The Benefits of Embedded Intelligence - Tasks and Applications for Ubiquitous Computing in Logistics

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Abstract. The concept of autonomous cooperating processes is an approach to solve complex logistical planning tasks by representing each object in the transport chain by a separate independent software unit. In general, these software units or agents are applied in a server network. Technologies from the field of the Internet of Things like wireless communication and RFID enable that software execution can be shifted to deeper system layers, even at the level of single freight items. This article examines the ancillary conditions and consequences of this shift. It focuses on whether the introduction of the intelligent parcel or vehicle is advantageous compared to server based planning. The second half of this article describes transport logistic examples for networks of autonomous objects with embedded intelligence.

1 Introduction

The idea of the intelligent parcel searching the way through the supply chain by itself has been discussed for several years. It looks for the best transport route and reacts to changed traffic situations or orders. In an extended scenario a parcel equipped with sensors supervises its content and environment. If it detects a danger threatening the quality of the content, the parcel looks for a solution.

The general technical questions are solved. Passive UHF RFID systems can identify items at transshipment points. Semi-passive RFID data loggers allow temperature recording at reasonable costs. Active tags or wireless sensor networks can communicate between freight, containers, warehouses and vehicles. Real time location systems can keep track of the location of a container.

Despite the technical feasibility, the possibilities for the practical implementation are restricted to mere identification or tracing tasks. Pallets are tagged with passive RFID labels by the biggest food suppliers, sea containers are identified by active tags. However, sensor applications on palette or item level are still in the prototype state.

1.1 Non-processing Sensors or Intelligent Objects?

These RFID and sensor systems are essential to monitor the transport chain. So far, they have mostly been regarded as information providers, instead of participants in planning processes or decision making. But should we constrain the implementation

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of planning processes to remote server platforms or is it more beneficial to equip the embedded devices with more localized computation power and intelligence?

This idea of shifting the intelligence into networked logistic objects has been a tempting vision in the past years, but the real benefits have not been figured out so far. How can the performance of the supply chain be developed without having to make more effort than in case of using a centralized planning system?

Passive RFID tags, active sensors and processing units on vehicle or container level will be considered as alternate platforms to realize the system intelligence. Aim of this contribution is to analyze the ancillary conditions and consequences of the transition from server based solutions to a network of distributed embedded processing units.

1.2 Outline

The first part of this paper presents a framework to classify and compare implementations intelligent objects on different system layers. **Section 2** examines the idea of intelligent objects in the broader context of autonomous cooperating processes. **Section 3** enumerates an extended set of criteria to evaluate the performance of a logistical planning system. The degree of decision freedom will be introduced in **section 4** as a means to categorize the amount of intelligence of an embedded object. The available computation power and additional costs to implement intelligence on different hardware layers are also discussed in this section. The current costs of the complete system are mainly determined by the extent of necessary communication. The concept of the 'length of the information path' will be presented in **section 5** in order to compare different levels of implementation in regard to the effectiveness of communication.

The second part comprises several case studies and demonstration examples for local intelligence on vehicle, sensor or tag level. **Section 6** presents the shelf life model as a basic approach to evaluate the effects of temperature deviation on the quality of the product. These models could be used by an intelligent container (**section 7**) to send automated notifications on predictable quality losses. In addition to the quality evaluation, parts of the route planning can be shifted onto the level of the means of transport (**section 8**).

Finally, a case study is described in the focus of **section 9** illustrating that it is not only economically worthwhile to invest into item level sensor supervision, but it is also necessary to process the sensor data in-place by intelligent objects.

2 Autonomous Cooperation of Logistic Processes

The autonomous cooperation of logistic processes is based on the paradigm to divide the solution of a complex logistical planning task into distributed processes [1]. Ideally, each object that participates in the supply or production chain is represented by its own software program, which autonomously searches a partial solution that is beneficial for the local object. In a transport scenario, the packages collect information, make decisions and negotiate with other entities to enhance the fulfillment of their common goal to perform all deliveries with minimal transport costs.

Autonomous Control has been defined by a workgroup of the Collaborative Research Centre SFB637 as *processes of decentralized decision-making in heterarchical structures. … The objective of Autonomous Control is the achievement of increased robustness and positive emergence of the total system due to distributed and flexible coping with dynamics and complexity.* [2].

Böse and Windt compiled a catalogue of thirteen criteria to characterize logistic systems based on the level of autonomous control [3]. The location the decision making is considered as the most important criterion. Individual decision processes for single objects do not necessarily require that a microcontroller integrated into an object should be in charge of implementing the decision algorithm. The software entities could run on a single or on a divided multi-server platform.

2.1 Representation of Logistical Objects by Software Agents

A common approach to represent autonomous objects is the implementation by software agents, which are a concept to run independent program units in a distributed network. These units autonomously perform a task on behalf of their owner. A more detailed description of software agents can be found in [4] and [5]. The most common environment to test and implement agents is the JavaAgentDEvelopment [6] framework (JADE). Each participant of the supply chain, like freight items, vehicles, sensors, traffic and logistic broker services can be represented by an agent [7].

3 Criteria for Performance Evaluation

In order to be able to benefit from embedded autonomous objects, it is necessary to provide dynamic planning. If everything is already determined before transportation is begun, there is no need for intelligence. But most complex transport optimization tasks need dynamic re-planning of route and freight allocation because of changes in traffic, unexpected delays or new incoming orders. A developed transport planning would also handle freight damage that occurs during transportation or predictable quality losses.

The second precondition is rather psychological: The freight owner has to yield control. Decisions are not made in a controlling room under the direct supervision of a human operator, but in the real world, on the road itself.

Furthermore, the criteria to evaluate the performance of a planning process have to be extended. Good planning cannot only be assessed in terms of finding the shortest route, the least transportation costs or the highest number of punctually delivered orders.

- The system should be flexible enough to react immediately to sudden situation changes.
- The network and the organization of planning entities should be robust to continue to work even in case of a communication failure.
- The privacy of internal planning strategies has to be kept. It should be kept confidential which customers are served first, and which are the ones whose deliveries are postponed in case of a shortage.

- Most information has to be transmitted over mobile networks. The communication costs should be kept low.
- A thorough search for the optimal route to deliver a great deal of items to several costumers could take hours or days. The computation time should also be taken into account. An optimal solution might quickly become obsolete due to changes in the traffic situation; therefore a recalculation should be possible with minimal computation by heuristic algorithms. In many cases it is possible to split up heuristic algorithm into independent distributed processes without the need for central collection of all the information.

The increase of robustness and ability to react to sudden changes overlaps with the goals of autonomous control [3], the criteria privacy, communication costs and computation time result from the implementation of embedded systems.

4 The Implementation Level of Decision Instances

Several factors should be taken into consideration in order to be able to decide on which hardware level the autonomy of the system should be implemented. The first one is the extent of intelligence that should be assigned to the embedded objects. As an alternative to the fuzzy term 'intelligence' possible solutions are classified on the basis of how much freedom an object has to make decisions by itself. Secondly, restrictions have to be taken into account in regard to computation power of the decision platforms and related costs. Effects on communication are examined in a separate section.

4.1 Degree of Decision Freedom

The objects in the supply chain can be equipped with a certain degree of decision freedom (**Table 1**). In a server based or central approach objects are only seen as sources of information, they only execute decisions of the central planning instance. On the next level of autonomy, freight items handle incoming data by local pre-processing. They observe and evaluate the conditions of their surroundings and decide when it is necessary to send an alarm notification to the planning system.

Table 1. Degree of decision freedom for mobile logistical objects

Class	Decision scope	Example
No freedom	None	Objects only executes centrally made decisions
Drawing conclusions from data	Evaluation of local sensor information	Object observes its environment and decides whether measured deviations form a risk for the freight quality
Adjust solution	Adaptive route planning	Freight might change transport route or swap vehicle by own decision
Adjust goal	Order management	Freight might changes its destination, according to new orders or changed quality state

In case of an adaptive route planning system a freight item or its software representation could additionally decide to alter the transport route or vehicle if necessary. If the freight item might also change its destination, triggered by new orders or an unexpected quality loss, the maximum degree of decision freedom for an autonomous freight item is reached.

4.2 System Layers

Shifting the autonomy into the network does not necessarily mean to add new hardware layers to the system, but rather equipping an existing layer with enhanced computation facilities so that it will be able to implement decision algorithms. Therefore, cost calculations should be based on the extra costs of additional processing power rather than on the basic costs of the related layer. The possible hardware layers range from item-level tags to powerful servers. The available computation power on the lower levels could be less than 0.1% compared to a PC. **Table 2** gives a summary of these factors as well as the current and future applications on different hardware levels.

In current solutions all information is collected on **server** level. An Object Name Server (ONS) links the Electronic Product Code (EPC) to a related data base. This data base contains an XLM description of the object or ideally even a web-page depicting the object properties and user instructions. Routing problems are commonly also handled at server level as well. A lot of research is being carried out in order to solve vehicle routing problems by multiple agent systems [8], [9].

Several telemetric systems can be currently found on the level of the **means of transport**. Equipped with mobile communication and GPS they measure the temperature, tire pressure and trigger an alarm if the doors are opened outside a specified area where it is allowed.

Supposing that the truck or container is already equipped with sensors and communication, the extra hardware costs for intelligence are about 100 Euro for an embedded processing module. The ARM processor used in our demonstrator for an intelligent container with a clock rate of 400 MHz reaches about 2% of the performance of a PC. An autonomous system on this level could pre-process sensor data or participate in the transport planning process.

Systems below the level of the means of transport have to operate without a fixed energy source; therefore, they are mostly battery powered. One main design goal is to reduce energy consumption in order to extend their lifetime, while communication can be active or passive.

Active devices usually use the ZigBee or the directly the basic IEEE 802.15.4 protocol in the 2.4 GHz range. Alternate proprietary protocols operate at 866 MHz or 433 MHz. This group of devices is comprised by the Auto-ID Labs as EPC class 4 active tags, which can communicate peer-to-peer with other active tags [10]. Tags for container identification, which are partly equipped with an additional temperature sensor, are a common example for the application of active devices.

Other research groups examine small battery powered devices with active communication under the term of **wireless sensor networks**. The focus lays on automated (Ad-hoc) networking and forwarding messages in order to extend the range of communication. The sensor nodes are equipped with an ultra-low-power microcontroller, typically the MSP430 from Texas Instruments. In combination with additional memory resources this processor might also be used as decision platform. Future wireless sensors could provide a spatial supervision of the cargo space so that local deviations of environmental parameters can be detected in time. Because of the components required for active communication and batteries, prices below 10 Euro will be hard to achieve.

Devices with **passive RFID** communication are not restricted to mere identification tasks. Semi-passive tags to record the temperature during transportation are already available on the market [11]. To operate in the absence of the reader field a small battery is required to power the device. The currently available RFID data loggers use the 13.56 MHz HF frequency range with limited reading distance. But UHF devices are expected to be available on the market in 2008. Future intelligent RFID will pre-process sensor data in the chip. The computation power will be even more restricted than in active devices due to the smaller energy budget. Because of the necessary extra components like sensors, processor and battery in addition to passive standard RFID tags, the price cannot go below 1 Euro.

Table 2. System layers as platform for decision processes

Location	Current application	Future applications	Computation power	Basic costs	Extra costs
Server networks	Objects representation by global database	Multi agent vehicle routing	100%	> 1000 €	low
Means of transport	Telemetric supervision, GPS	Intelligent Container	~2 %	< 1000 €	~ 100 €
Active communication devices	Active tags attached to containers	Spatial supervision by wireless sensors networks	~0.1 %	> 10 €	~ 1 €
(semi-) passive RFID tags	Identification / temperature logging	Intelligent RFID	<< 0.1 %	> 1 €	~ 1 €

5 Communication as a Limiting Factor

Wireless communication is one major pre-condition for the ‘internet of things’. Whereas stationary servers can use internet connection almost free of charge, the wireless communication of battery powered devices is restricted in terms of data rate, volume and accessibility. **Table 3** summarizes different types and their limiting factors. Shifting the decision making system from a server level solution into the network of autonomous objects could largely reduce the amount of communication, as well as related risks and costs. Implementation on different hardware layers can be compared by the resulting ‘length of the communication path’.

Passive RFID is the type of communication that is the most sensitive to interferences. Studies on the reading rate of tags mounted on single boxes inside a palette show a high dependency on the product type [12]. Because of the damping of UHF electromagnetically fields by liquids and metals, passive tags could be hardly read inside a palette or container that is packed with foodstuff. Access is only possible offline, at the end of transport. The items are typically scanned by a gate reader during the transshipment of the goods. The RFID tags are only visible for the second that a forklift needs to pass the reader gate during the unloading of the container.

Active devices allow higher reading range and data sizes. But the total volume of communication is limited by the energy budget. Commercial global mobile networks allow almost unlimited transmission of data at the price of higher energy and volume costs.

Table 3. Types and limits of wireless communication for battery powered devices

Type	Range	Limiting factor	Access
Passive RFID	~3 m	Access only during passage through reader gate	Offline
Active Wireless	~ 100 m	Volume limited by energy budget	Permanent
Commercial Networks	Global	Mobile connections costs (GPRS, UMTS, Satellite)	Permanent

The energy consumption of networked objects comprises the following three components: thinking, sensing and communication. Communication is normally the costliest factor; an example calculation for the TmoteSky wireless sensor node [13] shows that sending a message usually uses 16.5 mJ of energy, whereas reading temperature and humidity sensors requires 0.1 mJ and 200 ms of thinking costs 1 mJ [14]. The first aim in system design should be the reduction of communication by data pre-processing. If the costs for batteries and service are taken into account, embedded intelligence could even reduce the hardware costs.

5.1 Communication Sources and Sinks

To be able to compare the advantages of different implementation levels of intelligence in a logistical setting, it is necessary to asses how the shift of data processing to embedded devices affects the communication costs. The whole information path has to be taken into consideration: Which system component provides the data (**source**), who processes them and who needs the results (**data sink**) to execute an appropriate action.

Information sources can be a GPS module, sensors attached to the freight, RFID readers for object identification and traffic or order taking services. The data size ranges from 8 Bytes for a GPS position to several Kbyte (**Table 4**). To evaluate the costs, the data size has to be multiplied by the update rate.

Table 4. Information sources

Type of information	Location of data provision	Data size	Updates per hour
Vehicle location	GPS at truck or container	8 Byte	> 1
Influences to freight quality	Wireless sensors attached to freight or cargo space	~ 10 Bytes per object	>> 1
Object identification	Reader at vehicle or loading platform	16 Byte per object	<< 1
Traffic information	Global or regional information service	~ 1000 Byte	~ 1
New orders	Central or regional order taking service	~ 1000 Byte per order	~ 1

In case of RFID identification, the data is provided on the reader, not on the tag side. The warehouse knows what goods are delivered, but the tag does not know where it is. But it would be possible by some protocol extension to provide the tag with an additional reader identification number or location code.

After assessing dynamic changes in the supply network it could be advisable to change the route of a vehicle or to re-load a freight item to another truck or container. Because an intelligent parcel has no wheels it cannot carry out the recommended action itself. The results of the decision process have to be communicated to the driver of the vehicle, a forklift or the warehouse staff as data destination or sink.

5.2 Length of the Information Path

Most of the criteria to evaluate the performance of the planning process depend directly on the length of the information path from data source over processing to the execution unit:

- Some communication channels could be temporarily unavailable. A short information path increases the robustness of the system. The shortest possible path is found by integrating the decision system into the platform of the information source, its destination or inside an existing network hub between data source and sink. The autonomy of the system is increased if the decision task is divided into sub-tasks that can continue to operate independently if one of the information sources cannot be contacted.
- The outcome of a decision process can be communicated with few Bytes, whereas the required information could comprise the tenth of a Kbyte, e.g. the temperature history of a product combined with traffic information. By shifting the data processing close to the beginning of the information path the total volume and communication cost can be reduced. Data can be pre-processed directly at their point of origin if the related task is separated from the remainder of the decision system.
- The above mentioned points are also important in terms of the flexibility of the system. New information should be quickly communicated through short channels.
- A short information path also increases the level of privacy. The transmission of data over third party networks should be avoided.

The shift of the decision making system onto embedded hardware layers could either shorten or extend the length of the communication path, as the following example shows.

Adaptive planning according to new orders and traffic factors

As first example a transport planning system is considered that is responsible for processing information about new orders and traffic disruptions. Other source of information is the GPS position, available in the vehicle and RFID identification at loading or unloading, available at a door reader mounted inside the vehicle or at the warehouse gate. As data sink the vehicle driver has to be informed about necessary detours. Splitting the decision system into single entities per freight item leads to the idea of the intelligent parcel. It searches at each transshipment point for the next 'lift' by a vehicle that brings it nearer to its final destination. Following principles of existing routing protocols from internet data communication, packages and vehicles decide about the best route only on the basis of information provided by the local and neighboring hubs [15].

The implementation layer of these decision systems could be either inside the vehicle or on servers at the distribution centre or transshipment points. A system on vehicle level has to query traffic and order information from a global service provider, whereas a central decision system can get direct access to traffic and order information. However, it has to contact the vehicle to obtain freight identification and to send the results of the decision. The freight item itself is neither data source nor sink; the implementation of autonomy on this layer would add an additional edge to the information path. In this example the shift of the decision system directly into an intelligent parcel would result in total costs that are even higher than the ones generated by applying the central solution.

Supervision of sensitive goods

If the freight item produces information by itself, the situation is different from the previously described example. The supervision of sensitive goods as in the food sector, for instance produces high amount of data for monitoring deviations of the environmental parameters with local sensors. Even small differences of the temperature can have a major effect on the quality of the product.

Sensor-tags on item level or wireless sensor networks for monitoring the cargo space provide an information source in addition to the example above. The decision system consists of two sub-tasks: Sensor data evaluation and route adaptation. The information path for this scenario is depicted in **figure 1**.

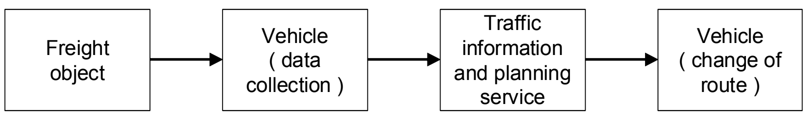

Fig. 1. Information path for the supervision of sensitive goods

The direct pre-processing of the sensor data at their origin by an intelligent parcel could largely reduce communication volume and costs. In another setting the vehicle assesses the data provided by a wireless sensor network. The following second part of this article presents several case studies for the implementation of transport supervision and planning systems for this sensor supervision scenario.

6 The Supervision of Quality Changes

The assessment of quality changes is the most important task for an intelligent freight object in the transportation of sensitive goods. Unfortunately, quality parameters like firmness or taste of fruits cannot directly be measured during transportation. Quality losses can be predicted only by taking the changes in the environmental conditions into account.

6.1 Ubiquitous Sensors

An intelligent object has to measure these conditions with appropriate sensors. Only few sensor types are suitable for integration into ubiquitous devices. The limiting factors are not only costs, but mainly the energy consumption. Temperature and humidity sensors consume the least energy; measurements have only to be taken in intervals of several minutes. Proper ventilation of cooling air can be checked with miniaturized thermoelectric flow sensors. Shock or acceleration sensors are more demanding, they have to operate with a duty cycle of 100%; otherwise they might miss a shock event. Typical metal oxide gas sensors consume the most energy, because heating for several minutes above 300 °C is required until all chemical reactions are balanced.

6.2 Shelf Life Modeling

The quality that is lost by a deviation from the recommended transport conditions depends on its duration and magnitude as well as the individual sensitivity of the product type. Among other parameters like humidity, light and atmosphere the temperature has the largest effect on the quality of food products. These effects are well examined especially in agricultural science.

The 'keeping quality' or 'remaining shelf life' model [16] is based on the Arrhenius law of reaction kinetics. The sensitiveness of some fruits to chilling injuries can be modeled by adding a second Arrhenius function with negative activation energy. The original static model was transferred into a form to calculate the curse of a quality index for fluctuating temperature conditions.

Figure 2 provides the acceleration factor for decay processes as a function of temperature related to a standard temperature (T_{St} = 15 °C). This value indicates how many days of shelf life have to be subtracted from the initial value Q_0 per day of transport at a certain temperature. The description of the quality curve can be compressed into a set of five parameters and stored on an item level tag as additional information. The curves in figure 2 are based on the parameters estimated by Tijskens [16] and Schouten [17].

In cases where the temperature sensitivity cannot be approximated by an Arrhenius type model, the quality changes can be estimated by interpolation of reverence curves [18]. The curse of certain quality conditions has to be recorded under laboratory conditions for several temperatures. To upload the model, the complete curves have to be transmitted to the evaluation device.

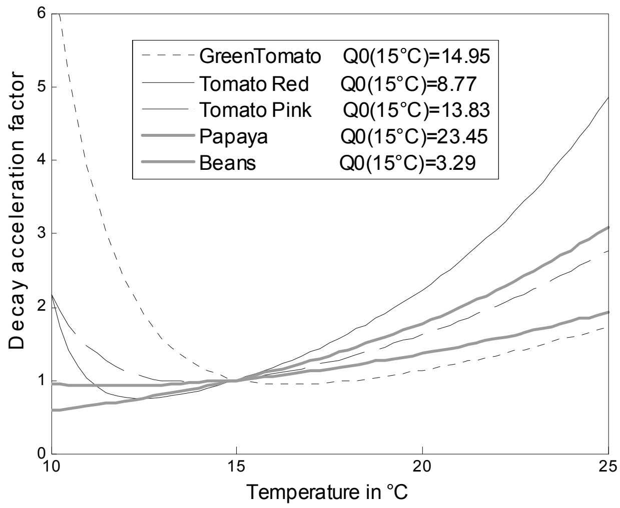

Fig. 2. Relative loss in shelf life in relation to a standard temperature

6.3 The Advantages of Local Sensor Data Evaluation

The major advantage of the localized evaluation of the environmental parameters by shelf life modeling is the minimal data update rate. The processing instance only has to submit a warning message if the quality falls below an acceptance limit or if it foresees a pending quality loss [14]. Instead of the sensor raw data, which needs several updates per hour, only one message has to be sent in case a problem arises. Furthermore, the robustness of the system is increased. The permanent quality supervision can continue during periods when external communication is not available.

7 Processing on Vehicle Level

The first implementation study shows how the pre-processing of sensor data can be realized on the level of the means of transport. Our demonstrator of this ‘intelligent container’ has been described in detail in earlier papers [19], [20]; this section gives a brief summary and relates it to the previous defined criteria to assess the benefits of embedded intelligence.

One key feature is the automatic adaptation of the supervision system to new freight items and their related quality models for specific kinds of goods. In contrast to common solutions the description of freight objects is not stored on a fixed server, but travels in parallel to the physical object through the supply chain. A mobile software agent carries out the individual supervision program on the computation platform of the current means of transport or warehouse.

The hardware of the reduced scale prototype consists of an RFID reader used to scan for new loaded items, a wireless sensor network for spatial supervision of the cargo space, a module for external communication and an embedded processor module as agent platform. If a new freight item is detected, a request is sent through the communication network to receive the corresponding freight agent.

7.1 Communication Path and Costs

The wireless sensor nodes provide as data source the temperature and humidity measurements by active communication. The limiting factor is the battery reserves of the sensor nodes. The processing unit on vehicle or container level compresses this data to single ‘change of quality’ notifications and sends it thorough an external network to the route and transport planning service as data sink.

The system costs mainly comprise single investments into the infrastructure like the processing unit and the wireless sensors belonging to the truck or container. This investment reduces the amount of constant expenses for communication and increases robustness. The additional hardware costs per transport unit consist only of one disposable standard RFID tag per freight item.

7.2 Future Research

One bottleneck is the transmission of the complete sensor raw data from the sensor nodes to the processing unit. Shifting the pre-processing into the sensor network could extend the battery lifetime. The related quality model has to be transmitted to all sensors in the surrounding of the freight item under supervision. Furthermore, the measurement period of the sensors could be adapted to the current situation: if a sensor node detects that it provides exactly the same information as its neighbors, it could set itself into sleep mode.

Another limiting factor is the performance of the agent platform on embedded systems. Although additional optimizations have been carried out on the JADE LEAP (Lightweight Extensible Agent Platform) [21], the transmission of one mobile software agent still takes several seconds. The performance of the supervision software might be increased by switching to another framework like OSGi, formerly known as the ‘Open Services Gateway initiative’ [22], which was developed for industrial applications. Special services for new kinds of products can be remotely installed, started, stopped or updated on the embedded Java runtime of the processing unit of the vehicle or container in form of software bundles.

8 Dividing the Route Planning Process

This section serves as an example for a setting with a higher degree of decision freedom by presenting an approach to how the route planning can be gradually shifted to vehicle level. The vehicle does not only draw conclusions about quality changes by the sensor data but also adjusts its solution for the goal to deliver as many items in proper quality as possible.

This approach depicts a further important aspect of distributed planning processes. Local entities often do not have full access to all information. The following software simulation shows how a processing unit at vehicle level could make best use of limited traveling information provided by a remote server. The route planning process is divided into two instances:

- A remote server holds information about **distances and traveling speed** based on the current traffic situation. This information is public, because it does not contain any confidential data.
- The vehicle assesses the **current quality** of the loaded items. In case of unexpected quality loss the originally planned route has to be modified. This freight state data has to be handled as a confidential piece of information.

Considered for a single vehicle the common task can be categorized as Traveling Salesman Problem with Time Window (TSPTW). The time window for each product starts with zero for immediate delivery and ends with its expiration of shelf life.

For a test case to deliver N_0 perishable items to N_0 different destination towns the route is modified on the basis of the following principle: During the stopovers at the customers the vehicle evaluates for the N undelivered items their remaining shelf life. The vehicle sends a request for a short round trip to cover the N missing towns. The remote traffic information server generates a round trip without accessing product quality data. Based on this proposal the vehicle generates 2*N route suggestions, which enter the round trip at different points and follow it clockwise or counter-clockwise. The route suggestions are assessed based on the degree to which they have fulfilled their goal to minimize the total driving time and strongly avoid zero shelf life products. A first performance test has shown that it is feasible to organize to route planning by this divided planning approach [23].

8.1 Reaction to Dynamic Quality and Traffic Changes

To test the ability to react to sudden quality and traffic changes the test setting has been expanded. Before leaving the depot the freight items are assigned to the vehicles. This first multi-vehicle optimization step can be done by a server at the depot. After leaving the depot the vehicles cannot swap freight items any longer. The traffic information server can only be contacted over mobile communication. After the first two deliveries the shelf life of the remaining items is reduced by an unexpected event. This could be either a change in temperature or a delay by traffic disruptions. The ability of different algorithms to find alternative routes which avoid late deliveries has been tested in software experiments (**Table 5**) for a setting with $N_0 = 20$ customers.

Table 5. Performance of different planning strategies (500 software experiments)

Method	Delivered Packages	Driving time	Improvement
Full re-planning	16.41	76.81 hours	100%
Local vehicle planning	15.66	76.82 hours	64.5%
Repeated vehicle planning	15.75	75.80 hours	68.6%
Unchanged route	14.30	74.68 hours	0%

Without changing the route 14.3 packages in average could be delivered in proper quality. The divided planning approach slightly increases the driving time because of the necessary detours. The number of average delivered items has increased to 15.66

packages. An extensive server based search for the best route gives a result of 16.41 packages. According to these figures the divided planning approach achieved 64.5 % of the possible improvement of the number of properly delivered packages. By allowing the vehicle planner to repeat the route request up to three times in the first step after a disruption, the performance has improved to 68.6 %.

8.2 Evaluation of the Communication Path

Freight quality information is kept completely confidential inside the vehicle. For this kind of data the vehicle is information source, sink and processing unit at the same time. The only piece of external communication is a route request per stop and the server's answer. The size of the answer is about 100 Bytes to transmit the sorted list of towns and the driving distances along a round trip. In case of a communication failure the vehicle can continue its planning based on already known round trips.

Although the performance of the above presented simple algorithm is not fully satisfying, this example depicts typical obstacles and questions of autonomous objects. In cases where the local object does not find an acceptable solution, the object would re-delegate the problem together with all relevant quality information to a server, which has direct access to all traffic data, at the price of higher communication costs and reduced privacy. Limits in communication bandwidth, availability and allowed response time make it in most supply chain application impossible to achieve the same performance as the ideal solution. However, it needs to be questioned whether the object makes use of the available information to the greatest extent. Failures to deliver orders in time should be assessed in the light of certain aspects like flexibility towards dynamic situation changes, robustness against communication failures, hardware and communications costs.

9 Data Processing on Item Level

The idea of data processing on item level is introduced by a study on potential cost saving achieved by extended temperature and quality monitoring. A new approach to warehouse management implements the following principle: Items with low remaining shelf life are sent to nearby stores for immediate sale, whereas items with longer usage expectancy are used for export or distant retail stores. By replacing the standard 'First In First Out' (FIFO) policy with this 'First Expires First Out' (FEFO) approach the amount of waste due to product expiration before delivery is reduced [24].

9.1 Case Study on Strawberries

A case study carried out by Ingersoll-Rand Climate Control and the University of Florida [25] has estimated how much less waste is produced when the above described FEFO approach is used. 24 pallets of strawberries were equipped with temperature loggers. The shelf life was calculated before and after the transport based on the temperature history of each palette. Two palettes were rejected before transport because of their bad temperature history. The remaining 22 palettes had a predicted shelf life between 0 and 3 days at the end of transport (**Table 6**).

Table 6. Waste with and without FEFO approach. Figures according to Emond [26], [18]

Number of palettes	Waste on random retail	Estimated shelf life	FEFO recommendation	Resulting waste
2	100%	-	Reject immediately	(rejected)
2	91.7%	0	Reject at arrival	(rejected)
5	53 %	1	Sell immediately	(25%)
8	36.7%	2	Nearby stores	(13.3%)
7	10%	3	Remote stores	(10%)

After arrival, the truck-load was divided and sent to retail stores with different transport distances. The pallets were opened in the shops; boxes with strawberries of low quality were sorted out. Column 2 of table 6 reports the measured waste grouped by the predicted palette shelf life. The current solution without quality based assignment results in a loss rate between 10% and 91.7% per palette. Column 5 gives the results of a thought experiment: If the palettes were assigned according to a FEFO recommendation to match driving distance and remaining shelf life for each retail shop, the waste could be reduced to 25 % at most. Considered for the whole truck load a loss of 2300 $ could be turned into a profit of 13000 $. If we assume a price of 10 $ per recording unit, the investment for additional hardware is still less than 10% of the profit, even if 4 loggers are attached to each palette.

9.2 Necessity and Feasibility of Data Processing on Tag Level

The above described study has been carried out by manual handling of the data loggers at end of delivery. But this handling has to be converted into an automated process before this approach can be applied in practice. The interface of the data loggers is restricted to passive RFID to enable low cost solutions. But due to the very limited data rate of RFID transmission, it is not possible to transmit the full temperature protocols of several measurement points during unloading. The tags are only visible to the reader for less than a second while the pallets are passed through the gate.

Because of this communication bottleneck, an automated evaluation of the temperature data can be achieved only if the system intelligence is shifted into the network. By on-chip pre-processing the data volume can be compressed into one Byte per item to transmit either the current quality state or just on state bit discerning between ‘green’ as ‘quality state ok’ and ‘red’ as ‘item needs further checking’.

The crucial point in the integration of the shelf life modeling into a semi-passive RFID data logger is the required computation power. The model has to be updated after each temperature measurement. The required calculation time for different shelf life modeling approaches was measured for the low power microcontroller MSP430 from Texas Instruments [18]. For all model types the required CPU time per model step was below 1.2 ms equivalent to an energy consumption of 7µJ per step or 20 mJ per month at an update period of 15 minutes. Compared with the capacity of 80 J for a miniature zinc oxide battery as used in the Turbo-Tag data loggers the energy for model calculation can be neglected. As a CPU facility only a 16 bit integer multiplication is required. The shelf life modeling will add only very low processing requirements to an RFID chip that already contains temperature sensor, clock and data storage. For demonstration purposes the modeling has been programmed into the processor of existing wireless sensor nodes, although this platform is too expensive for commercial applications. The sensor node has been programmed to behave as RFID: on request it transmits its identification code and the current shelf life state.

But future research will enable tags with integrated shelf live modeling as semi-passive devices at reasonable costs and surely reach the business case.

10 Summary and Conclusions

The aim of this paper was to analyze the boundary conditions and consequences of the shift of intelligence to ubiquitous devices. There are already many applications where RFID are used in a beneficial way, but the business opportunities for ubiquitous sensors in logistical applications have not been clearly figured out so far. There are only very few studies available on this topic, but the one quoted in the previous sections indicates that sensing on box or palette level can make a high return on investment.

The central question of this article was to determine in which of the above mentioned cases with a need for ubiquitous sensors and RFID it is worth, to make the additional investment for local intelligence. The implementation of local data analyzes and decision making needs extra computation power. However, the increase in hardware costs for additional CPU resources is still moderate in comparison to the primary costs of active wireless sensors and telemetric units. But communications restrictions related to costs and bandwidth are the major obstacle of the implementation of embedded intelligence. The concept of the ‘length of the communication path’ between information source and sink was introduced as a means to compare the effectiveness of different implementation levels.

The application field of the ‘intelligent parcel’ is mainly limited to settings where a high amount of local information has to be processed, like in the supervision of perishable products. In other applications it needs to be questioned whether it is worth extending the communication path by exchanging information and the results of the decision process with the parcel. This might be only the case when company information should be kept confidential inside the processing unit of the parcel. Other tasks, for instance parts of the route planning, can be better performed on the level of the means of transport.

The implementation of embedded intelligence is most beneficial in cases, where the object not only provides identification but also additional sensor information. Furthermore, there are also cases in which an automated supervision of the transport chain is only feasible if the sensor data is processed by an embedded system as in the example of the intelligent RFID. A share of the processing power, which is required to implement a logistical planning system, was shifted onto objects that are parts of the network. The equipment of logistical objects with embedded intelligence brings advantages in terms of reduced communication costs, higher robustness against communication failures and flexibility to react to unforeseen events.

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