Int. J. Production Economics 164 (2015) 400–408

Contents lists available at ScienceDirect

Int. J. Production Economics

journal homepage: www.elsevier.com/locate/ijpe

Reducing food losses and carbon emission by using autonomous control – A simulation study of the intelligent container

Rasmus Haass [a], Patrick Dittmer [b,*], Marius Veigt [b], Michael Lütjen [b]

[a] Kühne+Nagel (AG & Co.) KG, Hans-Böckler-Straße 48, 28217 Bremen, Germany
[b] BIBA – Bremer Institut für Produktion und Logistik GmbH, Hochschulring 20, 28359 Bremen, Germany

ARTICLE INFO

Article history:
Received 31 March 2014
Accepted 6 December 2014
Available online 15 December 2014

Keywords:
Perishable goods
Food waste
Intelligent Container
Quality driven distribution
Simulation
Rescheduling

ABSTRACT

During the past decades bananas were imported to Europe in reefer vessels. Often, these vessels returned to Central America empty. This resulted in high carbon emissions and high costs. Therefore, importers switched to reefer containers which are shipped to Europe by liner cargo services. However, the amount of spoiled bananas increased with that change. Now a research project has developed the so called "Intelligent Container". This Intelligent Container is able to calculate the green life of its cargo and this leads to the feasibility of quality driven distribution. Thus, the losses of bananas should be decreased and both transport costs and carbon emissions be reduced even further.

In this article we focus on the reduction of the food losses and the carbon emissions. To find the level of the reduction we conducted a computational simulation study. We used an existing distribution network and assumed that all shipped containers were "intelligent". Following the idea of the "Internet of Things" and "Autonomous Logistics" we developed an algorithm which enabled each container to make its own decisions, e.g. which route to take and to which customer it should be transported. The article describes this approach and the results of the simulation study.

1. Introduction

In the introduction we describe the state of the art and the latest research results of sustainability in food supply chains and then describe logistics processes in general and distribution processes for perishable goods in particular. This chapter closes with the presentation of the Intelligent Container and the considered use case of transportation of bananas from Central America to Europe.

1.1. Sustainability in food logistics

Sustainability in food logistics depends on several factors: efficiency of logistics networks, wasted produce during transport, efficiency of refrigeration equipment, etc. Globalized logistics networks using container ships are in general organized in a sustainable way. Taking into account that worldwide material flows are not evenly spread, empty containers have to be transported. Bretzke (2011) states that strategic decisions are typical examples of a company's responsibility, e.g. configuration of a distribution network. In contrast, companies neglect responsibility aspects of operational processes such as transportation of goods. The transport sector was responsible for 22% of global CO_2 emissions in 2011 (IEA, 2013).

Nearly one third of all the food produced in the world is wasted. There are several reasons why food is wasted, and one reason can be found in the distribution of goods (Gustavsson et al., 2011). The world's population is still growing, and so sustainable systems for producing food are necessary. The European Commission defined sustainability as economic growth, social cohesion and environmental protection (Commissions of the European Communities, 2001). In the past companies concentrated on economic growth, but today social cohesion and environmental protection are becoming more and more important. Furthermore, in the European Union a law has been passed mandating food traceability from the producer to the customer (European Parliament and the Council of the European Union, 2002). Wognum et al. (2011) state that food chains need to become more transparent to regain consumers trust. RFID technology can make a contribution to achieve this aim. These systems can be used to enhance not only quality but also social aspects of sustainability in food supply chains.

Another aspect in improving sustainability in food supply chains is the optimization of transport of refrigerated food. Refrigeration stops or reduces microbiological, physiological, and physical changes of food in postharvest processes. James and James (2010) analyzed the food cold-chain and the effects on climate change. On the one hand carbon emissions of food are extremely high if produced and transported food is not utilized (James and James, 2010). Quite apart from the disposal of food by the customer, failures in the distribution processes such as transportation or

* Corresponding author. Tel.: +49 421 218 50090; fax: +49 421 218 9850090.
E-mail address: dit@biba.uni-bremen.de (P. Dittmer).

http://dx.doi.org/10.1016/j.ijpe.2014.12.013
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storage can lead to wasted food. On the other hand, emission reductions can be easily achieved by correctly using and maintaining energy-efficient refrigeration (International Institute of Refrigeration (IIR), 2003).

1.2. Distribution of perishable goods

In a globalized world logistics processes play a major role since goods are transported around the world. In a supply chain four different types of logistics processes take place from the producer to the customer: procurement (inbound) logistics, production logistics, distribution (outbound) logistics and reverse logistics. Summarized, all these processes include transportation, storage and handling of goods. Fig. 1 illustrates these logistics processes in a supply chain.

Production logistics include all transport and storage processes within a company that add value in production. Typical goods are raw materials, auxiliary materials, operating materials, purchased items, semi-finished and finished products or spare parts. All inbound logistics processes are combined to procurement logistics. Procurement logistics typically comprises all materials transported in production logistics. Semi-finished and finished products, merchandise and spare parts are goods that are transported and stored in distribution logistics. Reverse logistics comprises residues (secondary raw materials and waste) such as used and worn products, rebuilt units, returns, empties and packaging (Pfohl, 2010).

Hub and spoke networks have been established for transporting containerized perishable goods (Vahrenkamp, 2007). In these hub and spoke networks there are three stages of transportation: preliminary leg, main leg, and subsequent leg. In the case of the transportation of bananas from Central America to Europe, the main leg is carried out on huge container ships that can transport thousands of containers. On the preliminary leg the containers and goods are transported to the port of loading. The containers are stored at the port of loading for a short time before they are loaded on the container ship. On arrival at the port of destination, the containers are transported to the customers on the subsequent leg. In the same way as on the preliminary leg, these transports can be carried out by road, rail, or feeder ships. The supply chain in a hub and spoke network is shown in Fig. 2.

The analysis of managing food supply chains is divided into distribution network design (long-term), distribution network planning (mid-term), and transportation planning (short-term) (Akkerman et al., 2010). Quality driven modeling and simulation approaches for optimizing the food supply chain have been described for mid-term (Rong et al., 2011; Dabbene et al., 2008; Rijgersberg et al., 2010) and short-term optimization (Chen et al., 2009; Osvald and Stirn, 2008; Hsu et al., 2007). Rong et al. (2011) investigated in a simulation study a generic modeling approach for food production and distribution planning by modeling the quality change of products along the supply chain. Dabbene et al. (2008) presented a novel approach for the optimization of fresh food supply chains combining logistics costs and indices measuring the quality of the food. Another quality modeling approach was conducted by Rijgersberg et al. (2010). By using quantitative microbial risk assessment (QMRA), the food safety in the food chain is modeled and simulated and the impacts on logistics processes were determined. For short-term optimization Chen et al. (2009) developed a simulation framework combining production scheduling, vehicle routing and time windows for perishable foods focusing on the maximum profit for the supplier. Osvald and Stirn (2008) developed an algorithm to calculate the quality of perishable foods using a linear relationship between quality and transportation time. Hsu et al. (2007) explored vehicle routing problems using a stochastic approach to enhance effective delivery decisions under time-varying temperatures and time-dependent travel. In summary, all these approaches use offline information to optimize the distribution processes of food supply chains. To provide online information and thus quality driven distribution of perishable goods, a new approach is necessary.

The distribution of perishable goods is effected by temperature controlling for storage and transportation. Within this temperature controlled network reefer container and reefer trailers can be used for transportation. Inside these reefer containers, a product specific temperature is set so the transported perishables will reach a maximum shelf life based on a defined quality. For distribution several warehouse management methods are used. Common methods are FIFO (First In First Out), LIFO (Last In First Out) and SIRO (Sequence In Random Out). Specialized warehouse management methods have been developed for distribution of perishables: FEFO (First Expires First Out), LQFO (Lowest Quality First Out), LEFO (Latest Expiry First Out) and, HQFO (Highest Quality First Out). Dada and Thiesse (2008) analyzed these methods in respect of selling perishable goods by the use of a simulation study. In this study LQFO achieved the highest rate of sold products and thus the minimum rate of wasted products. To use LQFO the quality has to be determined in quality checks. FEFO achieved the second best selling rate (Dada and Thiesse, 2008). The Intelligent Container can calculate the actual quality of the transported goods and provide this information online in order to match the goods to a customer order while the container is still being shipped. To supplement FEFO and the use of information from the Intelligent Container a new warehouse management method called “dynamic FEFO” has been developed (Jedermann, 2009). Additionally, Lütjen et al. (2013) developed a new scheduling method for quality driven distribution of Intelligent Containers based on a central optimization approach. In summary it can be stated that no approach of decentralized control for Intelligent Containers or food supply chains exists which can be used for the

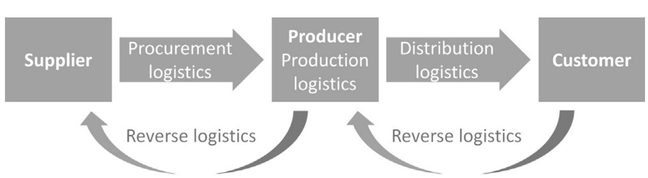

Fig. 1. General supply chain.
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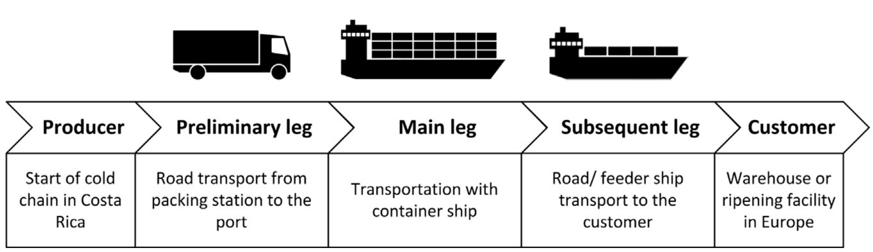

Fig. 2. Distribution of perishable goods.
(Source: own figure)

efficient rescheduling of containers based on current food condition.

1.3. Using the Intelligent Container for the distribution of bananas

Bananas are the most imported fresh fruits to the European markets. If bananas are handled wrongly during transport, they will start to spoil and consequently the fruit will be wasted. In order to stop this kind of loss, a project consortium funded by the German Federal Ministry for Research and Technology has developed the "Intelligent Container". The Intelligent Container consists of a wireless sensor network to measure relevant data, a so called Freight Supervision Unit to calculate the actual shelf life by means of a product specific shelf life model, a telematics unit and a middleware to optimize logistics processes according to the actual shelf life of the goods (Lang et al., 2011). The main use case in this project was an import scenario of bananas. Characteristics within this use case are the cooling temperature of 13.9 °C (57 °F), which is necessary to interrupt the ripening of the bananas while transported, and a long transport time from Central America to Europe, a journey that takes more than 14 days.

This Intelligent Container can adjust the correct set-point of the cooling unit autonomously, realizes if there are any power disturbances and sends alerts to the users. Furthermore, this container is able to calculate the green life of its cargo (Jedermann et al., 2013). This leads to some further possibilities, as shown in Fig. 3:

1. Quality driven distribution (Lütjen et al., 2013): The knowledge of the condition of the cargo can be used to control the logistics processes (Mack et al., 2014). That means bananas with a long green life will be transported a longer distance and bananas with a shorter green life will be carried to a customer closer by. Thus, the losses of bananas should be decreased and transport costs and carbon emissions reduced.
2. Feedback to the farm: If several Intelligent Containers coming from the same farm realize that the bananas they are carrying are starting to spoil, they can give feedback to the farm. The farm can then react by e.g. harvesting the bananas earlier. This way future food losses can be reduced leading to further reductions in transport costs and carbon emissions.
3. Ripening inside the Intelligent Container: In the event of spontaneous ripening of the bananas the Intelligent Container can begin a controlled ripening of the fruit. By infilling ethylene the bananas can be ripened inside the container. Thus, the bananas can be transported directly to the customer, bypassing the ripening center. This also leads to savings of costs and carbon emissions.

In this article we focus on the logistical part of the container transport, which is defined as quality driven distribution. Our aim is to research how much food loss and how much carbon emissions can be saved by implementing a quality driven distribution. To find the level of the reduction we conducted a simulation study based on decentralized control. We used an existing distribution network and assumed that all shipped

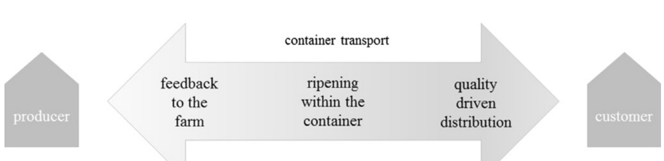

Fig. 3. Options to enhance the banana distribution. (Source: own figure)

containers were "intelligent". Following the idea of the "Internet of Things" and "Autonomous Logistics" (Scholz-Reiter et al., 2004) we developed an algorithm which enabled each container to make its own decisions, e.g. which route to take and to which customer it should be transported. This article describes this approach and the results of the simulation study.

2. Simulation study

In this section we investigate the benefit of the Intelligent Container by simulating a fruit distribution network. Firstly, we describe the distribution network as well as the simulation environment. The ripening function is a fundamental function of the simulation study. It is explained in Section 2.3. (Ripening function and quality prediction). Each simulation starts with the routing management, which is introduced in Section 2.4 (Routing management). During the simulation the logistics processes will be controlled by solving the "decentralized order exchange problem" (Section 2.5. Decentralized order exchange problem) by each Intelligent Container. We defined four test scenarios which are described in Section 2.6 (Test scenarios and evaluation approach).

2.1. Distribution network

The logistics network for the distribution of bananas under consideration has one point of origin (Moín/Costa Rica) and ten possible destinations (C1–C10), of which C2 and C6 receive customized labeled bananas. The European end of this network uses the ports of Bremerhaven and Hamburg in Germany and Antwerp in Belgium. Once a container is unloaded at one of these ports, it may be transferred to Oslo, Helsingborg or Helsinki by vessel or to a warehouse from where they are transported to a ripening facility by truck. During transportation the condition of the bananas is checked at different locations (as illustrated in Fig. 4). When using regular reefer containers, the customer order decoupling point is either at the warehouses or at the ports in Scandinavia. The concept of the Intelligent Container provides no such fixed decoupling point, because quality can be checked every day and orders may be changed whenever it is necessary (Dittmer et al., 2012).

2.2. Simulation environment

The simulation is set up in the logistics network described above, which is represented by nodes and directed edges. A container therefore follows a transport route that contains both nodes and edges in alternating sequence. Once a container arrives at a node, it might take a certain amount of time until the container is loaded on to the next truck or vessel, because of handling or waiting for a vessel to arrive at the node. Vessels do not leave a harbor on a daily basis, but in a cycle of 2 or 14 days, depending on the route. Vessels that follow routes in Europe, e.g. from Hamburg to Oslo, operate more frequently than ships which leave Central America in the direction of Europe. Furthermore, the logistics network is not capacitated and trucks are available every day. Nodes and edges are able to hold as many containers as ordered and the processing time it takes to transship a container through a node is one day.

There are ten customers who place orders for every week of the year. The weekly day of demand is always the same day, e.g. Friday. The amount of ordered bananas is given in the unit of one container load (CL) of bananas. For every customer, the average weekly order, the standard deviation and the maximum and a minimum order are given in Table 1. These calculations are based on data from a major fruit importer. Each order contains a place and date of

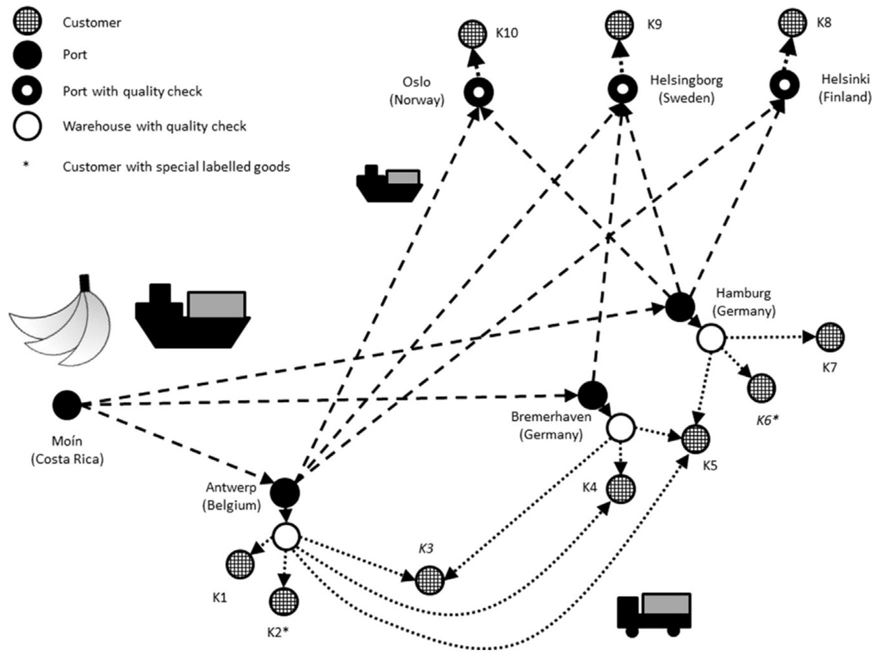

Fig. 4. Logistics network for banana distribution (cf. Lütjen et al., 2013).

Table 1
Amount of weekly orders demanded by customers.

Customer	Average amount of orders [CL]	Standard deviation	Max	Min
1	23.125	3.72011905	30	20
2	9	4.17475406	15	3
3	28.125	4.99821397	35	20
4	1.125	0.35355339	2	1
5	8.5	3.50509833	15	5
6	4.75	1.98206242	8	2
7	15.5	2.67261242	19	11
8	1.125	0.35355339	2	1
9	1	0	1	1
10	4.5	2	9	3

delivery and demands exactly one container load (2 TEU[1]). Therefore, the simulation starts off by calculating the amount of the weekly orders and generates a list of containers equal to the total amount of orders. Afterwards, each order is linked to a container and its transport route and the start of the transport is selected. Each container enters the logistics network according to the calculated start of the transport and follows the individual transport route until reaching its destination.

2.3. Ripening function and quality prediction

In general, the degree of ripening of bananas can be determined by comparing the color of the bananas with seven ripening categories, of which four are relevant for distribution. When the bananas are loaded in the container they are usually colored in category 1, whereas at the POS (point of sale) most customers demand a ripening degree of 4. In Central America the bananas are containerized with a ripening degree of 1. During transport the containers are cooled to 13 °C. During this time, the ripening process of the bananas is slowed down. (Zhang et al., 2010). In most cases the bananas arrive at their destination in the condition specified (ripening degree between 1 and 2). However, there are various factors that can cause a spontaneous ripening inside the container. One of these factors is an error in the cooling chain. An increase in temperature then results in a progressive rise of the ripening speed.

The process by which bananas ripen is still not understood in every detail. Therefore, the simulation is based on a simplified mathematical ripening function which focuses on temperature changes. In most cases, the temperature inside a container stays under 15 °C (Jedermann et al., 2013). After 42 days the ripening degree of 2 is reached, representing the ripening category specified at the destination. Every day while the container is on its way to its destination, the temperature might rise because of an error e. g. in the power supply. Thus, four different conditions are possible. The probability for no change in temperature during a day of transport for a given container is set at 99.79%. The remaining 0.21% is divided into three different temperature conditions at 20 °C, 25 °C and 30 °C. All four temperature conditions result in different ripening functions. The bananas start in temperature condition 1 and a ripening category of 1 represented by a ripening parameter (RP) set to 1, which increases daily by 0.0238. Once the temperature condition (TC) climbs to 2, the daily addition rises to 0.0909. Once temperature condition of 1 is exceeded, the new ripening function is final until the bananas arrive at their destination and the date of delivery is reached. Table 2 states the different temperature conditions with their related probabilities and ripening functions.

By combining temperature condition and ripening function, the remaining durability (time until ripening value reaches two) can be predicted for the bananas in every single container in the logistics network (as illustrated in Fig. 5).

2.4. Routing management

For each container, the transport route and the day the transport to Europe starts is calculated. The Intelligent Container is capable of doing this autonomously. For a mathematical description of the routing management process, it is necessary to point out some parameters in advance. The amount of Containers is represented by C whereas K_i contains all nodes that belong to the

[1] TEU is the abbreviation for twenty-foot equivalent unit. 2 TEU means 2 twenty-foot container or 1 forty-foot container. We only consider forty-foot container because they are the standard container for the import of bananas.

transport route of container i. The specified date of delivery is given by z_i and the day transport starts is described by the variable v_i. Once a node k is reached, the container may have to wait for a certain time because of handling activities (d_k) or because a vessel has not arrived yet (w_k). Finally, the time it takes to transport a container from node k to node l is represented by s_{kl}. The routing management problem is formulated as follows:

$$\min \sum_{i \in C} z_i - v_i$$

subject to

$$v_i \le z_i - \left(\sum_{k \in K_i} d_k + w_k + \sum_{k,l \in K_i} s_{kl} \right) \; \forall \; i \in C \tag{0}$$

The objective function states that the time a container is transported through the logistics network is to be minimized by varying v_i. Restriction (0) defines that v_i has to be less or equal to the date of delivery minus the combination of time aspects linked to a possible transport route. By solving the problem, the fastest transport route is selected and v_i is set to be the latest possible day on which a vessel may set off for Europe and arrive by the specified day of delivery.

Table 2
Temperature conditions during the transport.

Temperature condition	Temperature [°C]	Probability [%]	Ripening function
TC 1	15	99.79	$r = RP_{current} + 0.0238\Delta t$
TC 2	20	0.12	$r = RP_{current} + 0.0909\Delta t$
TC 3	25	0.06	$r = RP_{current} + 0.1316\Delta t$
TC 4	30	0.03	$r = RP_{current} + 0.25\Delta t$

2.5. Decentralized order exchange problem

The features of the Intelligent Container provide the opportunity to implement a decentralized order exchange algorithm. For this purpose, the containers are empowered to communicate with each other autonomously. Taking into account the restraint it is thus possible to formulate the *Decentralized Order Exchange Problem* (DOEP) for rescheduling, which aims at rescheduling interacting containers so that the amount of containers (p_i) that reach their destination in time and in the demanded state of ripening is maximized by order exchange. For the formulation of the DOEP, additional parameters have to be defined. The set A represents the total amount of orders. The node that has to be reached to fulfill order j is defined as a_j and the set of reachable nodes for a container at a specific time t is stated as F_i^t. Finally, r_i is the time that remains for the goods in container i until reaching the demanded ripening degree. The DOEP then can be formulated as follows:

$$\max \sum_{i \in C} p_i$$

subject to

$$\sum_{j \in A} (z_j \cdot x_{ij}) \ge v_i + \left(\sum_{k \in K_i} d_k + w_k + \sum_{k,l \in K_i} s_{kl} \right) \quad \forall \; i \in C \tag{1}$$

$$\sum_{j \in A} x_{ij} = 1 \quad \forall \; i \in C \tag{2}$$

$$x_{ij} \le \begin{cases} 1, & \text{if } a_j \in F_i^t \\ 0, & \text{if } a_j \notin F_i^t \end{cases} \quad \forall \; i \in C, \; j \in A \tag{3}$$

$$p_i = \begin{cases} 1, & \text{if } z_i \ge t + r_i \\ 0, & \text{if } z_i < t + r_i \end{cases} \quad \forall \; i \in C \tag{4}$$

$$x_{ij} \in \{0, 1\} \tag{5}$$

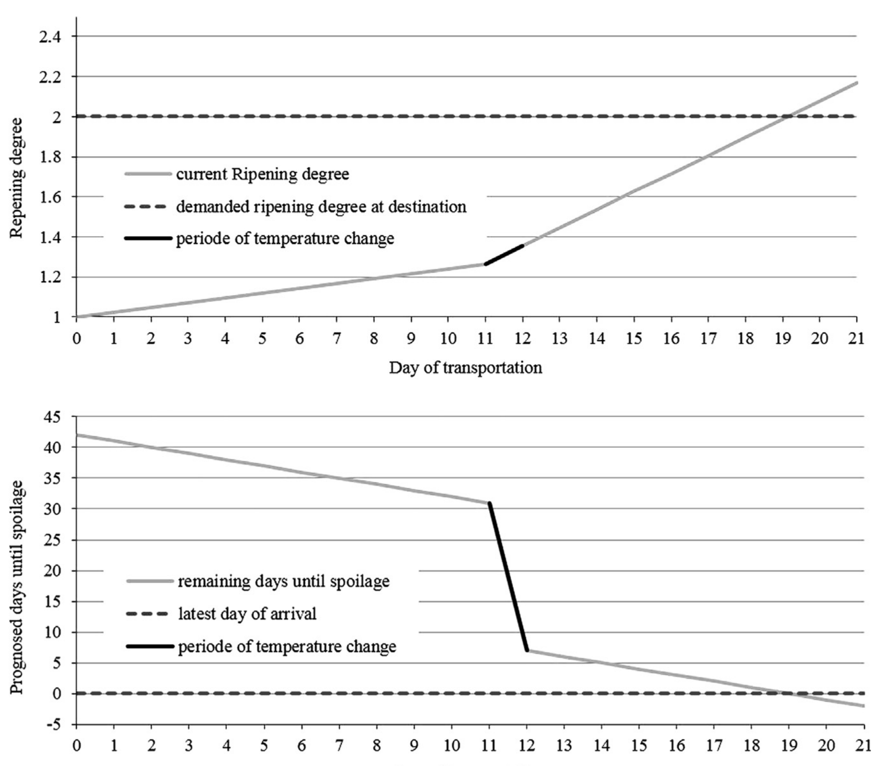

Fig. 5. Ripening and quality prediction of bananas; temperature change from 15 °C to 20 °C. (Source: own figure)

The objective is to maximize the amount of containers which arrive at their destination on time. Constraint (1) states that both containers reach their destination not later than the day of demand. Furthermore, the containers have to be assigned to exactly one order (2). The assignment of an order to a container is only possible if its destination lies within the set of destinations attainable by the container (constraint 3). Finally, constraint (4) and (5) define the setup of p_i and x_{ij}.

The process which enables the solving of the DOEP starts off by activating the algorithm in the software of a container at the beginning of transportation. Once a container is on its way, it measures the current temperature, humidity as well as ethylene inside the container and daily calculates the remaining days until the ripening degree reaches two. If the remaining days are less than the sum of days it would take the container to arrive at its destination, the so called "active" container starts interacting with other containers also carrying bananas. It starts off by communicating with those at closer range and thus interacts with containers on the same ship or at the same port.

The active container begins by sending its order parameters as well as the current status of the goods it is carrying to all other containers. These "passive" containers analyze the received data. At first, they compare the order parameters with their own transport route to find out if they are able to change their route to reach the destination of the active container in time. If this is possible, they check the ability of the active container to fulfill the requirements of their own order. If the two constraints are met, the degree of improvement that a change of order would bring about is determined. If $\sum_{i \in F} p_i$ (the amount of containers that arrive at their destination in time) with an exchange of orders is greater than without, the passive container sends a message to the active container and states the possibility of exchanging orders. As soon as the active container receives such a message, it confirms the re-assignment of orders. Subsequently, both containers implement the new order and re-calculate their transport routes. If no container in the immediate surroundings is able to exchange orders, communication is expanded to a longer range (other vessels or ports) and the procedure explained above is run through again. Fig. 6 demonstrates this process. The process model divides between actions performed by an active or passive container as well as general actions. General actions are not performed by containers but represent environmental aspects such as finding the next passive container or initiating the next simulation day.

2.6. Test scenarios and evaluation approach

To evaluate the performance of transportation with Intelligent Containers in combination with the decentralized order exchange algorithm, four different scenarios were computerized. The first scenario (con) represents the transport process with regular reefer containers and without an exchange of orders. Intelligent Containers are used in the second scenario (int) and they exchange orders by solving the DOEP. In another variation (intT) the Intelligent Containers not only exchange orders but also reduce the possibility of an increase in temperature, resulting in a lower probability of changing from the basic ripening status (15 °C) to a faster ripening status (as illustrated in Section 2.3). This effect is due to the multitude of sensors and alert processes which are integrated into the Intelligent Container. Consequently, the possibility of an error during the cooling process is reduced. In addition, containers in the last scenario (intTdel) are able to change their orders although this could result in a delay at their destination. Table 3 states the differences between the four scenarios.

The testing is carried out for a simulated time of one year. This way it is possible to discuss economic and ecological aspects on a realistic basis. Every simulated week, between 67 and 136 container enter or leave the distribution network because they are at the beginning or at the end of transportation. Therefore it is necessary to fill the network with containers according to the procedure explained in Section 2.2 and to establish a stable basis before evaluating the four different scenarios. Furthermore, every scenario is run 50 times. In Fig. 7 the amount of containers in the logistics network is stated over time and the evaluation period is illustrated.

3. Results

In the following, we give a summary of the simulation results obtained. We shall examine to what extent food losses can be decreased and what impact this has on CO_2 emissions. Afterwards, in Section 4 we give a broad approximation on the potential of these effects if the results of the simulation study are applied to the global transportation of bananas.

The more changes are made from scenario 1 (con) to scenario 4 (intTdel), the more the amount of spoiled bananas decreases (as shown in Fig. 8). When bananas are transported in regular containers, 4.27% of the total amount of transported containers arrive at their destination with spoiled bananas. By using Intelligent Containers and implementing the decentralized order exchange algorithm, this amount could be reduced to 3.9%. If one also takes into account the effect that Intelligent Containers decrease the possibility of a temperature change, spoilage could be decreased by another 0.38 percentage points. Therefore, the amount of fulfilled orders can be increased by 0.75 percentage points, without permitting delays. Communication in these two scenarios is performed at close range (same ship or port) only, resulting in lower communication costs. However, if delays are accepted and long range communication is affordable, the amount of spoiled bananas could be reduced by another 0.17 percentage points. Thus, the performance of the transport process could be enhanced by 0.92 percentage points in total. This represents approximately 22% less food loss than when using regular reefer containers. All relevant results are shown in Table 4.

With an average of 5068 containers transported to Europe every year, a decrease in the amount of spoiled bananas from 4.27% to 3.35% represents approximately 47 containers which could then fulfill their orders, but would not do so without using Intelligent Containers. It takes a container an average of 25.26 days to be transported to its destination. Including a buffer time of 2.74 days in each direction, it takes the container eight weeks to be back at its point of origin. Approximately 97.34 containers enter the distribution network every week and thus a rounded amount of 779 Intelligent Containers are required for the transport process in total.

Since food losses are covered by shipping more reefer containers, a decrease in food losses results in a decrease of transported reefer containers and thus less CO_2 emissions. According to HamburgSued[2] the total amount of CO_2 emissions that is linked to the shipment of a 2 TEU reefer container from Puerto Limón to Hamburg is 1.8 t per trip. If 47 fewer reefer containers have to be transported to Europe, at least 84.6 t of CO_2 emissions could be saved within the main leg of the distribution network per year. According to the United States Environmental Protection Agency (EPA)[3] this amount of CO_2 is approximately sequestered by 0.255 km² of U.S. forests in one year. While this level of CO_2 emissions reduction is not the sole reason for the use of Intelligent Containers, the numbers illustrate the fact that the reduction of food loss protects the environment in more than one respect.

[2] ⟨http://www.hamburgsud.com/ecommerce-hs/carbonfootprint/group.xhtml?lang=de⟩, last access: 01. September 2014.

[3] ⟨http://www.epa.gov/cleanenergy/energy-resources/calculator.html#results⟩, last access: 31. May 2014.

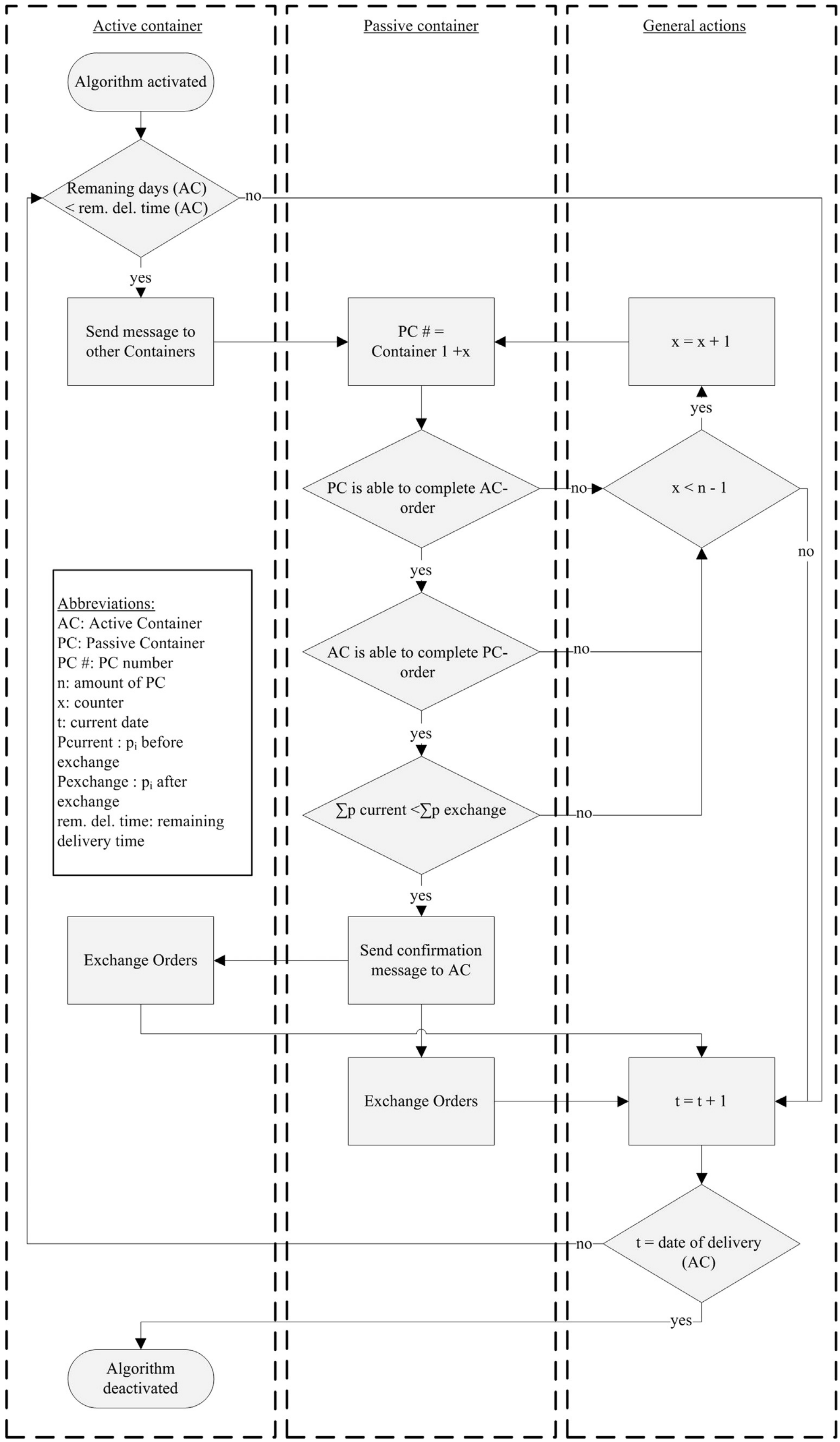

Fig. 6. DOEP solving process.
(Source: own figure)

4. Discussion and conclusion

In this contribution we presented a simulation study which shows the potential of quality driven distribution of perishable foods by Intelligent Containers. We developed an order exchange algorithm to enable a decentralized re-scheduling by Intelligent Containers and applied it to the distribution scenario of bananas. As a result, we state that food losses can be reduced by quality driven distribution. In the distribution network under discussion up to 22% of losses could be avoided. However, there are some uncertainties in the simulation; for instance the ripening function as well as the probability of spontaneous ripening during the transport. In these cases we assumed conservative values. Thus, the amount of wastage avoided could be higher in reality than in the simulation.

Furthermore, we discussed the potential of reducing CO_2 emissions by decreasing the total amount of containers that are shipped from Central America to Europe. In the simulation study 22% less food losses would lead to a reduction of CO_2 emissions by 84.6 t a year. The simulation was set up in a specified simulation environment and thus represents only a small amount of the total banana transportation. However, we try to make a broad approximation of the potential of a global use of Intelligent Containers for banana transportation. According to GDV (2014) about 1.2 million reefer container transports are performed during a year and thus the total amount of banana distribution worldwide is much higher than the amount considered in the simulation scenario. As it would not be very accurate to transfer the simulation results to the global transportation of bananas one-to-one, it is only possible to regard the tendency of the simulation results as a broad estimation. Since this tendency points in the direction of a reduction of food losses and CO_2 emissions, we can assume that this would also happen when Intelligent Containers are used for the transportation of bananas worldwide.

The results of this simulation study demonstrate the potential of autonomous systems to reduce carbon emissions in logistics processes. Along the supply chain several stakeholders such as producers, shippers, forwarders or customers could benefit from better allocation of goods and orders and thus lower carbon emissions. From an economic point of view, higher profits can be achieved. Furthermore, the information about the quality of the transported goods can lead to a higher transparency for all stakeholders along the supply chain. With this information new services can be provided.

In summary we can state that quality driven distribution enabled by Intelligent Containers reduces food waste as well as carbon emissions. Therefore, Intelligent Containers are a promising option for trading companies to enhance the sustainability of their operational processes and to generate transparency to gain consumers trust. However, these ecological and ethical advantages are accompanied by certain additional costs. Therefore, future work must be done to investigate the profitability of Intelligent Containers and if necessary to enhance the efficiency of these systems.

Table 3
Scenario characteristics.

Scenario	Order exchange	Exchange modalities	Probability of a change in temperature [%]		
			20 °C	25 °C	30 °C
con	–	–	0.12	0.06	0.03
int	Decentralized	No delay allowed	0.12	0.06	0.03
intT	Decentralized	No delay allowed	0.108	0.054	0.028
intTdel	Decentralized	Delay is allowed	0.108	0.054	0.028

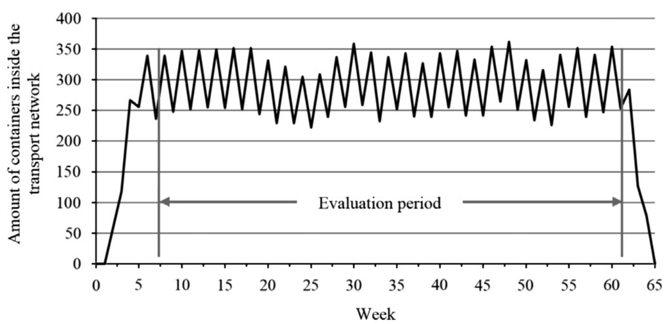

Fig. 7. Amount of simultaneously transported containers.
(Source: own figure)

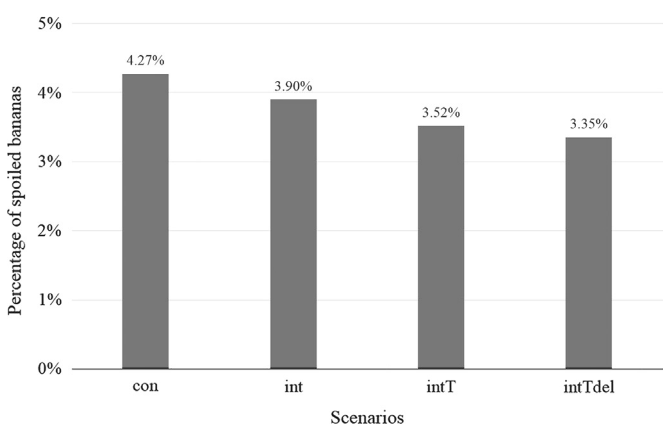

Fig. 8. Average amount of spoiled bananas.
(Source: own figure)

Table 4
Detailed simulation results.

Parameter	con	int	intT	intTdel
Average amount of spoiled bananas [%]	4.27	3.90	3.52	3.35
Standard deviation	0.27	0.24	0.27	0.27
Average amount of exchanges in near range	0.00	18.86	17.05	17.62
Average amount of exchanges in long range	0.00	0.00	0.00	8.47
Average percentage of delays [%]	0.00	0.00	0.00	0.17
Average amount of transported containers[a]	5063.02	5063.02	5070.02	5076.5

[a] Differences in the average amount of containers are due to the simulation set-up. Simulation scenarios were processed successively on dynamic test instances resulting in the possibility of changing amounts of containers shipped through the logistics network. However, since the differences are marginal, and spoilage is given as percent of total container amount, the total results are interpreted as stable.

Acknowledgment

The German Federal Ministry of Education and Research (BMBF) funded the innovation alliance "The Intelligent Container" with the reference number 01IA10001. Rasmus Haass did his primary contribution to research during his time as a student research assistant at the BIBA. From September 2013 to July 2014, he was student research assistant at the research group "Computational Logistics" of Prof. Dr. Tobias Buer at the University of Bremen and started working for Kühne + Nagel (AG & Co.) KG in August 2014.

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