive products at low temperatures, and for products subject to fluctuating temperatures.
As a result, a shelf-life prediction based on this quotient is a rather crude estimation and doesn't take into account many significant influences on quality decay.

5.1.2 *The time-temperature model*

Also time-temperature models are based on product respiration, but take into account that the storage temperature may vary with time. One of these models considers the cumulative time-temperature (the area under the temperature-time-curve) an important quality-decay parameter. The higher the time-temperature, the lower the resulting shelf life. This model takes into account that a temporarily high temperature can have a negligible effect if the time span is sufficiently short, while its effect on the shelf life may be large in case of an extended time-period. Similar models taking into account the time-temperature relationship are based on chemical reaction kinetics with the so-called Arrhenius law. The resulting quality-decay curves often have the shape of a logistic curve, which is shown in Figure 22 below. The most commonly and widely applied model is one based on a simple logistic curve with the two independent variables time and temperature. However, this logistic model does not take into account any other variables like the ambient gas composition or relative humidity. It also is unable to capture the effects of product variety within a single batch. Despite this, the time-temperature model is able to provide a simple description of quality decay and good estimates for the remaining shelf-life of fresh produce. [40]

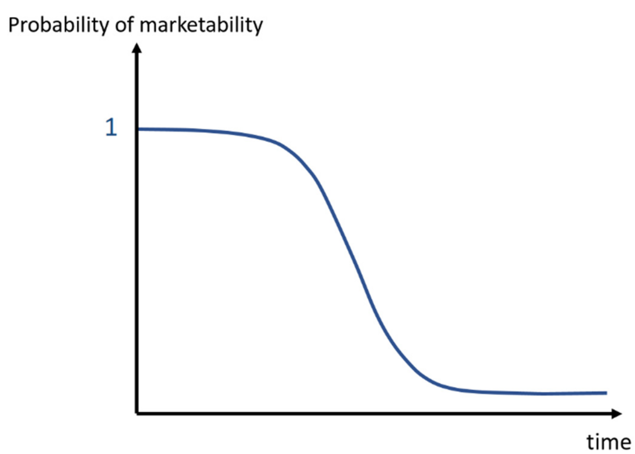


Figure 22: Schematic representation of the form a logistic curve for quality decay modelling.

5.1.3 *The logistic-regression model*

Logistic regression is a statistical modelling technique. It describes the relationship between the probability of a binary event (e.g., marketability of the product) and a set of variables (like time, temperature, firmness, ripeness variety or average sugar content). The probability of being able to market a tomato, for instance, can be 100% at the point of harvesting, but decreases with time and sugar content. In contrast, it *increases* with the firmness of the flesh of the tomato. Examples of the above-mentioned logistic curves are shown in Figure 23 and Figure 24.

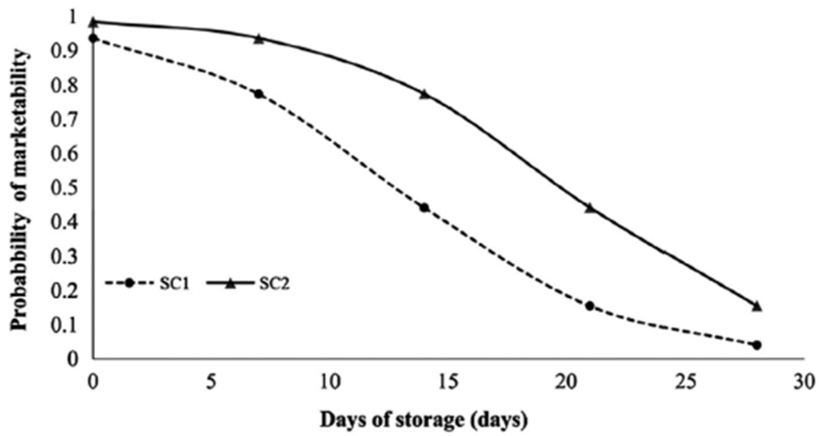


Figure 23: Probability of tomato marketability as a function of the storage time. SC1 is an ambient storage environment, while SC2 is a cooler storage environment. Source: Tolesa 2017 [41].

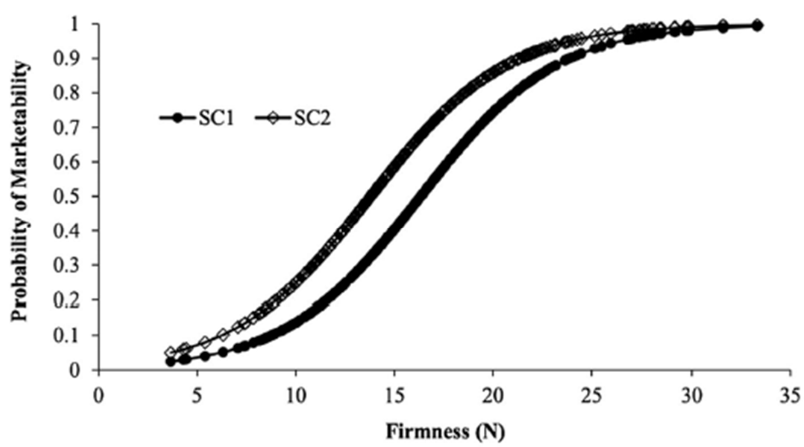


Figure 24: Probability of tomato marketability as a function of the flesh firmness. SC1 is an ambient storage environment, while SC2 is a cooler storage environment. Source: Tolesa 2017 [41].

The logistic regression model can include one or more predictor variables, as well as model parameters that are unknown. The regression then estimates the unknown model parameters by fitting the logistic curve to test data. This procedure is slightly more computationally complex than the simple time-temperature model and to some extent lacks a biological foundation. However, it has the advantage that several variables can be simultaneously included in the regression function, which can improve the accuracy of the predictions.

5.1.4 *Big data techniques*

Both the logistic time-temperature model and the logistic regression model are *parametric models*. This means that the number of variables influencing the quality decay is limited and already known a priori. However, the parameters affecting quality-decay are numerous, and many of them are intercorrelated.
Also, the exact effect of a model parameter is not always precisely known.

A temperature fluctuation of the ambient air, for instance, may occur very fast, but the temperature inside the flesh of the produce changes much more slowly and possibly in a non-uniform way. How the temperature change spreads in a volume again depends on other factors, like the relative humidity, pressure and amount of air flow.

As a result, modeling only a small number of parameters can sometimes result in inaccurate or wrong predictions. The most accurate logistic models depend on a large number of parameters simultaneously and are computationally very complex. However, recent developments in big data techniques like machine learning now allow for *non-parametric* models with large numbers of variables. Examples for these are Bayesian Networks and Neural Networks, which are increasingly being applied in predictions of food quality. With machine learning techniques, also other information like weather data can be incorporated into the model for better accuracy. If implemented and trained well, machine learning techniques can provide excellent quality estimates and shelf-life predictions. Programs to detect defects and diseases based on *images* of the products, for instance, can exhibit accuracies higher than 95% in many different commodities.

Big data techniques have not yet been able to entirely replace the more traditional decay models based on logistic or other mathematical functions. This might be due to their somewhat higher complexity and innovative character. Models based on machine learning can require large databases and significant training as well as time and financial investments before becoming sufficiently accurate. Also, big data models ion the fruit and vegetable sector face a similar lack of standards as traditional decay models. For a breakthrough of quality-controlled logistics, standardized and commonly accepted definitions of fruit and vegetable quality are therefore highly needed.

5.1.5 Dynamic quality decay modelling

The type of quality-decay model to be used in logistics applications depends strongly on the selected sensors, the data communication infrastructure and the required calculation speed. If only a temperature logger is present in the container, then the traditional time-temperature model should be used due to its lower computational complexity and higher biological foundation than machine learning techniques. If several gases as well as the temperature and humidity are tracked, then logistic regression or machine learning can be employed. However, this comes at the cost of computational complexity. In all cases, the chosen model should be able to incorporate newly collected information and update the product quality or shelf-life estimation in *real time*. This type of model is called a *dynamic quality decay model*, in contrast to static decay models that have all input parameters fixed before the start of the logistics operations.

In dynamic quality decay modeling, not only the type of model has to be chosen according to the type of sensor and computational complexity involved. Also, the time span between updates or recalculations of the shelf-life prediction is variable. It should be chosen depending on the time scales of decision making, as well as the time needed to perform the model calculations. If the time between recalculations is very short, it might cause unnecessary computational complexity and possibly high costs and energy consumption. A long time between updates of the model might cause issues with on-time decision making in the logistics chain. As a result, simpler models are preferred in case frequent updates are needed, and more complex models can be run if the time span between recalculations is set longer. A smart option to run frequent quality updates is to communicate only the raw sensor data to an online platform and outsource the model calculations to larger computers physically present, or to the cloud.

Another challenge to be faced with widely applied dynamic quality decay models is that significantly more computational power is required the more containers (or other decision units) are monitored. A remedy for this is to implement “update calculations” that are computationally more simple than the full model calculations, or to *review* the newly available input parameters. The full model calculation is then only triggered if significant changes of the sensor data have occurred.

5.2 Logistic interventions and data-driven decision making

Based on sensor data and the resulting shelf-life predictions, the supply chain can be adapted, offering a potential reduction of product losses. In fact, if there is no room for alternative logistic decisions, then the availability of sensor data has no added value. Logistic adaptations can include rerouting of goods in distribution centers or during transport, as well as dynamic pricing strategies.

5.2.1 Adaptations in distribution centers

Two of the simplest and most commonly applied inventory management systems in distribution centers are 1) First In First Out (FIFO) and 2) Last In First Out (LIFO). These methods take the arrival time of the cargo in order to determine which batch of products is sent out first. In contrast, in the Least Shelf-life First Out (LSFO) system, also called First Expired First Out (FEFO), the predicted *shelf-life* of the produce is used to take logistic decisions. While FEFO can slightly increase the complexity of goods flows, it provides a very promising opportunity to mitigate large amounts of product losses of perishable cargo.

Without *en-route* cargo-monitoring, a static single shelf-life prediction of the products can be determined post-harvest. This prediction can subsequently be assigned to a single item in the form of a label or a tag, or to an entire batch or shipment. If IoT-enabled quality-monitoring is available, however, shelf-life predictions are dynamic and become more accurate than their static counterparts. This offers a possibility to mitigate an even larger amount of cargo losses. In addition, updates of the shelf-life prediction can be used to facilitate *en-route* sorting for more homogeneous product batches, or further adjustments of the supply chain.

5.2.2 Adaptations of the supply chain

Next to inventory management in distribution centers, logistic adaptations of the supply chain can be used to shorten (or prolong) the transport lead time depending on the shelf-life prediction.

Possible options include:

- Modal shifts and route adaptations (i.e., transport by truck instead of barge);
- Express treatment in terminals;
- Skipping milestones in the supply chain;
    - Direct cross-docking instead of storage in distribution center;

  - Omitting the ripening station and shipping directly to the customer;
- Changing destination (unload in France/Spain instead of the Netherlands) and selling at a different market.

However, there are certain prerequisites for these adaptations to be possible. In all cases mentioned above, flexible contracts and agreements are needed to allow logistic adaptations in the first place. Also, changes of customer or sales channels in transit needs to be possible, similar to the way that liquid bulk currently changes ownership several times during sailing. In addition, it needs to be determined which of the parties is responsible to cover the increased cost of logistic operations, and which party gets the benefits. For the case of express treatment, it is required that sea terminals be able to reliably manage complex flows dynamically with a lead time of, e.g., 24h before the vessel ETA.

5.2.3 Dynamic pricing strategies

Adaptations that do not necessarily require supply-chain interventions are dynamic pricing strategies. The price of the product batch is then based on the (dynamically estimated) product quality and shelf life prediction. If the quality or shelf-life is estimated to be low, the price can be reduced in order to still find a buyer, which can avoid large amounts of food waste. As low-quality products can have different applications and target audiences than high-quality goods, dynamic pricing can also result in a change of customer or destination and an accompanying supply chain adaptation. Like the logistic interventions mentioned above, dynamic pricing requires flexible contracts that allow for real-time adaptations of the price and goods flows.

5.2.4 Manual vs. automated decision-making

Logistic interventions can be taken in two ways: In the first scenario, the dedicated logistics controller (i.e., a person) takes decisions based on sensor data and/or model recommendations. The second option is that logistics decisions are automatically taken by computers according to an optimized model. In the first case, the controller can change product conditions or take logistic decisions based on the results from quality decay models, while also taking into account their personal knowledge and experience. The amount of support by computer model predictions can vary, meaning that algorithms may or may not suggest several logistic strategies. The outcome of the calculations is then always reviewed by the controller, who ends up taking the final logistic decision.

In the second scenario, all logistics interventions are entirely taken by computer algorithms. An advantage of decision making by computers is that it is fact-based and efficient, and no human interaction is needed. Also, elaborate computer algorithms are often less prone to logical errors than human decisions. However, computer-only scenarios can be vulnerable to hardware or software failure. A central breakdown of decision-making computing clusters can have massive consequences on worldwide logistics operations. Therefore, redundancy must be implemented, and it might be beneficial to spread the data flow and computational power over more than one service provider. An advantage of the controller-based scenario with human interaction is that the controller can manually fact-check the decisions suggested by the computer algorithm, and logistics decisions can be taken even in case of a hardware or software failure. Also, creative out-of-the-box logistic decisions can be taken by controllers in uncommon or difficult cases. These advantages come at the cost of added complexity, added man-hours and the increased possibility of human failure.

Regardless of whether logistic decisions are taken by human controllers or by computer algorithms, the time span and thresholds for logistic interventions must be optimally chosen. If the threshold for an alarm based on sensor data is too high or the time before the alarm is long, it might already be too late to prevent quality loss. In contrast, a threshold that is too low or an alarm that is sent too fast can suggest unrealistically high numbers of intervention procedures or even “overwhelm” the decision making unit.
As logistic interventions have a financial cost associated with them, alarm thresholds also need to depend on the business strategy of the respective company, and the benefits must surpass the associated intervention costs. If the main goal is quality maximization, then the threshold should be lower to allow for timely adaptations. However, if the goal is to keep the costs as low as possible, high alarm thresholds are more sensible. In order to find the optimal operational plan, the design of a generic procedure is necessary, in which it becomes clear where and how IoT technology should be applied from a cost-benefit perspective. Such a generic procedure is proposed in the form of a conceptual framework in a recently submitted article [4]. The necessary criteria of cost-benefit analyses and possible implementations of IoT-devices in the supply chain of fruit and vegetables are discussed in the following chapter.

6 Integration into the application domain

In this chapter, we discuss how a complete integration of existing knowledge about the fruit and vegetable ripening process, sensor technologies, communication and data processing is necessary for a full valorization of the digitalized supply chain and quality-controlled logistics. In addition, we address practical and financial considerations that should be taken into account for the implementation, as well as remaining challenges of the technology.

6.1 Implementation of IoT-based quality-controlled logistics

The transport of perishable cargo includes, amongst others, medicine, flowers and food products. In medicine transport, temperature is a common parameter to be measured, and other influences on the product quality like light or the relative humidity can be avoided by suitable packaging. As a result, the medicine transport sector is rather conservative in investments and has low profit margins, making it not very promising for the application of new IoT-based technologies. In contrast, the fruit and vegetable supply chain provides great opportunities to mitigate product losses and therefore has large investment potential. This is demonstrated by the growing interest in quality-controlled logistics, [31] and by recent developments showing that IoT-devices are getting more commonly used in fruit and vegetable supply chains, in particular in the US and Canada [42].

Several IoT-devices with temperature and relative humidity sensors, as well as GPS tracking, are already available. This development is accelerated by the increasing availability of affordable *single-use* temperature and humidity sensors and loggers. Also, recent developments in communication technologies like 5G and LPWAN are becoming more affordable and reliable, and might cause a breakthrough of supply-chain digitalization. While the lack of data roaming agreements in cellular technologies is still posing a practical challenge in the application domain, provider agreements are expected to be finalized in the near future. In the meantime, improvised software-based solutions or multiple SIM cards can be used in practice to circumvent the roaming issue. Furthermore, recent investments of large ocean carriers contribute to the growing IoT infrastructure and accelerate the uptake of sensors in the supply chain of fruit and vegetables. The deployment of large amounts of smart containers in the near future may aid the breakthrough of IoT technologies.

While temperature and humidity sensing are becoming more and more widely applied, the use of gas and shock sensors is slightly lacking behind. To this point in time, accurate and affordable ethylene sensors are often too costly for *en-route* IoT-applications. However, the existing logging, communication and dashboard infrastructure for temperature and humidity monitoring can serve as a basis for the fast uptake of additional sensors for oxygen or CO_2. Also newly developed gas sensors or optical ripeness scanners may be added to the existing sensor infrastructure in the future. For the plant hormone ethylene, we expect sensors to be primarily applied in reefer containers, as this avoids challenges arising from a short battery lifetime.

6.2 Evaluating cost-benefit tradeoffs

In the application of IoT-based quality-controlled logistics, there is always a tradeoff between the benefit from quality-related sensor data and the costs associated with sensor deployment. Temperature sensors, for instance, are widely applied because their added value is significant, while the associated costs are very low. In the case of an ethylene sensor, however, the costs and maintenance effort at this point in time often do not justify its use during transport in the supply chain, even though ethylene can be one of the major influences on quality decay for some commodities.

While each sensor type can in principle rely on its own business case, *combining* different detection mechanisms in multi-sensor applications can result in larger financial advantages. The optimal combination of sensors strongly depends on the requirements of the transported commodity as well as the business strategy of the respective company. For reusable multi-sensor devices, it may be beneficial to have several sensors integrated into a single IoT-device or into a smart container, and to switch the relevant sensors on and off depending on the commodity and the wishes of the client.

In addition, the supply chain can be further optimized by combining *en-route* monitoring with independent methods like fixed sensors in large warehouses, optical pre-sorting at the harvest site, pre-transport treatment or special packaging. In fact, most quality sensors to date are immobile and installed in distribution centers or other fixed milestones in the supply chain. Other types of sensors are mobile, but lack real-time communication technology. These types are often inexpensive and can be used in a defensive manner to identify the root causes of quality decay in the chain. However, with a lack of real-time information they cannot be used to adapt the supply chain on the fly.
These alternative methods can complement IoT-enabled data loggers, but could also pose a threat to the IoT technology. As large product losses may already be mitigated by a suitable optical sorting or packaging procedure, the use of IoT devices may become less important. Again, it depends on the exact supply chain scenario whether postharvest sorting, fixed warehouse sensors and IoT-based sensing devices compete or complement each other. In a business case analysis, the tradeoffs between real-time information and the associated investment costs need to be analyzed and evaluated in view of the company's quality-control strategy.

Next to the type of sensor, also the sensor location, implementation level and number of sensors need to be determined in a cost-benefit analysis. Sensors can be applied to entire containers, pallets, boxes/crates or individual products.
The selected sensor application level directly impacts the sensor performance and investment costs, as well as the shelf-life predictions and resulting logistical decisions. More sensors result in higher costs, but also in increased data reliability and possibly more detailed quality information on within-unit variations. Information on ripeness variations in a bulk package, however, is only beneficial if the products in the bulk can practically be reorganized into more homogeneous batches, for instance by sorting them in distribution centers. If breakbulk is not possible, the variety-information does not provide added value in decision-making, and fewer sensors on a higher implementation level are more appropriate. Also, if only one or

two sensors are present at container level, their optimal location needs to be determined in order to get the highest-quality information. In other words, the placement and number of sensors ideally depends on the smallest logistic decision-making unit in the supply chain.

6.3 Dynamic cost-benefit analyses

In the most efficient scenario, a cost-benefit analysis is based on real data from the implementation of IoT-enabled quality-controlled logistics in the supply chain. This is because advantages and disadvantages can be evaluated best in a real business setting. While the concept of using IoT-devices in fruit and vegetable supply chains is expected to offer great financial and sustainability advantages, it has not yet been systematically proven in practice. Therefore, it can be beneficial to first evaluate practicability, costs and benefits in computer simulations. Also, small-scale pilot experiments will provide valuable insight on tradeoffs between costs and benefits and can serve as a proof of concept. In addition, pilot studies may provide valuable input for larger studies or for more extensive computer simulations on a realistic business scale.

Moreover, in a simulation or realistic pilot study, the costs and benefits can be evaluated also from social and environmental viewpoints. This includes the associated impact on employment opportunities as well as greenhouse gas emissions or energy use. Higher energy use by an increased number of sensors may increase greenhouse gas emissions, but might get compensated by reducing large amounts of food waste. The digitalization of the supply chain may result in fewer jobs in manual quality control, but at the same time enables the creation of more IT-related jobs.

6.4 Supply chain digitalization

As mentioned above, logistical and sensor data do not only need to be collected, they also need to be communicated, visualized and analyzed for efficient decision-making processes. At the moment, sensor providers typically offer their own proprietary dashboard for data visualization. For the purpose of learning from each other and making the decision-making process more effective, however, it is beneficial to design an integrated information management platform with multiple users, on which different companies may benefit from each other’s (anonymized) data. This can include order and logistics data, as well as real-time sensor data. Connecting logistic- and order data seamlessly can then help to set up an efficient decision-making process and greatly reduce transport costs and product losses. Additional real-time sensor data can then increase the profit margin even further. However, agreements on data privacy must be made and properly implemented to protect the competitive advantage of certain companies in the fruit and vegetable supply chain, while ensuring that the benefits of data sharing are fairly distributed.

Like traditional supply chains, a digitalized supply chain needs to be resilient, meaning that it can easily recover from an unexpected event or disruption. Supply chain disruptions may, for instance, occur due to plant or human disease outbreak, bad weather conditions or infrastructure failure. In the case of a digitalized supply chain, it may also occur by failures of the quality decay model, connectivity loss,

soft- or hardware failure, cyberattacks or platform collapse – with systematic consequences for the businesses involved.
To improve supply chain resilience, redundancy and decentralized function realization are advised to mitigate the risk of severe disruptions. Also, a certain extent of human intervention is desirable even in heavily digitalized supply chains. In contrast, a strongly digitalized and automated supply chain (including decision making processes) is advantageous in situations that limit the possibility of human interference. An example of such a situation is the current coronavirus pandemic, in which social distancing requirements can limit or complicate the on-site presence of human workforce.

6.5 Future developments

The Internet of Things offers a promising technology for the digitalization of perishable supply chains and quality-controlled logistics. IoT devices are undergoing fast developments and are being deployed more and more in containers and packages for monitoring and tracking purposes. Recent developments have shown that the big ocean carriers CMA-CGM, MSC and Maersk each ordered 50,000 IoT devices from Traxens to get installed in their container fleets, and that the entire Maersk and Hamburg Süd reefer fleets are now equipped with a remote container management system. This is expected to further accelerate the uptake of IoT-technology in quality-controlled logistics operations, as well as the development of more flexible contracting. However, the future development of the market is still largely unclear. Whether there will be room for alternative solution providers in the future and real-time logistic adaptations can take place, for instance, strongly depends on the preferences of supply chain parties, the flexibility of contracts and the cooperation and trust between companies. It also remains to be seen on what scale ethylene sensors can and will be applied during fruit and vegetable transport.

In the short term, IoT-enabled quality-controlled supply chains are the first step to improve the supply chain efficiency and mitigate losses of fresh produce. In the medium and long term, however, quality-controlled distribution networks need to be designed. This means that systematic quality bottlenecks are identified in a strategic network evaluation. As a result, the flow of goods can require a systematic change of transport modality or get redirected to different locations. With sensor data on the fruit and vegetable quality, optimal locations of distribution centers and optimal stock levels can then ideally be determined at different milestones in the supply chain.

Despite the fast development and increased deployment of IoT technology, some challenges remain in the course of the large-scale application of IoT-enabled quality-controlled logistics. A full summary and analysis of all strengths, challenges and benefits for the application of the technology in perishable supply chains is given in the SWOT analysis in the following chapter.

7 SWOT-analysis

After reviewing the main technologies and the state of the art of IoT-use in quality-controlled logistics in this report, we now turn to a summary and an analysis of the main **S**trengths, **W**eaknesses, **O**pportunities and **T**hreats of IoT-enabled quality-controlled logistics of perishable cargo. At the end of this chapter, we present a table summarizing the results and discuss the role of this project.

7.1 Strengths

Among the strengths of IoT for quality-controlled logistics is the fact that existing IoT sensor and communication technologies are already in use for real-time cargo monitoring and much more affordable than satellite communication. In addition to automated alarms in the case of certain events, online dashboards exist for customers to monitor and track their cargo. These dashboards can also be used by import authorities to check the compliance of the imported goods with local laws, reducing the required import paperwork. In addition, the sensors that are most commonly used like temperature, humidity, light, shock or GPS are typically low-cost and widely available in reefers, controlled atmosphere containers or IoT-devices. In cold chains, the temperature inside the reefer can sometimes be adapted according to a time schedule. The concept of using IoT infrastructure is therefore proven in the context of real-time supply chain monitoring, and the deployment of smart logistics assets and the corresponding cloud-based data infrastructures is strongly accelerating.

Complementary to the existing IoT technologies, there are several well-developed and tested quality-decay models that allow for a deeper analysis of sensor data and decay predictions. This can serve as input for data-driven decision making. In addition, the Dutch horticulture sector is quite advanced in IoT applications and supply chain digitalization. The knowledge and experience gained in this sector will be useful for a faster adoption of IoT-based quality-controlled logistics in the supply chain.

7.2 Weaknesses

A weakness of the IoT sensor technology at this point in time is that some types of accurate gas sensors are large and complex, and require a high-power input. As a result, they can be expensive and sometimes unfeasible for sensing in remote battery-powered devices. While the ethylene level is one of the main parameters to predict and influence product quality, to this point in time sufficiently accurate ethylene sensors are often not affordable for widespread use in IoT devices.

Depending on the product and season, the profit margin of fruit and vegetable supply can be small (0%-10%) and not allow for large upfront investments. In addition, the financial benefit of IoT-enabled quality-controlled logistics is not yet broadly and systematically proven, and financial investments may only get compensated at a later point in time. This may be one of the reasons why *en-route* cargo monitoring, with the exception of temperature tracking, is not yet widely used. In addition, some species of fruit and vegetables exhibit a large variety in ripeness, and the standardization level of quality decay models is low, meaning that there are many different ways to model and predict product ripeness. The choice of model can sometimes appear arbitrary, and resulting quality estimations can exhibit only moderate accuracy. This can slightly complicate shelf-life predictions and the strategic interpretation of sensor data.

Focusing on the supply chain itself, we currently face a lack of differentiation in the field of logistic services. Transportation of goods is typically a standard service. Logistic service providers like transport companies and ports are not yet used to real-time adjustments to the planning and do not deploy quality-based service models. With approx. 6-7% of the global container fleet, controlled atmosphere containers are in fact commonly used, but also conditioned transport is often based on predefined settings like fixed or scheduled temperature and humidity values. Real-time control of the container atmosphere is often not available.
Contractual agreements between operator, consignor and consignee often do not yet allow for invoicing additional service costs for re-routing or adjusting transport conditions. As a result, options for real-time service differentiation are limited or not offered at all. Examples would be express treatment at ports or in distribution centers, relaxation of the supply chain, or adaptations of the product destination. Also, the field faces a lack of elaborate logistics optimization and decision-making models that could recalculate and adapt the supply chain in real time, depending on the quality status of the product.

Other weaknesses lie in the state of current data-sharing and wireless communication technologies. In general, it can be concluded that the standardization level of IoT-technology is rather low. The exchange of digital documents in logistics such as invoices or shipping information typically follows global electronic business standards determined by, for instance, UN/CEFACT (the United Nations Centre for Trade Facilitation and Electronic Business). However, this standardization level does not hold for real-time re-routing information or other adaptations of the logistic chain. Also, the format of saving and communicating sensor data as well as the context in which they have been measured is not yet standardized. As a result, every service provider currently has their own customer dashboard for data visualization.

While the cellular Narrowband-IoT and 5G standards are very promising technologies, the negotiations of provider agreements on the handling and cost of data roaming are still ongoing. This slightly complicates connectivity with these technologies in the case of border crossings. In contrast to the abovementioned global cellular network standards, the LoRa technology is proprietary: Companies aiming to use LoRa must purchase LoRa-capable chips at different frequencies to achieve global network coverage. Also, network coverage with low-cost communication technologies cannot always be guaranteed in remote areas or at sea, meaning that the monitoring may be incomplete, or that more costly technologies like satellite communication must be used in these cases.

7.3 Opportunities

Using data-driven logistics in the supply chain of perishables offers the possibility to mitigate significant financial losses that occur due to quality decay, and to reduce large amounts of food waste. Assuming that 3.84% of all fruit and vegetables spoils during transport alone, yearly global losses that could potentially be mitigated amount to ca 50 billion USD. For fruit and vegetables imported to the European Union, a total value loss of 772 million Euros may be avoided. In addition, agriculture and supply chains become more efficient and more sustainable with the use of IoT technology. Relaxing part of the supply chain and mitigating food losses may increase sustainability by reducing unnecessary CO_2 -emissions.

The re-routing of products in the supply chain can provide possibilities for finding and exploring new options for sales markets and transport partners. Due to better visibility of specific process steps in the chain, bottlenecks or points of failure may be identified, for instance unwanted temperature or mechanical shocks. In these cases, the transport parties involved can be identified and made responsible for the quality of their material handling. This can strongly improve the overall quality of transport, and offers new perspectives and differentiation also to the insurance market. In addition, the increased attention for food safety and (food) sustainability stimulates the need for an improved supply chain visibility.
A digitalized supply chain also provides traceability with regard to the product origin and compliance with food safety protocols. Furthermore, the investments of supermarkets in local quality control mechanisms for fruit and vegetables can be leveraged by IoT devices throughout the end-to-end supply chain.

On the technology side, the biggest opportunities lie in the fact that both sensor- and wireless communication technologies are developing very fast and have recently become much more affordable. In particular, advancements in the field of LPWAN and Narrowband-IoT have gained momentum and might cause the breakthrough of IoT applications on the market. This is supported by the fact that big ocean carriers like Maersk, CMA-CGM, MSC and Hapag Lloyd have made large investments into smart embedded container devices. It is thus accepted that the technology is strongly relevant for a broad market in perishable fruit, vegetables and flowers, but also fragile goods or chemicals. Also, the Dutch horticulture sector has gained experience in supply chain digitalization and appears to be open to innovative ideas. This can facilitate the quick adoption of new technologies.

With an existing IoT sensor infrastructure already in place, the threshold of integrating newly developed sensor technologies in the future will become lower, and business cases for multi-sensor devices are likely to be more promising than single-sensor applications. IoT cargo monitoring may additionally be combined with more traditional methods for quality control steps such as optical post-harvest ripeness sorting. Successful quality decay monitoring can also lead to a change in the treatment or type of food to be transported. Strict monitoring and timely logistics adaptations may, for instance, enable non-chemical treatment, leading to more organic products on the market. It could also encourage a switch to faster-ripening species, which often exhibit better taste.

7.4 Threats

While sensor and communication technologies are becoming more affordable, there are increased costs associated with data-driven logistics, which might be a threat in case the profit margin of the respective commodity is very small. These costs lie in high-tech IoT-devices required for cargo monitoring, but also in the need for more agile logistics operations. Often, it is not clear which parties in the supply chain are responsible and able to make this investment, and effective gain-sharing business

models are widely lacking. While some of the largest ocean carriers have invested in sensor technology and developed their own data-driven service models, sound business cases for many embedded single-sensor applications are yet to be fully developed and identified. Moreover, if only a fraction of the container fleet is equipped with sensors, there can be an increased logistical complexity associated with transporting smart containers or sensor devices to the required location.
The incompatibility of different parties' data- and communication standards and the breach potential of sensitive business data may pose additional challenges. At this point in time, contracts and agreements made are typically not sufficiently flexible to allow for additional logistic activities, costs made or risks taken.

Turning to the quality sensors themselves, we note that some sensors for complex gases like ethylene, even if further developed, may exhibit a large power consumption. As a result, they are possibly only feasible for use in reefer containers, which are by default equipped with an external power supply. Whether gas sensors in general can have valid business cases also in *non-refrigerated* containers still remains to be seen. This could be the case, for instance, if quality sensors and a flexible supply chain allow for perishable cargo to be transported in dry containers instead of reefers without causing additional product losses.

Another threat is that alternative treatments of fruit and vegetables might not always *complement* IoT-sensing-devices in a quality-controlled supply chain, but also *compete* with it. Examples of complementary or competing technologies are optical pre-sorting, protective packaging, (sensorless) modified atmosphere bags or preventive addition of antimicrobial substances like pesticides or ozone. Furthermore, advancements in selective plant breeding technologies may result in products that are less vulnerable to suboptimal transport conditions.

Another threat to the use of IoT-technologies for data-driven logistics is the fact that data alone is not sufficient to adapt the logistics chain. Supply chains are complex, with many stakeholders and large volume streams. Therefore, efficient and reliable decision making based on sensor data is and will remain one of the largest challenges in this context. In combination with a lack of data format standardization, this is expected to be one of the most critical hurdles of the IoT evolution. As IoT promises billions of connected things, it requires common standards to operate with an acceptable, manageable and scalable level of complexity. In the future, the challenge of smart and agile decision-making will likely be addressed and resolved with global data standards and software-based approaches using artificial intelligence and machine learning. This is in line with recent developments towards the physical internet and self-organizing logistics.

7.5 Summary Table

Table 7 Summary of the Strengths, Weaknesses, Opportunities and Threats

STRENGTHS (present)	WEAKNESSES (present)
Proven wireless communication technologies and infrastructure	Accurate gas sensors typically complex, large and high-power consumption
Proven sensor technology	High cost of some sensors relevant for ripening
Development of more affordable communication technology than satellite communication	No small, affordable and accurate sensors available for ethylene

Dashboards available to visualize data	Current amount of *en-route* monitoring low
Online import compliance check for authorities	Possibly small profit margin (0-10%) of fruit/vegetables - product and season dependent
Customer alarms in case of certain events	Large ripeness variety at production source
Some sensors easily available and affordable (temperature, humidity, light, shock, GPS, …)	Limited quality segregation & value stream differentiation
Breakthrough in deployment of IoT devices and cloud-based infrastructures	Low standardization level of quality-decay models
Scheduled adaptation of temperature possible	Lack of real-time logistics optimization model
Existing quality decay models to predict quality at given atmosphere	Hardly any service differentiation like express treatment available in logistics
Advanced Dutch horticulture sector, with experience in supply chain digitalization	Limited availability of (live) container-wide atmosphere control
	Low standardization level of electronic sensor data and real-time logistic data
	Roaming conditions for 5G cellular IoT technologies not yet regulated
	Some communication technologies use proprietary standards
	High cost of communication technologies at sea.
	Contracts do not allow for invoicing additional costs for quality-control
	Lack of business model to share investments and benefits between logistic parties
OPPORTUNITIES (future)	**THREATS (future)**
Large potential for avoiding food waste and financial losses (50 billion USD globally)	Increased supply chain cost for IoT devices in combination with potentially small profit margin
Transport more sustainable if supply chain is relaxed	Increased cost and effort for agile logistics in combination with potentially small profit margin
Adaptations in logistics (i.e. rerouting) might open new markets	Many supply-chain partners and stakeholders with different goals
Possibility to track bottlenecks/failures in the chain	Lack of effective gain-sharing models and contracts that allow for flexible invoicing
Differentiation on insurance market resulting from improved point-of-failure tracking	Lack of data format and communication protocol standards
Supply-chain visibility for traceability of product origin and food safety	Breach potential of sensitive business data
LPWAN and NB-IoT technologies becoming more affordable	Increased maintenance and logistical effort to ensure availability of sensors
Momentum in the field: Big Ocean carriers are making large investments in smart containers	High power consumption of some sensors (in particular ethylene detection)
Technology relevant for a very broad market (food, flowers, fragile goods, chemicals…)	Data possibly not sufficient to accurately predict ripening/rotting
Sensor technologies becoming more affordable	Cargo-specificity of sensor data adds complexity
Newly developed sensors can hitchhike on existing technology and infrastructure	Competing quality-control mechanisms (pre-sorting, MA bags, selective breeding, ….)
Multi-sensor-applications advantageous for business case	Challenge of efficient data-based decision making due to large & complex volume streams

Combination with industrial pre-sorting according to ripening status -> sensor data more valuable	
Reducing chemical use & retaining “organic” labels	
Monitoring enables use of faster-ripening species with better taste	
Dutch sector open to innovation and the adoption of new technologies	

7.6 Conclusions and role of this project

In conclusion, we find that the concept of IoT-based quality-controlled logistics is able to reduce large amounts of food waste and financial losses in fruit and vegetable supply chains. The technology does still face some challenges in the fields of

1. Scalable and affordable data exchange infrastructure (in the cloud);
2. The reliability of quality decay model predictions;
3. The availability of low-cost ethylene sensors;
4. Effective real-time decision making and decision support;
5. Flexible contractual agreements with supply chain partners and customers, allowing for real-time supply chain agility;
6. Fair and effective gain- and costs sharing models.

However, our analysis shows that many of the current challenges are very promising opportunities for future development. The fact that the current adoption level of quality-controlled logistics is rather low provides extensive room for improvements on several levels in the supply chain of perishables. Product losses can already be avoided with small incremental steps in quality monitoring and logistic adaptations, without immediately facing the major weaknesses or threats. This way, experience can be gained with pilot studies and small-scale IoT deployment in order to further explore the possibilities and full business potential of quality-controlled logistics.

Due to the increased interest, strong momentum in the field and the large financial potential, we expect fast and innovative developments mitigating many of the weaknesses and threats in the near future. This holds in particular for the availability of service differentiation in material handling, cellular roaming agreements, the cost of communication technologies and the accuracy of quality decay models. While data format standardization and the availability of logistics optimization models are expected to remain bottlenecks for a large scale-up in the short term, we expect the quality and availability of logistics automatization to continuously improve in the future due to the large potential benefits and the resulting growing interest for this field.

What remains after our SWOT-analysis are several open questions on the feasibility and practical applicability of IoT-based sensing devices in quality-controlled logistics. A few of the questions we intend to address in this project are:

- What are the main *practical* challenges in applying IoT technology in the supply chain of perishables?

- How large are the financial and sustainability benefits of a quality-controlled supply chain, and how do they compare to the increased costs and effort?
- How can the technology build on existing strengths to be most efficient and cost-effective?
- How can the supply chain be adapted in practice, and on which time scales?
- Which of the more complex/expensive sensors are necessary for a good quality- and shelf-life prediction?
- Where do sensors need to be placed for most valuable measurements, and how many sensors are required?
- How can existing quality-decay models be improved and standardized?
- Which of the *opportunities* named above are the most relevant, and can be converted into *strengths*? For instance:
  - Is it (in some cases) desirable and feasible to relax the supply chain?
  - How beneficial is it to combine IoT-applications with optical pre-sorting?
  - How relevant is point-of-failure tracking for perishable cargo?
  - How easy is it to find and sell at new markets?

To answer several of the questions listed above, we aim to perform an integral pilot experiment as a practical proof-of-concept, as well as a business case analysis. The goal of the pilot study is to collect relevant product data with IoT-technology, which can subsequently be used as input for theoretical quality decay models. With these models, it is then possible to investigate to which extent the product quality can be improved by logistic supply chain adaptations, and what the financial consequences are. In addition, the pilot experiment provides insight as to which supply chain adaptations are currently feasible in practice, and which types of service differentiation are still highly needed for the breakthrough of quality-controlled logistics. It also gives valuable information on the feasibility and potential of IoT-enabled supply chain control as a whole, and on how the deployment of IoT-devices may be scaled up in the future.
The business case analysis is needed in order to weigh the additional sensor, tracking and logistic costs against the financial benefits of reduced food loss. With a sound business case available, more information can be gathered in the pilot study on optimal scale-up procedures and scope of deployment, as well as on expected future developments.

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9 Signature

The Hague, 17 July 2020

TNO

Silja Eckartz
Projectleader

Shari Finner
Author

Chantal Stroek
Research Manager