A scenario analysis for evaluating RFID investments in pallet management

Maria G. Gnoni * and Alessandra Rollo

Department of Innovation Engineering, University of Salento, Campus Ecotekne, Lecce, Italy

Abstract. Pallet management, which involves direct and reverse logistic models, may represent a critical activity for logistics provider firms. Pallets are needed in order to ship products from the producers/distributors to the retailers. Recently, pilot projects have demonstrated that performances of pallet management system could be improved by an advance tracking system based on Radio Frequency Identification (RFID). RFID systems can increase effectiveness in acquiring data about properties of any entity – such as pallet – that can be physically identified and traced. In this paper, an effective model, based on the well known Activity Based Costing (ABC) technique, is proposed to evaluate economic feasibility of different design decisions regarding the whole pallet management system of a logistics provider. The model has been applied to different operational scenarios in a real case study. The scenario analysis aims to compare different configurations of pallet management systems based on RFID applications. Results obtained highlight how an RFID application is economically sustainable to reduce the overall cost of pallet management activities in different operational conditions. Finally, based on cost structure previously evaluated by the ABC model, an investment evaluation based on traditional indexes (e.g. ROI, Net Present Value, etc.) has been carried out. Therefore, the integration of the ABC model with traditional investment analysis has improved the effectiveness and the reliability of the feasibility study for evaluating RFID investments in pallet management.

Keywords: Pallet management, RFID application, Activity Based Costing

1. Introduction

In logistics activities, producers, distributors and retailers share a common objective, such as optimization logistic costs. Logistic activities are mainly based on a standardized equipment: the pallet. Several researches are focalized on pallet loading problem, however, reduced attention has been assigned to the overall pallet management process. The reverse logistic of empty pallet usually represents a valuable activity; a recent survey has evaluated the annual volume of palletized load units in Italian logistic market about 600.000 units (Dallari & Marchet, 2007). In brief, all these issues contribute to confirm that pallets represents an important company asset;

*Corresponding author: Maria Grazia Gnoni. Tel.: +39 832297366; E-mail: mariagrazia.gnoni@unisalento.it.
therefore, enterprises have to face with new organizational, economic and managerial issue regarding pallet management.

According to several studies the Radio Frequency IDentification technology could improve supply chain management in several ways (Twist, 2005; Tajima, 2007). RFID is a multipurpose technology referring to the use of radio waves to identify objects in such a context; recently, it has been effectively applied in both manufacturing and logistics context (Kärkkäinen, 2003; Prater et al., 2005; Hou & Huang, 2006; Vijayaraman & O SYk, 2006; Wang et al., 2008). In pallet management, RFID application could support more efficiency: pallet losses – which annually represents about 6% of business turnover of logistic providers (Dallari, 2009) – could be reduced by an advanced tracking system based on RFID technology. Otherwise, though benefits of RFID application in supply chain management are deeply analyzed in the scientific literature, the cost analysis is yet a complex activity as usual for IT investments evaluation (Peacock & Tanniru, 2005).

The purpose of the present paper was to propose an investment analysis model, which could supply an efficient design of a RFID-based pallet management system. The model is based on the Activity Based Costing (ABC) approach; a scenario analysis has been carried out for the model application. Thus, the redesign of pallet management system has been evaluated according to different pallet type (wooden versus plastic) and different information systems (RFID-based and traditional tracing systems); the aim was to evaluate all factors, which could contribute to improve such a performance of pallet management activities. The model application has been developed on a real case study of a logistics provider, which has to evaluate the economic feasibility of different design alternatives for its own pallet management organization.

The paper is organized as follows. At first, a brief review about investment analysis models of RFID applications is reported (paragraph 2). In paragraph 3, it is proposed an analysis of main issues affecting pallet management activities: the aim was to highlight critical factors in those activities, where RFID application could support an economic value addition. Then, the proposed model is detailed in paragraph 4; model application hypotheses and alternative scenario features are detailed in paragraph 5. At last, results obtained are discussed and compared with information supplied by traditional financial indexes (such as ROI, NPV) evaluated according to data supported by the ABC model developed previously.

2. The investment evaluation in RFID applications: A brief review

RFID is a generic technology concept that refers to the use of radio waves to identify objects. Its main advantage is to identify several objects simultaneously without direct contact as traditional identification systems, i.e. optical barcodes. Current request for greater level of automation has forced RFID technology as the leading data capturing procedure in such a context (Kelepouris et al., 2007; Ustündag et al., 2007; He et al., 2008; Prezadovic et al., 2008). An interesting review about RFID application in several industrial fields has been carried out by Tajima (2007). Thus, several applications of
RFID have been recently developed as in manufacturing and distribution of physical goods (Choy et al., 2008; Huang et al., 2008; Abad et al., 2009; Abarca et al., 2009), warehouse (Chow et al., 2006; Zhou et al., 2007; Martinez-Sala et al., 2009; Poon et al., 2009), and inventory management (Wang et al., 2008; Rekik et al., 2009).

On the other hand, RFID technology will have a large financial impact on operations carried out in a supply chain (Twist, 2005); thus, one critical problem is currently to assess key drivers, limits as well as benefits regarding RFID adoption in a specific supply chain (Bhattacharya et al., 2008). According to a literature review developed about investment analysis of RFID applications, three main model types could be highlighted: qualitative, quantitative, or hybrid approaches. Results are classified in Table 1 according to different operational parameters such as application domain, the presence of a real world scenario, etc. Following, a brief analysis of each paper is proposed aiming to highlight advantages and criticalities for RFID investment evaluation.

Qualitative approaches for RFID investment analysis, based on a strategic analysis, are proposed in Sellitto et al. (2007), Tajima (2007), Kim et al. (2008), Katz et al. (2009).

Table 1
Review analysis of RFID investment models

<table>
<thead>
<tr>
<th>Paper</th>
<th>Approach type</th>
<th>Methodology</th>
<th>Application domain</th>
<th>Real world scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sellitto et al. (2007)</td>
<td>Qualitative</td>
<td>A literature content analysis</td>
<td>Retailing</td>
<td>No</td>
</tr>
<tr>
<td>Tajima (2007)</td>
<td>Qualitative</td>
<td>Organisational learning theory</td>
<td>Not specific</td>
<td>No</td>
</tr>
<tr>
<td>Kim et al. (2008)</td>
<td>Qualitative</td>
<td>Survey analysis</td>
<td>Retailing U.S. and Korean firms</td>
<td>No</td>
</tr>
<tr>
<td>Katz et al. (2009)</td>
<td>Qualitative</td>
<td>Survey analysis</td>
<td>Healthcare U.S. and Korean firms</td>
<td>No</td>
</tr>
<tr>
<td>Ustündag &amp; Cevikcan (2007)</td>
<td>Quantitative</td>
<td>Break-even analysis</td>
<td>Inventory management</td>
<td>No</td>
</tr>
<tr>
<td>Deor et al. (2006)</td>
<td>Hybrid</td>
<td>Traditional financial indexes based on survey results</td>
<td>U.S. Army</td>
<td>No</td>
</tr>
<tr>
<td>Hou &amp; Huang (2006)</td>
<td>Hybrid</td>
<td>Cost-benefit analysis based on survey results</td>
<td>Printing industry Turkish courier firm</td>
<td>No</td>
</tr>
<tr>
<td>Oktaysi et al. (2007)</td>
<td>Hybrid</td>
<td>Simulation model and time-driven cost analysis</td>
<td>Distribution processes Turkish courier firm</td>
<td>No</td>
</tr>
<tr>
<td>Bottani &amp; Rizzi (2007)</td>
<td>Hybrid</td>
<td>Traditional financial indexes based on survey results</td>
<td>Distribution processes Retail</td>
<td>No</td>
</tr>
<tr>
<td>Müllner-Seitz et al. (2009)</td>
<td>Hybrid</td>
<td>Survey integrated by a technology acceptance model</td>
<td>Distribution channel of an electronic retailer</td>
<td>No</td>
</tr>
</tbody>
</table>
Sellitto et al. (2007) propose a literature content analysis about RFID adoption within the retail supply chain; the paper is focused on evaluating RFID adoption by an organizational point of view; technological issues have been considered as information attributes (e.g. accuracy, timeliness, etc.). As a result, authors propose a RFID benefits-information value chain to map benefits and information attributes across the whole retailing process. Tajima (2007) proposed a strategic analysis of RFID investments by providing critical examination of its value to achieve firm competitiveness. Based on a literature survey, the author develops a conceptual framework of RFID benefits (i.e. process automation, closed-loop tracking, and supply chain visibility). Then, these benefits are deeply analyzed according to learning organization theory, in order to assess how RFID adoption could contribute to generate and maintain competitive advantages. In Kim et al. (2008) and Katz et al. (2009), results obtained from a survey analysis are proposed aiming to assess strategic performances of RFID adoption in a specific context (retailing and healthcare sector, respectively).

On the other hand, quantitative approaches, proposed in Hou & Huang (2006), Orbayi et al. (2007), Ustundag & Cevikcan (2007), de Kok et al. (2008), are mainly oriented to an operational level rather than qualitative approaches: models are focused on evaluating the economic profitability of a RFID project in a specific supply chain. Ustundag & Cevikcan (2007) described an investment analysis based Return On Investment (ROI) analysis in the distribution sector (i.e. a Turkish cargo firm). Authors compared different operational scenarios for RFID adoption according to specific activities (i.e. cargo and document operations) and tag prices. In de Kok et al. (2008), an investment evaluation model is described in order to evaluate how RFID technology could support to prevent shrinkage (essentially due to theft) in inventory management. A cost-benefit analysis is carried out by comparing potential gains of using RFID systems – essentially in terms of better knowledge on the actual inventory status – with such a criticality (e.g. read errors) occurring after its implementation. Results proposed are in terms of break-even prices of RFID technology; finally, a full factorial design was carried out to analyze the influence of the relevant factors on the break-even prices.

The last category evaluated in the literature review is the hybrid model: usually, these models integrate different type of approaches in order to increase the global effectiveness of the investment evaluation. In Doerr et al. (2006) and Bottani & Rizzi (2007), traditional index methods for investment evaluation are integrated by a survey analysis to improve model effectiveness.

Doerr et al. (2006) proposed an hybrid investment analysis based on traditional indexes, such as the Internal Rate of Return (IRR) and the Net Present Value (NPV), in order to assess economic feasibility of RFID in inventory management at the U.S. Army. The analysis is integrated by a qualitative model, based on a survey analysis, for evaluating several potential benefits of RFID application. Finally, a sensitivity analysis is detailed to evaluate both cost savings and implementation obstacle for an RFID application. In Bottani & Rizzi (2007), a feasibility analysis of RFID adoption
in the Fast-Moving Consumer Goods (FMCG) supply chain is described. At first, a questionnaire survey has been developed to analyse logistics and supply-chain management practices in FMCG supply chains. Then, a supply chain reference model has been defined for evaluating different RFID scenario applications by quantitative indexes such as the Net Present Value, the Internal Rate of Return, the Pay-Back Period (PBP) and ROI index.

Hou & Huang (2006) proposed a cost-benefit analysis of RFID applications in the printing supply chain. Authors apply results supplied from a survey conducted with the dominant players in Taiwan’s printing industry for defining potential field of RFID application in this supply chain. Then, the analysis is carried out by comparing potential benefits (e.g. in terms of time saved and performance increasing) obtained by RFID application to manual and barcode based information systems. Oztaysi et al. (2007) proposed an hybrid model applied to compare performances of barcode versus RFID information systems in a postal courier firm. The simulation model has been integrated by a simplified application of time-driven activity based costing in order to assess quantitative performances of the two scenarios.

Finally, in Müller-Seitz et al. (2009), an evaluation of RFID technology adoption in the retailer sector starting from a customer perspective is described. An analysis carried out by the so called “Technology Acceptance Model” which is a strategic approach frequently applied for evaluating innovative technology tools by a customer. The approach aims to evaluate the level of usefulness of RFID applications in an industrial context. The development of the model has been supported by a specific survey analysis in order to validate the general framework proposed.

Overall, previously analyzed models have highlighted several approaches for facing RFID investments in different applications: when problem complexity arises, review results highlight different approaches have to be integrated for evaluating in a more effective way the economic feasibility of the RFID technology.

3. The pallet management problem: Main issues and organizational scenarios

Pallet management represents a relevant source cost in logistic activity (Indico-ECR, 2006; Creazza et al., 2007); pallets are needed in order to ship products from the manufacturer to the retailers. The most widespread pallet type is the wooden pallet – the so called EURO pallet – which is characterized by unified features defined by the European Pallet Association (EPAL). This standardization activity aims to assess a shared level for quality assurance and inspection standards in pallet management. Different pallet types are mainly made by plastic and aluminium.

Pallet represents an industrial asset like equipment; main services for pallet management start from supply to customers through recovery, reconditioning and final disposal. Main activities involved in pallet management are depicted in Fig. 1. Thus, one of the main cost added activity is the pallet reverse logistic: pallets have to be
collected downstream in the supply chain where products are delivered to final customers. Two organizational procedures are mainly implemented: the direct and the postponed interchange. In the direct interchange, all pallets have been collected by the pallet carrier (the producer or the logistical provider) at the final customer (such as the wholesaler or the retailer) during delivery activities. Therefore, the total delivery time increases due to required interchange activities, such as quality and integrity check of pallets. By an organizational point of view, an identification pallet activity will be carried out by pallet carrier. In the postponed interchange, a fee system is introduced to reduce waiting time of pallet carriers: the final customer supplies a voucher to the pallet carrier for each pallet that is not provided for return to its facility. Pallet recovery activities are usually carried out after collection. In detail, cleaning activities are required by an international Standard for Phytosanitary Measure – the standard ISPM-15 (FAO, 2002) – aiming to disinfect wooden pallets. This treatment is being progressively implemented in several industrial countries including the EU, North America, Canada, Mexico, China, Korea, Australia and New Zealand. Plastic pallet requires a periodic – but not obligatory – cleaning activity. All these activities could be carried out by the producer/distributor directly or by an external service provider (such as a logistical service company). The development of third-party pallet management companies and networks of individual pallet companies provides an efficient way for companies to manage their pallets.

In both the organizational procedures previously described, tracking and tracing pallets during all their operational life represents a cost activity: the quality check and the administrative procedure for pallet order management affects the overall logistic cost. Thus, the application of RFID systems could support an increase in performances obtained by traditional pallet tracing systems. Currently, RFID is rapidly spread for
improving tracking and tracing in several industrial contexts such as logistics. In the field of pallet management, RFID may support an automatic access to information by using fixed, mobile or handheld readers unlike individual scanning; moreover, several different labels could be traced simultaneously as demonstrated by a test project developed at Nestlé and German Metro Group (Sato Europe, 2005). Following, according to this analysis, the development of the proposed model for evaluating overall operating costs in pallet management is discussed.

4. The ABC model for RFID investment evaluation in pallet management

The aim of the paper is to develop a model for evaluating economical sustainability of an RFID application in pallet management. Thus, a general model based on Activity Based Costing (ABC) theory has been developed for assessing overall operating costs of activities involved in pallet management. The ABC approach was introduced by Kaplan and Cooper as an alternative to traditional accounting techniques (Cooper & Kaplan, 1999). This approach refers to activities as a source of resource consumptions: at first, it consists of evaluating costs and performances of all process activities; then, the relationship between activity costs and their resource levels are carried out. Traditionally, the ABC approach has been applied for overcoming such a limit of labour-based cost systems in physical productions. Several studies have focused on application of ABC in manufacturing context as an accounting technique. Pirttila & Hautaniemi (1995) proposed an application of ABC in the distribution warehouse management; while, in Gunasekaran & Sarhadi (1998), it is described a general framework for the ABC implementation in advanced manufacturing systems applied for improving process productivity and quality. In Ozbayrak et al. (2004), an ABC model has been developed to estimate in a more effective way manufacturing costs according to a material requirements planning and/or just in time policy in inventory management of a firm.

Thus, the proposed ABC approach will be applied for supplying a logistics provider an effective evaluation of RFID investments in the design of its own pallet management system. In this case, several decisions variables – such as pallet type, organizational procedure for reverse logistics, etc. detailed in the paragraph 5 – could influence the economic feasibility of such a design alternative. Usually, investments in RFID pallets have to be evaluated in all its effects in process cost analysis to effectively assess their economic performances. Traditional investment evaluation models – such as Return On Investments (ROI), Net Present Value (NPV), etc. – could not be effectively suitable for evaluating innovative IT investments (Peacock & Tanniru, 2005) in complex activities such as a pallet management system.

According to the ABC theory, the model has been developed in three main steps: resource identification, activity and cost driver identification, activity cost evaluation and target cost assignment.

Phase 1 – Resource identification: In pallet management, resources are represented by pallets (i.e. wooden and plastic pallets), warehouse areas, personnel and
the pallet tracing system, whose performances could be improved by an innovative IT infrastructure (i.e. RFID). Pallet transportation systems have been neglected.

**Phase 2 – Activity and cost driver identification:** According to an ABC approach, each process consists of one or more activities defined by their outputs. Then, main activities involved in pallet management have to be deeply analyzed to assess resource consumptions for each activity. In this model, resource consumption for each main activity is evaluated according to their utilization levels, the so called “cost driver”. The proposed model structure is summarized in Table 2 according to cost driver and process activities involved in pallet management which could influence mainly investments evaluation: activity cost evaluations are reported in the last column (i.e. the model equation). Each process activities and cost drivers introduced in the model are described in detail.

**Pallet replenishment:** This activity refers to the annual cost supported for annual pallet park renewal due to breakage or loss. The unitary cost \( \text{CostPP} \) varies according to pallet type (wooden or plastic) and the tracing system; the total purchase cost incurred has been evaluated based on a specific renewal level defined by the firm management.

**Pallet disposal:** Wooden and plastic pallets represent a source for recycling; otherwise, if recycling option is not suitable, pallets have to be disposed as a waste. Wooden pallets have a shorter life cycle than plastic pallets; they are easily disassembled due to their simple designs and standardized part sizes (Bejune et al., 2002). Wooden pallet recycling activity usually provides a secondary material applied as a landscape mulch or a biomass fuel; plastic pallet requires a more complex recycling activity. However, based on the national agreement between ANCI (the National Association of Italian Municipalities) and CONAI (the Italian National Packaging Consortium), secondary materials are valorised by a predefined unitary costs \( \text{CostPD} \).

**Maintenance:** The activity involves all repairing actions – e.g. adding new nails, metal brackets or replacing a broken board – carried out periodically on pallets aiming

### Table 2

<table>
<thead>
<tr>
<th>Activity type</th>
<th>Cost driver</th>
<th>Model variable</th>
<th>Unitary cost [€/pallet]</th>
<th>Model equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purchase</td>
<td>Pp</td>
<td>CostPP</td>
<td>PR = Pp × CostPP</td>
<td></td>
</tr>
<tr>
<td>Disposal</td>
<td>Pd</td>
<td>CostPD</td>
<td>PD = Pd × CostPD</td>
<td></td>
</tr>
<tr>
<td>Maintenance</td>
<td>Pm</td>
<td>CostPM</td>
<td>PM = Pm × CostPM</td>
<td></td>
</tr>
<tr>
<td>Cleaning</td>
<td>Tc</td>
<td>CostTR</td>
<td>TR = Tc × CostTR</td>
<td></td>
</tr>
<tr>
<td>Storage</td>
<td>St</td>
<td>CostAREA</td>
<td>PS = St × CostAREA*</td>
<td></td>
</tr>
<tr>
<td>Reverse logistic</td>
<td>RL</td>
<td>CostPers</td>
<td>RL = RL × CostPers</td>
<td></td>
</tr>
<tr>
<td>Tracking and tracing</td>
<td>Ht</td>
<td>CostPers</td>
<td>PT = Ht × CostPers</td>
<td></td>
</tr>
<tr>
<td>Accounting</td>
<td>Ac</td>
<td>CostPers</td>
<td>AC = Ac × CostPers</td>
<td></td>
</tr>
</tbody>
</table>

*CostAREA is expressed as €/pallet, considering the standard dimensions of EURO pallet \((0.8 \times 1.2 \times 0.1 \text{ m})\) and a maximum height for stacking of 2.5 m.*
to maintain their full functionality as defined by the European Pallet Association, (2009). Maintenance activity affects mainly wooden pallets; usually, plastic pallets could not be repaired, because they are a one-piece design. For a RFID pallet, a specific maintenance activity is the Tag Replacement (TR), which consists of the substitution of the RFID tag on each pallet.

Cleaning: The specific activity depends on pallet type. It mainly consists of the sterilization activity carried out by a specific heat treatment (as reported in paragraph 3) for wooden pallets; a periodic washing activity is carried out for plastic pallets by a specific equipment.

Storage: A percentage of empty pallets needs continuously a dedicated storage areas inside and/or outside the plant. The percentage level (defined by the $S$ variable in the model) depends on organizational procedures for pallet management (i.e. the direct and the postponed interchange).

Reverse logistics: A closed loop system affects pallet management at the wholesaler/retailer level. The variable $H_{RL}$ mainly depends on organizational scenarios applied by the firm for managing the reverse flow of pallets from retailer: if direct interchange is working, pallet quality has to be verified among retailer and pallet carriers. Otherwise, in postponed interchange, usually pallets are stored by the retailer in a dedicated area; thus quality control is reduced because carrier retires its own pallets.

Pallet tracking and tracing: Pallets, like other industrial assets, require an effective control during all their lifecycles; thus, tracking and tracing refer mainly to monitor load and empty pallet trips along the distribution chain. In traditional pallet management systems, the main cost is due to accounting activities required for evaluating the actual number of pallets available in the systems; usually it represents a high management cost. The application of the RFID technology could support a more effective control system: the tag allows to identify in real time where pallets – and products – are located. As a consequence, a reduction of accounting time (i.e. the model variable $H_t$) together with an increase of efficiency could be obtained; a more effective control system based on RFID could also supply a reduction of pallet losses. This activity represents a focal point in the proposed model for evaluating the economic convenience of RFID in pallet management; thus, several sub-activities have been identified in order to effectively evaluate the whole cost detailed as follows:

Pallet information management: Data about pallet availability (both in terms of quantity in the storage areas and at each destination) have to be placed in the Warehouse Management System (WMS); in traditional systems, this represents a high time-requiring activity, that could be reduced by the application of RFID systems. Moreover, pallet management systems based on RFID application requires an additional managing activities to write down in the WMS pallet identification codes. This activity supplies an information reporting system about pallet utilization.

Inspection activities: It regards control carried out by the carrier during both pallet loading and empty pallets returned from end users. These activities are carried out
manually by an operator or semi-automatically by optical barcode readers when RFID technology is not applied in pallet management. RFID application allows to carry out this activity automatically when a pallet crosses an RFID portal.

Accounting: This activity is closely linked to tracking and tracing systems and specific organizational procedures for pallet management applied in the firm. It also includes administrative activities involved in pallet vouchers management if postponed interchange is applied. In the proposed model, the management of legal disputes between actors involved has been neglected.

Phase 3 – Activity cost evaluation and target cost assignment: Activity costs have to be assigned to outputs based on individual output consumption or activity demand. In the proposed model, the main purpose is to calculate total activity costs in order to highlight activities that mainly contribute to the overall cost of the pallet management.

5. The case study

Pallet management can represent a complex issue for logistic providers. The case study for the model application regards an Italian logistic provider which has to evaluate its optimal pallet management organization. The logistics provider carried out all activities involved in pallet management, from pallet park purchase, to tracking and shipping to final customer and, finally, collection and maintenance activities. These activities represent critical points for the firm as its average number of handled pallets are about 2000 per day; currently, pallet park is mainly composed of wooden pallets; tracing and tracking system is manually developed. Aim of the firm is to evaluate the economic feasibility of an investment in innovative system, based on RFID technology, for tracking its own pallet park. RFID application has demonstrated its efficacy in maximizing the pallet utilization as reported by a test project developed by CHEP, the world’s largest supplier of wooden pallets (Roberti, 2004) based on the application of High Frequency (HF) tags. Moreover, the EPAL Association has recently started a pilot project in order to verify performances obtained in identifying pallets by RFID technology; the main purpose is to control pallet quality and, consequently, to reduce maintenance costs (Wessel, 2008). Thus, the logistics provider aims to apply RFID technology in order to both improve customer service by a more efficient tracing of pallet lifecycle and to reduce its own operational cost in pallet management. Traditional investment indexes, such as ROI, NPV, etc., could be not effective in this case, due to both the complexity associated with pallet management issues and to uncertainty connected with RFID benefit evaluation (as described in paragraph 2). Hence, the ABC model previously proposed aims to support a structured economic analysis by evaluating cost drivers, which affect different operational scenarios (i.e. wooden versus plastic pallet, and RFID versus not RFID tracing systems). Increased investment and operational costs due to RFID implementation could be compared by evaluating actual outputs in terms of an increase or a reduction of overall costs. The application of the proposed model aims to highlight in a more effective way – as
compared to traditional index methods – the actual use of resources in a complex IT investment. Moreover, this model could supply an effective tool also for the operational phase by upgrading real data about resource consumption derived from pallet management activity.

Following, scenario hypothesis required for the model application are detailed.

5.1. The scenario definition

Two types of decisions are evaluated in this investment analysis: the first affects the pallet type – i.e. wooden versus plastic pallet; the second type affects the tracking and tracing systems – i.e. traditional versus RFID identification system. Therefore, four different alternatives have been analyzed for evaluating their global economic suitability.

Scenario 1: This represents the current organization of the logistics provider. In this option, wooden pallet are not equipped with RFID systems. Therefore, the logistics provider applies traditional tracking and tracing systems. In this scenario, the evaluated pallet unitary cost is 8.75 (Indico-ECR, 2008a). Wooden pallet lifetime has been assumed as two years (Dallari & Marchet, 2008); this value has been confirmed by the current practise developed by the logistics provider. The reverse logistics option currently applied is postponed interchange with no dedicated storage area at the retailer level, described in paragraph 4; otherwise, for all other scenarios, a direct interchange option with dedicated area has been evaluated.

Scenario 2: Wooden pallet are equipped with RFID systems. Compared to the first scenario, investment costs increase due to the RFID equipment and infrastructure. As an hypothesis, a unitary cost (i.e. 1.5€) has been introduced: in detail, HF tag cost is 0.3€ and its installation cost has been evaluated about 15% of the purchase cost of a wooden pallet. HF passive tags have been evaluated as the optimal solution for the case study as they are less sensitive to liquid or metal contact than UHF (Ultra High Frequency, UHF) and cheaper than active tags. Moreover, Low Frequency (LF) tags have not been considered for this application due to their lower reading rate. RFID equipment and infrastructure costs are detailed in Table 3: investment costs (regarding RFID hardware, middleware and software) are amortized over a five year period and annual maintenance costs has been considered as a constant percentage (i.e. 15%) of investment costs. As reported in Table 3, the RFID maintenance and annual investment amortization contribute quite equally in the annual operational cost (i.e. about 43% and about 57%, respectively).

Scenario 3: The park is composed by plastic pallets, which are not equipped with RFID systems. Investment costs increase due to the high price of pallet purchasing. Usually, plastic pallet price could varies according to their quality (CHEP, 2009); in the present application, the unitary cost has been evaluated as 20€. Plastic pallet are characterized by a higher lifetime compared with wooden pallets. Thus, in the model application has been considered a lifetime of two years for wooden pallets and five years for plastic pallets by considering 20 rotations/year (MHM Staff, 2009).
Table 3
RFID equipment and IT infrastructure costs

<table>
<thead>
<tr>
<th>Equipment and infrastructure</th>
<th>Quantity</th>
<th>Unitary cost [€/unit]</th>
<th>Total cost [€]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 HF Gate composed by</td>
<td>10</td>
<td>4,020</td>
<td>40,200</td>
</tr>
<tr>
<td>Reader HF</td>
<td>1</td>
<td>2,200</td>
<td>2,200</td>
</tr>
<tr>
<td>Antenna HF</td>
<td>2</td>
<td>260</td>
<td>520</td>
</tr>
<tr>
<td>Sensor</td>
<td>1</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>Traffic light</td>
<td>1</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Monitor</td>
<td>1</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Installation</td>
<td>1 day</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>Portable readers</td>
<td>5</td>
<td>750</td>
<td>3,750</td>
</tr>
<tr>
<td>Middleware and software</td>
<td></td>
<td></td>
<td>45,000</td>
</tr>
<tr>
<td>software application</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total cost</td>
<td></td>
<td>88,950</td>
<td></td>
</tr>
<tr>
<td>Amortization amount</td>
<td></td>
<td>17,790</td>
<td></td>
</tr>
<tr>
<td>Hardware maintenance</td>
<td></td>
<td>6,593</td>
<td></td>
</tr>
<tr>
<td>Software maintenance</td>
<td></td>
<td>6,750</td>
<td></td>
</tr>
<tr>
<td>Annual cost</td>
<td></td>
<td>€31,133</td>
<td></td>
</tr>
</tbody>
</table>

**Scenario 4:** In this last option, **plastic pallets are equipped with RFID systems.** Investment cost required for RFID equipment and its infrastructure is equal to scenario 2 (see Table 3); plastic pallet unitary cost has been increased (i.e. 1.5€), compared to scenario 3, as previously described for the scenario 2.

Main data characterizing the examined case study are:
- the pallet park is composed of 10,000 units;
- pallets average handled by the logistics provider are 2,000 per day (i.e. the 20% of the whole pallet park);
- the annual horizon consists of 300 work-days;
- the cost of pallet disposal is considered negligible as it’s rewarded by revenues from recycling activities carried out by the firm.

5.2. The model application

Cost driver variables have been defined according to the model described in paragraph 4.

Main model variables (i.e. $P_p$, $P_m$, $T_r$, $P_c$ and $S_t$) have been expressed as a predefined percentage of the total number of pallets according to current practices realized by the logistic provider. For each scenario, model parameter values estimated in the case study are reported in Table 4; following, a brief description of values applied for model development. The $P_p$ variable level decreases from 2,000 pallet/year to 1,000 pallet/year in scenario 4: it affects the annual cost for park renewal. Two main factors have influenced this issue: firstly, by comparing scenario 2 and 4, the application of RFID technology could support a reduction of pallet loss (Roberti, 2004); moreover, the pallet quality affects its replenishment rate, which has been evaluated as 10% for wooden pallet and 3% for plastic pallet.
Table 4
The ABC parameter values estimated for the model application

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Pallet number</td>
<td>10,000</td>
<td>10,000</td>
<td>10,000</td>
<td>10,000</td>
</tr>
<tr>
<td>Resource cost (€/year)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CostPP</td>
<td>8.75</td>
<td>10.25</td>
<td>20.00</td>
<td>21.50</td>
</tr>
<tr>
<td>CostPM</td>
<td>3.00</td>
<td>3.00</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>CostTr</td>
<td>0.00</td>
<td>1.50</td>
<td>0.00</td>
<td>1.50</td>
</tr>
<tr>
<td>CostPC</td>
<td>5.00</td>
<td>5.00</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>CostAREA (€/pallet)</td>
<td>2.30</td>
<td>2.30</td>
<td>2.30</td>
<td>2.30</td>
</tr>
<tr>
<td>CostPers (€/h)</td>
<td>15.00</td>
<td>15.00</td>
<td>15.00</td>
<td>15.00</td>
</tr>
<tr>
<td>Cost driver</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pp (pallet)</td>
<td>2,000</td>
<td>1,700</td>
<td>1,300</td>
<td>1,000</td>
</tr>
<tr>
<td>Pm (pallet)</td>
<td>-400</td>
<td>-400</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Tr (pallet)</td>
<td>0</td>
<td>27,900</td>
<td>0</td>
<td>9,300</td>
</tr>
<tr>
<td>Pc (pallet)</td>
<td>100</td>
<td>100</td>
<td>10,000</td>
<td>10,000</td>
</tr>
<tr>
<td>HAc (hour)</td>
<td>100</td>
<td>60</td>
<td>80</td>
<td>60</td>
</tr>
</tbody>
</table>

*Maintenance activities have not been evaluated for plastic pallet.

Maintenance costs, as defined in Table 4, are not been evaluated for plastic pallet: it has been supposed that repair activities could not be easily realized on these pallets as they are usually one-piece designed. The level of variable $P_m$ has been evaluated as a fixed percentage (i.e. 4%) of the whole pallet park dimension, according to data supplied by the firm.

Tag replacement activity cost has been assessed according to this hypothesis: for plastic type, tags are replaced once a year for effectively collected pallets (i.e. the pallet loss has been evaluated); for wooden pallet, the value is three times a year, i.e. once for each shipping. Consequently, a total amount of 27,900 and 9,300 pallets have been considered for scenario 2 and 4 respectively; moreover, total annual costs depend on unitary cost due to purchasing and installation activities (detailed in the previous paragraph).

Cleaning activity costs vary from wooden and plastic pallet. For the first type, annual cost depend on the sterilization process (described in detail in paragraph 3) cost. According to case study data, a small percentage of total Pallet number requires this treatment; thus, the level of $P_c$ has been evaluated as low percentage (about 1%). On the other side, plastic pallets require usually a cleaning activity carried out once in a year; all pallet are involved in this activity (i.e. the $P_c$ value is 10,000 in scenario 3 and 4).

Reverse logistics cost varies according to pallet management scenarios: thus, lower costs incur if a dedicated storage area is organized. For storage level evaluation, a predefined level (10%) of the whole park dimension has been defined in 2 and 4 scenarios. This level decreases (4%) in the scenario 1 and 3, where postponed interchange and no dedicated area is applied.
Labour cost evaluation depends on two main activities, as described in paragraph 4: pallet information management and inspection activities. An Excel model simulation\(^1\) has been carried out for evaluating resource consumptions required by each sub-activity in each different scenario.

6. Results analysis

Results of the ABC application in the case study are reported in Table 5 for each operational scenario. Results show that the first scenario (i.e. the current applied by the logistics provider) is characterized by the highest overall cost for the whole pallet management system, i.e. 231.213\(\text{€}\); the scenario 4 (i.e. plastic pallets with a RFID-based tracking and tracing system) is characterized by the lowest overall cost (158.291\(\text{€}\)).

Next, alternative scenarios have been analyzed according to the cost structure developed according to the ABC proposed model. Firstly, the introduction of RFID technology constantly determines a reduction of overall costs: the reduction cost is about 31% by comparing scenario 1 with 4; a lower (about 15%) reduction is observed by comparing scenario 1 and 2 as scenario 2 is characterized by higher investment costs. This issue is less effective when plastic pallets are considered: a minor (about 3%) reduction could be evaluated by comparing scenario 3 and 4 respectively. In this case, investment costs differ slightly for the two scenarios.

Moreover, the other scenario variable – i.e. pallet type – strongly affects the total cost of pallet management system: a reduction in overall costs is highlighted by comparison wooden versus plastic pallet scenarios i.e. scenario 1 and 3, and scenario 2 and 4 respectively. In detail, for non-RFID scenarios (scenario 1–3), the reduction is

<table>
<thead>
<tr>
<th>Cost [€]</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Park purchase</td>
<td>43.750</td>
<td>51.250</td>
<td>40.000</td>
<td>43.000</td>
</tr>
<tr>
<td>RFID equipment and infrastructure</td>
<td>0</td>
<td>17.790</td>
<td>0</td>
<td>17.790</td>
</tr>
<tr>
<td>Indirect</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Replenishment</td>
<td>8.750</td>
<td>8.713</td>
<td>5.200</td>
<td>4.300</td>
</tr>
<tr>
<td>Maintenance</td>
<td>1.200</td>
<td>1.200</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Tag Replacement</td>
<td>0</td>
<td>41.850</td>
<td>0</td>
<td>13.950</td>
</tr>
<tr>
<td>Cleaning</td>
<td>500</td>
<td>500</td>
<td>5.000</td>
<td>5.000</td>
</tr>
<tr>
<td>Storage</td>
<td>922</td>
<td>2.304</td>
<td>922</td>
<td>2.304</td>
</tr>
<tr>
<td>Reverse logistic</td>
<td>111.266</td>
<td>45.261</td>
<td>45.261</td>
<td>45.261</td>
</tr>
<tr>
<td>Tracking and tracing</td>
<td>63.325</td>
<td>12.443</td>
<td>63.325</td>
<td>12443</td>
</tr>
<tr>
<td>RFID system maintenance</td>
<td>0</td>
<td>13.343</td>
<td>0</td>
<td>13.343</td>
</tr>
<tr>
<td>Accounting</td>
<td>1.500</td>
<td>900</td>
<td>1.200</td>
<td>900</td>
</tr>
<tr>
<td>Overall cost of pallet management system</td>
<td>231.213</td>
<td>195.553</td>
<td>162.289</td>
<td>158.291</td>
</tr>
</tbody>
</table>

\(^1\) The Excel function applied is the \(\text{casual}(b-a)+a\) with \((a, b)\) interval of number generation.
about 30%; for RFID scenarios, a lower reduction (about 19%) is observed; this is mainly due to the effect of a reduction in reverse logistics costs evaluated when direct interchange and dedicated storage are applied. Thus, the application of the proposed ABC has pointed out hidden costs (i.e. for pallet reverse logistics) currently not effectively evaluated by the firm: results show that the interchange time consumption at the retailer level is lower if pallets are stored in a dedicated area; thus, the pallet carrier retires its own pallets thus reducing time to localize and control their quality. Moreover, the application of RFID technology could also contribute to reduce this lead time. In this model application, it has to be noted that dedicated area at the retailer level does not determine additional costs.

Finally, after the ABC model application, traditional financial indexes could be easily evaluated as critical activities and their total costs have been deeply analyzed by the ABC model. Usually, as described in the literature review, the evaluation of these indexes requires actual information about costs and benefits connected to the investment in analysis. Thus, the NPV, the PBP, the Internal Rate of Return (IRR), and the ROI evaluation has been estimated for last three scenarios as incremental costs compared with the scenario 1, as it represents the current option applied by the firm. The index analysis has been developed according to the approach proposed by Bottani & Rizzi (2008). The ROI evaluation is based on the following equation:

\[
\text{ROI} = \frac{\text{Total savings}}{\text{Investment}}
\]

where the benefit is expressed by total cost savings compared to the baseline (i.e. scenario 1). The actualization rate applied for investment evaluation is 6% (IndicoECR, 2008b).

Results for 2, 3, and 4 scenarios are reported in Tables 6–8, respectively. Annual investment reported in each table regards IT system maintenance and pallet replenishment, according to analysis carried out in the ABC model.

Analogously to the results obtained by the ABC model, scenarios characterized by plastic pallet option (3 and 4) determine highest values for the NPV analysis (122,791€ and 102,399€). Otherwise, scenario 2 is characterized by the lowest PBP (2.52 years), the highest IRR value (34.18%) and the highest ROI value (62.42%). It has to be noted that these results are not characterized by a general validity, as they are obtained under such an hypothesis evaluated for the specific case study.

In conclusion, for the specific application of this case study, investment analysis pointed out that RFID application in pallet management could support an overall system performance increase; furthermore, several parameters – such as pallet life time, reverse logistics organization – have to be evaluated in a feasibility study. Thus, the case study application has pointed out hidden costs not currently evaluated by the logistics provider. Moreover, the application of the proposed model has supported a more effective analysis of the investment alternatives than traditional index analysis: indexes usually supplies more synthetic evaluation while information required level is quiet high as the ABC approach. The case study application has highlighted that the
Table 6: Traditional investment analysis for scenario 2

<table>
<thead>
<tr>
<th>Year</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discount rate</td>
<td>1.00</td>
<td>0.94</td>
<td>0.89</td>
<td>0.84</td>
<td>0.79</td>
<td>0.75</td>
</tr>
<tr>
<td>Cost savings</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maintenance</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Tag Replacement</td>
<td>-41,850</td>
<td>-41,850</td>
<td>-41,850</td>
<td>-41,850</td>
<td>-41,850</td>
<td>-41,850</td>
</tr>
<tr>
<td>Cleaning</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Storage</td>
<td>-1,382</td>
<td>-1,382</td>
<td>-1,382</td>
<td>-1,382</td>
<td>-1,382</td>
<td>-1,382</td>
</tr>
<tr>
<td>Reverse logistics</td>
<td>66,006</td>
<td>66,006</td>
<td>66,006</td>
<td>66,006</td>
<td>66,006</td>
<td>66,006</td>
</tr>
<tr>
<td>Tracking and tracing</td>
<td>50,881</td>
<td>50,881</td>
<td>50,881</td>
<td>50,881</td>
<td>50,881</td>
<td>50,881</td>
</tr>
<tr>
<td>Account management</td>
<td>600</td>
<td>600</td>
<td>600</td>
<td>600</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>Total savings</td>
<td>74,254</td>
<td>74,254</td>
<td>74,254</td>
<td>74,254</td>
<td>74,254</td>
<td>74,254</td>
</tr>
<tr>
<td>Initial investment</td>
<td>103,950</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual investment</td>
<td></td>
<td>13,268</td>
<td>13,268</td>
<td>13,268</td>
<td>13,268</td>
<td>13,268</td>
</tr>
<tr>
<td>Amortization</td>
<td></td>
<td>18,800</td>
<td>18,800</td>
<td>18,800</td>
<td>18,800</td>
<td>18,800</td>
</tr>
<tr>
<td>Gross margin</td>
<td></td>
<td>55,454</td>
<td>55,454</td>
<td>55,454</td>
<td>55,454</td>
<td>55,454</td>
</tr>
<tr>
<td>Taxes</td>
<td></td>
<td>14,851</td>
<td>14,851</td>
<td>14,851</td>
<td>14,851</td>
<td>14,851</td>
</tr>
<tr>
<td>Net profit</td>
<td></td>
<td>40,604</td>
<td>40,604</td>
<td>40,604</td>
<td>40,604</td>
<td>40,604</td>
</tr>
<tr>
<td>Net cash flow</td>
<td></td>
<td>-103,950</td>
<td>46,136</td>
<td>46,136</td>
<td>44,404</td>
<td>46,136</td>
</tr>
<tr>
<td>Discounted cash flow</td>
<td></td>
<td>-103,950</td>
<td>46,136</td>
<td>46,136</td>
<td>44,404</td>
<td>46,136</td>
</tr>
</tbody>
</table>

NPV (€) 88,937  
PBP [years] 2.52  
IRR [%] 34.18  
ROI [%] 62.42  

The construction of the ABC model requires a significant computational effort (both for information acquisition and in the model structure development) but it supplies efficient analysis on actual cost drivers which could influence actually the economic feasibility study. This evaluation is essential when complex activities – i.e. pallet management – and, also, innovative IT tools – i.e. RFID application – are involved.

7. Conclusion

IT investment evaluation can usually represent a complex activity due to such intangible factors; complexity increases when innovative IT technology – such as Radio Frequency Identifications – are applied. Traditional models for investment evaluation lack in assessing all costs along a common metric. Thus, more accurate cost information models are emerging based on both quantitative and qualitative approaches. In the present paper, authors propose an Activity Based Costing (ABC) model for evaluating RFID investments in pallet management. The model has been applied in a real case study concerning a logistics provider, which has to evaluate economic feasibility of the pallet management system re-design. Two design variables have been evaluated.
Table 7: Traditional investment analysis for scenario 3

<table>
<thead>
<tr>
<th>Scenario 3: plastic pallet without RFID</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>Discount rate</td>
</tr>
<tr>
<td>Cost savings</td>
</tr>
<tr>
<td>Maintenance</td>
</tr>
<tr>
<td>Tag Replacement</td>
</tr>
<tr>
<td>Cleaning</td>
</tr>
<tr>
<td>Storage</td>
</tr>
<tr>
<td>Reverse logistic</td>
</tr>
<tr>
<td>Tracking and tracing</td>
</tr>
<tr>
<td>Account management</td>
</tr>
<tr>
<td>Total savings</td>
</tr>
<tr>
<td>Initial investment</td>
</tr>
<tr>
<td>Annual investment</td>
</tr>
<tr>
<td>Amortization</td>
</tr>
<tr>
<td>Gross margin</td>
</tr>
<tr>
<td>Net cash flow</td>
</tr>
<tr>
<td>Discounted cash flow</td>
</tr>
<tr>
<td>NPV (€)</td>
</tr>
<tr>
<td>PBP [years]</td>
</tr>
<tr>
<td>IRR (%)</td>
</tr>
<tr>
<td>ROI (%)</td>
</tr>
</tbody>
</table>

by a scenario analysis: pallet type (wooden versus plastic) and the pallet tracking and tracing system (traditional versus RFID-based system). The model application has allowed to evaluate computational effort required for its development. In this case study, the highest time-consuming activity has been represented by determining cost drivers; otherwise, activity identification has required less effort. Several data have been evaluated according to current firm experience; other data have been evaluated according to literature review or by a specific simulation model. A critical activity has been represented by the pallet reverse logistics: currently, the firm has no data about time and resource effectively managed in this specific task; thus, an excel simulation model has been developed in order to evaluate data for cost analysis.

Results supplied by case study application highlight the proposed model has provided an effective way to clearly allocate costs of a RFID implementation in alternative scenarios; moreover, potential benefits are introduced in the model as cost savings. After the feasibility evaluation carried out by the ABC model, traditional financial indexes has been calculated in order to integrate the feasibility study. The application of the ABC model has heavily supported this analysis by supplying more reliable data for developing index calculations. The proposed application has shown effective
Table 8
Traditional investment analysis for scenario 4

<table>
<thead>
<tr>
<th>Year</th>
<th>Discount rate</th>
<th>0.99</th>
<th>0.94</th>
<th>0.89</th>
<th>0.84</th>
<th>0.79</th>
<th>0.75</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cost savings – Cost arising</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maintenance</td>
<td>1.200</td>
<td>1.200</td>
<td>1.200</td>
<td>1.200</td>
<td>1.200</td>
<td>1.200</td>
</tr>
<tr>
<td></td>
<td>Tag Replacement</td>
<td>-13,950</td>
<td>-13,950</td>
<td>-13,950</td>
<td>-13,950</td>
<td>-13,950</td>
<td>-13,950</td>
</tr>
<tr>
<td></td>
<td>Cleaning</td>
<td>-4.500</td>
<td>-4.500</td>
<td>-4.500</td>
<td>-4.500</td>
<td>-4.500</td>
<td>-4.500</td>
</tr>
<tr>
<td></td>
<td>Storage</td>
<td>-1,382</td>
<td>-1,382</td>
<td>-1,382</td>
<td>-1,382</td>
<td>-1,382</td>
<td>-1,382</td>
</tr>
<tr>
<td></td>
<td>Reverse logistic</td>
<td>66,006</td>
<td>66,006</td>
<td>66,006</td>
<td>66,006</td>
<td>66,006</td>
<td>66,006</td>
</tr>
<tr>
<td></td>
<td>Tracking and tracing</td>
<td>50,681</td>
<td>50,681</td>
<td>50,681</td>
<td>50,681</td>
<td>50,681</td>
<td>50,681</td>
</tr>
<tr>
<td></td>
<td>Account management</td>
<td>600</td>
<td>600</td>
<td>600</td>
<td>600</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td></td>
<td>Total cost/savings</td>
<td>98,854</td>
<td>98,854</td>
<td>98,854</td>
<td>98,854</td>
<td>98,854</td>
<td>98,854</td>
</tr>
<tr>
<td></td>
<td>Initial investment</td>
<td>216,450</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Annual investment</td>
<td>17,343</td>
<td>17,343</td>
<td>-52,658</td>
<td>17,343</td>
<td>17,343</td>
<td>17,343</td>
</tr>
<tr>
<td></td>
<td>Gross margin</td>
<td>59,854</td>
<td>59,854</td>
<td>59,854</td>
<td>59,854</td>
<td>59,854</td>
<td>59,854</td>
</tr>
<tr>
<td></td>
<td>Taxes</td>
<td>19,771</td>
<td>19,771</td>
<td>19,771</td>
<td>19,771</td>
<td>19,771</td>
<td>19,771</td>
</tr>
<tr>
<td></td>
<td>Net profit</td>
<td>40,084</td>
<td>40,084</td>
<td>40,084</td>
<td>40,084</td>
<td>40,084</td>
<td>40,084</td>
</tr>
<tr>
<td></td>
<td>Net cash flow</td>
<td>-216,450</td>
<td>61,741</td>
<td>61,741</td>
<td>131,741</td>
<td>61,741</td>
<td>61,741</td>
</tr>
<tr>
<td></td>
<td>Discounted cash flow</td>
<td>-216,450</td>
<td>58,246</td>
<td>54,940</td>
<td>110,612</td>
<td>48,905</td>
<td>46,137</td>
</tr>
<tr>
<td></td>
<td>NPV [€]</td>
<td>102,399</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PBP [years]</td>
<td>4.05</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>IRR [%]</td>
<td>13.13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ROB [%]</td>
<td>45.67</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Further development could be focused on evaluating effects of different organizational scenarios (such as pallet pooling and postponed interchanged) aiming to assess how RFID application could contribute to reduce their operational costs.

Acknowledgements

Authors are grateful for improvements suggested by reviewers and the editor.

References


Correlating distributed RFID-based event data for logistics process monitoring

Kerstin Werner∗, Alexander Schillb and Jan Scheibea

aSAP Research Center Dresden, SAP AG, Dresden, Germany
bInstitute for System Architecture, Technische Universität Dresden, Dresden, Germany

Abstract. Decreasing sizes and a static decline in production costs are fostering the use of RFID tags and sensors in cross-company logistics networks. The EPCIS specification comprises interface standards for capturing and querying RFID based event data and its exchange in a standardized data format. Additionally, modern technologies for event processing enable novel event based applications whose potentials have not been precisely examined in this context so far. Our contribution covers this issue by exploring the utilization of the given technologies for the monitoring of complex inter-organizational logistics processes. The monitoring should detect contract violations, product shrinkage and counterfeiting. We introduce requirements for the monitoring of individual quality objectives and process constraints using distributed event data. In consideration of these, we propose a monitoring system architecture and argue that it can nearly seamlessly be integrated into existing EPCglobal compliant RFID infrastructures. Furthermore, we estimate the value of event processing technologies in addressing the given requirements and identify challenges in application design.

Keywords: EPCIS, logistics monitoring, event processing

1. Introduction

The RFID technology is currently used in combination with sensor technologies in intra and inter-organizational settings to capture identification and status data of trade items whereas inter-organizational applications are still in their early development. To foster their adoption among multiple industries, the industry-driven standardization organization EPCglobal develops and ratifies standards to enable cross-company RFID application scenarios and to overcome problems caused by heterogenic RFID infrastructures. Complex logistics processes exhibit a predestined utilization context for these standards. They comprise combined point-to-point transportation and distribution or consolidation processes of goods between partners in a logistics network. The superior objective is to move goods along supply chains by complying with specific requirements concerning conditions of goods or the transportation process itself.

∗Corresponding author. Kerstin Werner, Chemnitzer Straße 48, 01187 Dresden, Germany. Tel.: +49 351 4811 6134; Fax: +49 6227 78 46912; E-mail: kerstin.werner@sap.com.

1754-5730/10/$27.50 © 2010 – IOS Press and the authors. All rights reserved
These conditions cover for example times or locations of departure and delivery as well as quantities of transported items. They mainly result from customer needs, competitive pressure or laws. We refer to these requirements as Service Level Objectives (SLOs) which are negotiated and defined on an individual shipments and transportation legs base. Logistics Service Providers (LSPs) have to ensure the compliance with several SLOs during logistics process execution. To realize this, they negotiate dedicated contracts with subcontracted carriers. These contracts are called Forwarding Instructions. They serve as a basis for documents called Waybills which are used as accompanying documents for transported trade items by carriers. Besides these quality objectives, several other matters have to be considered. For example, counterfeit products expose significant problems in a wide range of industries, especially food, pharmacy, and textile. In addition, shrinkage and theft during transportation results in considerable monetary losses every year and thus has to be minimized and recognized by appropriate measures (International Chamber of Commerce, 2004; Sharma, Subramanian & Brewer, 2008).

RFID related event data is currently used for Tracking and Tracing applications (Agrawal, Cheung, Kailing & Schonauer, 2006) to monitor SLOs associated with transportation processes and transported goods. Unfortunately, these applications are either proprietary developments or require the availability of complex message infrastructures. These imply extensive integration efforts and thus cannot be provided and maintained easily by small or medium enterprises within dynamically changing logistics networks. Furthermore, they are restricted to the evaluation of single events against thresholds and thus neglect the potential of continuously correlating multiple event data for the monitoring of more complex SLOs. To benefit from this potential, efficient mechanisms to integrate event data from distributed EPCglobal compliant RFID infrastructures have to be developed and combined with mechanisms that correlate it to business relevant monitoring information (Werner, 2008; Werner & Schill, 2009a). Currently, it has been mainly investigated to apply this approach to enable automatic fraud and counterfeit detection or to provide transparent product traces (Staake, Thiesse & Fleisch, 2005; Ilic, Andersen & Michahelles, 2009). These application areas primarily require the evaluation of static rules or queries on event data to detect certain patterns. They differ from the monitoring of transportation processes because this application would require the evaluation of mostly individual queries on event data to detect the success or violations in respect of individual SLOs. The suitability of utilizing modern event processing technologies for the near real time information detection in this logistics context has not been examined in detail so far. Nevertheless, manifold research in event based systems has been performed for many years already. Concerning event processing architectures in particular, there are currently many approaches available which mainly differ in their realization as either central or distributed systems (Tarkoma & Raatikainen, 2006). Diverse research prototypes have been developed. Unfortunately, most of them are not available for further enhancements. Furthermore, their design cannot be sufficiently extended for the utilization in the application context considered in this work. For example, it does
Our contribution investigates the design of a system for the near real time monitoring of individual SLOs during transportation process execution with respect to existing interface and data format standards. Furthermore, we focus on the development of mechanisms to integrate distributed RFID based event data and to correlate it to detect anomalies such as product duplicates or shrinkage during the execution of complex transportation processes. In this context, we follow our objective to investigate mechanisms to integrate the technologies introduced in this section. In addition, we examine their potential for the monitoring of multiple individual SLOs by evaluating many queries on large amounts of events. Our results judge the value of the technologies considered for this specific utilization and give insights into several challenges in the design of respective monitoring applications.

The remainder of this paper is structured as follows: Section 2 introduces the application context and illustrates the requirements a monitoring system has to meet. In Section 3, a monitoring system architecture and its components are presented which address the given requirements. Section 4 gives an overview of the existing prototypical implementation and Section 5 comprises its validation by the realization of a concrete use case scenario. Related work in this area is presented in Section 6. Section 7 summarizes our work and gives an overview about future work directions and objectives.

2. Requirement analysis

This section describes the utilization context of a monitoring system based on distributed RFID event data as well as the requirements it has to address.

2.1. Utilization context

The event based monitoring system is intended to be applied in the context of transportation processes within diverse industries such as the pharma and the textile industry or in cool chain scenarios as they are already applying the RFID technology in cross company settings. In addition, they represent examples of industries which have to meet multiple quality requirements driven by laws and customers. Transportation processes cover the point to point movement of goods as well as their consolidation and distribution within a supply chain. Furthermore, they comprise the packing and unpacking of goods to different levels of aggregation (e.g. packets, pallets or containers).

Besides the companies involved in transportation processes along a respective supply chain, there is often an LSP who organizes and coordinates the transport and the subcontracted carriers which are responsible for the actual transportation of goods. An LSP has to manage multiple individual transportation processes concerning process structure and associated SLOs. Together with other companies participating in
a logistics network, he wants to monitor negotiated quantities of goods and their status as well as times and locations. Furthermore, he wants to be informed about process executions anomalies if detected, e.g. if a delivery has been picked up at a certain location and has then been delivered at another location without being processed at an obligatory quality checkpoint in between. For that, he can utilize a monitoring system which integrates and correlates event data stored in different EPCIS Repositories to evaluate the compliance with specified SLOs.

To enable such a monitoring, carriers use vehicles (trucks and ships) equipped with RFID readers that periodically capture RFID data and pass it to a respective event repository. Readers can be statically installed at multiple locations along supply chains, like goods issue or goods receipt gates, or dynamically moving with transportation vehicles to capture data of tagged goods. Goods can be equipped with tags storing a unique identifier called Electronic Product Code (EPC) which allows for the unique identification of goods within the EPCglobal Network. A detailed description of the structure and semantics of this data format is given in (EPCglobal Inc., 2008). Additionally, sensors can be applied to capture humidity data which is accessed and linked to the respective EPCs when goods pass an RFID reader. Furthermore, each partner in a supply chain can host an event repository which stores associated RFID event data. These repositories comply with the EPC Information Services Specification (EPCglobal Inc., 2007) ratified by EPCglobal which includes interfaces for capturing and querying RFID based event data in a specified data format. Software systems implementing these interfaces and data formats are called EPCIS Repositories. They represent databases with interfaces for inter-organizational access and exchange of EPC related event and meta data. Data stored in such repositories is enriched with information about an objects business context, location and condition at the time of detection by an RFID reader. Fig. 1 illustrates the utilization context.
described and depicts a monitoring system which integrates RFID event data and processes it to evaluate certain SLOS.

2.2. Requirements

The monitoring of transportation processes according to individually defined SLOs supports LSPs with their management of complex logistics processes and allows participating partners to be informed about problems or succeeded deliveries immediately as well as to react accordingly. A system which supports such a scenario has to address the requirements described in the following.

2.2.1. Fine-grained description of individual SLOs (R1)

The LSP has to be provided with fine-grained and easily extensible description mechanisms for the SLOs which are to be monitored. Furthermore, logical operators like the negation, disjunction or conjunction of SLOs have to be representable in a way which can be automatically processed by the monitoring system. An appropriate data format has to be provided and respective documents have to be put in a dedicated document repository which can be accessed by the monitoring system.

2.2.2. Representation of contract dependencies (R2)

Documents containing SLOs like Forwarding Instructions and Waybills are dependent of each other. Waybills contain the SLOs for one single transportation leg and are based on exactly one Forwarding Instruction document. As complex transportation processes consist of multiple transportation legs, the monitoring of the SLOs contained in one specific Forwarding Instruction document requires the monitoring of potentially many Waybills. This is why these dependencies have to be made explicit in the respective documents and accessible by the monitoring system.

2.2.3. Integration of distributed RFID event data (R3)

The use case described in Section 2.1 introduced three companies between which goods are shipped and which capture RFID based event data as shipments travel along and store it in their EPCIS Repositories. This data has to be integrated by the monitoring system of the LSP for further processing which could be realized by sending queries to the EPCIS Repositories of interest. In response, only relevant event data is sent to the monitoring system in near real time.

2.2.4. SLO based monitoring instructions generation (R4)

SLOs are individually negotiated for each transportation process. Therefore, monitoring instructions have to be defined in the form of event patterns or synonymously event queries (Luckham, 2002) frequently. They are then processed by the monitoring system to determine whether a process is executed compliant with specified SLOs or not. The syntax and semantics of monitoring instructions have to be expressive enough to evaluate the compliance to typical SLOs within transportation processes.
Their definition has to be executed automatically. A manual definition done by users would imply too high expectations on their programming skills and would not scale due to the high number of transportation processes which are to be coordinated within short time intervals (Werner & Schill, 2009b).

2.2.5. Processing of monitoring instructions and events (R5)

The processing and matching of automatically generated event patterns with the event data gathered from distributed EPCIS Repositories has to be performed by an appropriate event processing engine. Especially, it has to process multiple event patterns on large amounts of event data. The system is intended to monitor many transportation processes at one time, while the number and complexity of event patterns to be evaluated per process varies with the SLOs to be monitored. There are currently several commercial and academic solutions available which already serve this need, e.g. Streambase (StreamBase Systems, Inc., 2009), Esper (EsperTech, 2009), cayuga (Brenna et al., 2007), and Coral8 (Coral8, Inc., 2009). These processing engines correlate and combine event data resulting from different sources according to given event patterns. They create notification events if patterns are matched with a certain set of incoming event data. Then, either a violation or a successful fulfillment of a specific SLO has been detected.

2.2.6. Management of monitoring results (R6)

The monitoring system produces results in the form of notification events which mainly correspond to the output of the installed event processing engine. The system has to support two kinds of output: instantaneous notifications and historical log files. The historical log files have to be persistently stored in combination with the associated SLO descriptions. This allows for the later processing or exchange of this data.

2.2.7. Notification of external business applications (R7)

The monitoring system has to provide mechanisms to notify external business applications if an SLO violation or its successful fulfillment has been detected. For example, the producer in our use case might wish to be informed about any failure during the transportation process to send substitutes immediately. Therefore, the system has to expose an interface which can be accessed by applications to subscribe to certain kinds of notifications. They would be informed by the monitoring system as soon as a respective notification occurs.

2.2.8. Minimal integration efforts (R8)

The integration effort of the monitoring system into existing EPCglobal compliant RFID infrastructures has to be kept at a minimum. This implies that interfaces and data formats specified by EPCglobal have to be supported to allow users with compliant infrastructures to utilize the system with minimal efforts in time and costs.
3. Conceptual design

This section describes the architecture of a monitoring system which integrates event data from distributed EPCIS Repositories to automatically monitor individual SLOs as well as consistent process execution and addresses the requirements defined in Section 2.2. Fig. 2 gives an overview of its components and their interactions which are described in more detail in the following. There are two areas distinguished in the figure which could be referred to as external system components like data sources and accessing applications and the inner monitoring system. An accessing application might be a Web Frontend for direct access to the monitoring system which would be
used by an LSP. Or it might be a Business Application like a planning tool which could be hosted by the monitoring systems owner or partner companies which want to be informed about certain monitoring results. Furthermore, EPCIS Repositories and the Document Repository are considered to be external system components as well. The EPCIS Repository contains RFID based event data gathered during transportation process execution and offers access to it. It is hosted by each partner company of a supply chain which wants to capture data related to trade items. The Document Repository is hosted by an LSP and offers access to stored Forwarding Instructions or Waybills which are inserted by LSPs or carriers after negotiations. The contained documents are called Extended UBL Documents. They are instances of an extension of the Uniform Business Language (UBL) document standard we developed to enable fine-grained SLO and dependency descriptions between several documents. UBL is a standard which allows for the XML representation of common business documents. It is driven by the non-profit consortium Organization for the Advancement of Structured Information Standards (OASIS). The Document Repository and the extension of the UBL XML schema address the requirements R1 and R2.

The monitoring system in the center of Fig. 2 is subdivided into three logical parts: Data Integration, Event Correlation and Output Management. The Data Integration part includes system components that gather relevant information from external information sources and prepare it for further processing. The SLO Handler is activated when an accessing application initiates the monitoring of a specific transportation process. It queries the Document Repository to extract the relevant Waybills for all transportation legs of the given transport process. It uses the documents returned to determine the expected duration of the process, the involved partner companies and one or more EPCs of the goods included in the shipment which is to be monitored. This data is sent to the Event Gathering component. Furthermore, the SLO Handler extracts SLO descriptions from Waybill documents and sends them to the Monitoring Instructions Generator. The Event Gathering component addresses requirement R3. It receives data from the SLO Handler which identifies the relevant EPCIS Repositories which have to be queried to receive event data according to the monitoring of a specific shipment. Event data stored in EPCIS Repositories can either be queried by ad-hoc queries with immediate responses or by so called Standing Queries (Subscriptions). These Subscriptions for specific queries are internally stored by the EPCIS Repository and are evaluated periodically within a given time interval. Event data which matches a specific query is sent to the requesting application. Thus, the Event Gathering component sends event queries as Subscriptions to the EPCIS Repositories of interest which persist during the expected time of the transportation process and are deactivated afterwards. Captured event data is sent to the Event Gathering component and transferred to the Event Processing Engine.

The Event Correlation is the second logical part of the monitoring system. It includes the Monitoring Instructions Generator component which addresses requirement R4. This component uses data submitted by the SLO Handler to automatically create monitoring instructions which can equally be referred to as event patterns.
Event patterns describe correlations of a set of single events to complex events with new semantics. To evaluate whether the duration of the transportation of a certain shipment does not exceed 24 hours after the departure from its origin (see use case in Section 2.1), it has to be searched for an event indicating the departure and an event indicating the final arrival at the shipment’s destination. Additionally, it has to be examined if the time interval between the time of departure and the time of arrival is less than 24 hours to infer that this SLO has been met. Monitoring instructions have to express this event correlation and constraints information. Operators supported by common event pattern description languages include disjunctions, conjunctions, negations or temporal sequences and periods. Our architecture design proposes a processing of patterns and event data by an Event Processing Engine which relates to requirement R5. The Event Processing Engine receives event patterns produced by the Monitoring Instructions Generator and matches them against incoming event data from the Event Gathering component. The processing of events can be performed by one of the implementations introduced in Section 2.2. The Event Processing Engine generates notification events and sends them to the Output Manager if event patterns are matched by sets of certain events.

The third logical part of the monitoring system is the Output Management which addresses the requirements R6 and R7. The system produces historical and instantaneous monitoring data. Historical monitoring data is stored in an internal database by the Output Manager and can be queried by eligible users or applications. Instantaneous monitoring notifications are produced by the Event Processing Engine. They are sent to accessing applications by the Output Manager which beforehand evaluates Subscriptions stored in its internal database to discover which applications have to be informed and where to send the notifications.

For clarity reasons, Fig. 2 does not depict any interfaces which are used by the system components to expose and access functionality. Thus, we would like to give a brief textual overview of the available interfaces which in addition address requirement R8: The EPCIS Repository implements the interfaces specified in (EPCglobal Inc., 2007). These include the Query Interface to provide access to stored event data for eligible applications and the Capture Interface which can be accessed by appropriate RFID middleware solutions to send RFID based event data to a Repository. The Document Repository implements a Control Interface to allow users to store, delete, and update documents which are validated against the extended UBL XML schema. Furthermore, it implements a Query Interface which allows applications (e.g. the monitoring system) to access certain documents or document parts given a unique identifier. The monitoring system itself implements a Query Callback Interface which is accessed by an EPCIS Repository when event data is sent according to a Subscription. Additionally, it implements a Query Interface which can be addressed by accessing applications like a Web Frontend of an LSP or other Business Applications. This interface enables them to send ad hoc queries for historical monitoring data or to submit Subscriptions for certain kinds of notification events which are then returned as soon as they are detected by the monitoring system. To receive such
instantaneous notification events an accessing application has to implement a **Query Callback Interface** which can be accessed by the monitoring system.

4. **Prototypical implementation**

Our work on this topic is still in progress but we have implemented almost all of the system components introduced in Section 3 to validate our concepts and evaluate them. We have currently finalized our work on the UBL XML schema extension for fine-grained SLO descriptions. Our extension comprises a set of so called **Basic Components** which add useful SLOs to the ones already contained in the original UBL schema, e.g. statements for the description of humidity constraints. Second, our extension includes **Aggregate Components** which cover operators like AND, OR, NOT to enable the logical combination of SLOs and to allow for more powerful semantics. Fig. 3 depicts an example SLO description using our extended XML schema. It indicates that measured humidity values must not exceed 75% during the transportation of a specific shipment. In addition, Fig. 4 exhibits an example SLO which requires a certain shipment to be delivered at its destination within 24 hours after its departure.

We set up a Document Repository which implements the interfaces introduced in Section 3 and stores document instances which validate against our XML schema. Furthermore, the Event Gathering component has been prototypically implemented to integrate RFID-based event data. It implements a Query Callback Interface and sends Subscriptions to multiple distributed EPCIS Repositories defining a time schedule when the Repository should periodically process the submitted query. The syntactical

```xml
<estac:SLO>
  <estac:Expression>
    <estac:Term operation="LessThanOrEqual">
      <estac:Humidity unitCode="percent">75</estac:Humidity>
    </estac:Term>
  </estac:Expression>
</estac:SLO>
```

Fig. 3. SLO example: Humidity requirements.

```xml
<estac:SLO>
  <estac:Expression>
    <estac:Term operation="LessThanOrEqual">
      <estac:Duration unitCode="hr">24</estac:Duration>
    </estac:Term>
  </estac:Expression>
</estac:SLO>
```

Fig. 4. SLO example: Shipment duration.
The query requests any event having the type specified in the parameter `eventType` and the EPC contained in the parameter `MATCH_anyEPC` whose value is `$contract.epc_of_delivery` contained in a particular EPCIS Repository. `contract` indicates that the values required are obtained from the transportation contract which is to be monitored. Events resulting from this query are sent to the URL submitted in the parameter `dest` whereas `config` refers to a system-wide accessible properties definition. An EPCIS Repository executes a query according to the time intervals specified in the parameter `controls`. This parameter has to reflect the estimated start and end time of the transportation process which is to be monitored. Furthermore it has to define the frequency a query has to be evaluated. This frequency could be configured using the system-wide available properties as well.

We use an open source EPCIS Repository implementation by Fosstrak (Auto-ID Labs, 2009) in version 0.4.2 which runs in Apache Tomcat version 5.5 or higher to model a distributed environment and to query and store event data. This implementation requires the storage of events in a MySQL database using MySQL version 5.0 or higher. The event data stored in EPCIS Repositories is produced by a simulation tool. This tool allows for the simulation of product flows in complex supply chains with multiple RFID readers which capture event data as products move along. The simulation tool is able to access the Capture Interface of an EPCIS Repository to send simulated event data. The events which are received by the Event Gathering component are sent to the Event Processing Engine. We use Esper version 3.0 for this processing because it provides an open source solution. It represents a good example of currently available event processing engines according to its performance and the complexity of its provided Event Pattern Language (EPL). EPL is an SQL-like language with SELECT, FROM, WHERE, GROUP BY, HAVING, and ORDER BY clauses. PATTERN is also available to provide a language construct missing in SQL which is specific for event processing. The Event Processing Engine produces notification events. They are structured as depicted in Fig. 8 and sent to other applications by the Output Manager. Besides a unique identifier, each notification event has an attribute called `eventTime` which indicates its time of creation, e.g. by an RFID reader or the Event Processing Engine. An event is classified by the value of `eventType` which

```java
subscribe(queryName="SimpleEventQuery",
params={'eventType':'"ObjectEvent",
        "AggregationEvent", "QuantityEvent",
        "TransactionEvent"},
MATCH_anyEPC='$contract.epc_of_delivery',
dest:$config.url,
controls=create($contract, $config),
subscriptionID=$config.autoinc)
```

Fig. 5. Subscription query for a specific set of events.
The eventContext stores pairs of names and values (propertyNames and properties) which enables the combination of complex context information with a certain event. This allows for the enrichment of notification events with information about their origination. Together, the attributes sourceType and sourceLocation refer to an internal or external system component which produces events, e.g. a specific EPCIS Repository or a particular Event Processing Engine. The field complex indicates whether an event is complex, which means that it results from the correlation of a set of other events. Complex events have a list of children attached which refer to the respective set of correlated events.

5. Validation and evaluation of results

To validate and evaluate our work we realized a use case from the pharma industry. The structure of the respective transportation processes and the underlying supply chain relates to the information given in (Müller, Poepke, Urbat & Zeier, 2009). Corresponding to this, a generalized view on the pharma supply chain distinguishes four tiers consisting of manufacturers (first tier), wholesalers (second and third tier) and retailers (fourth tier). The wholesalers are responsible for extensive quality checks and thus have to unpack and pack the goods and sell them either to the next wholesaler or a retailer. To move the goods between these four tiers, three carriers are required. We chose fictitious numbers of transported goods and the overall time used for their actual transportation. The respective transportation process was modeled with a dedicated tool we developed for the generation of EPCIS events. This tool allows us to model random product shrinkage and temporal deviations as well. The resulting events and their types are listed in Table 1 according to the activities executed by the participating stakeholders during the transportation process. For clarity reasons, ObjectEvents are denoted by OE and AggregationEvents by AE respectively. All together, there were 80 events generated per transportation process and we simulated 100 processes. The event data was captured in five EPCIS Repositories with each representing one of the different stakeholders, whereby we assumed the carriers sharing one repository. Furthermore, we assumed the presence of five Accessing Applications which are interested in the notification events produced by the system.

We build monitoring instructions with the Esper EPL to detect violations considering the expected duration of the process, the sequence of planned activities and quantities of transported goods. Fig. 6 shows such an EPL query which detects whether a shipment which has been picked up at the Manufacturer has been delivered at the Retailer within 48 hours. A second example query is depicted in Fig. 7. It observes whether a certain shipment is actually transferred via the second wholesaler to ensure that the goods pass the quality checkpoint. This is based on the assumption that the detection of certain objects by an RFID reader serves as an evidence for their presence at the reader’s location. A notification event triggered by one of the event queries described would indicate an inconsistent process execution according to the SLOs and the process structure originally planned.
Table 1

<table>
<thead>
<tr>
<th>Stakeholder (events per process)</th>
<th>Activity</th>
<th>Event type</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer (4)</td>
<td>Register package</td>
<td>OE</td>
<td>ADD</td>
</tr>
<tr>
<td></td>
<td>Pack 20 packages per box</td>
<td>AE</td>
<td>ADD</td>
</tr>
<tr>
<td></td>
<td>Pack 100 boxes to 1 pallet</td>
<td>AE</td>
<td>ADD</td>
</tr>
<tr>
<td></td>
<td>Register pallet at goods issue</td>
<td>OE</td>
<td>OBSERVE</td>
</tr>
<tr>
<td>1. Carrier (20)</td>
<td>Periodically register pallets on truck</td>
<td>OE</td>
<td>OBSERVE</td>
</tr>
<tr>
<td></td>
<td>Register pallet at goods receipt</td>
<td>OE</td>
<td>OBSERVE</td>
</tr>
<tr>
<td></td>
<td>Unpack pallet</td>
<td>AE</td>
<td>DELETE</td>
</tr>
<tr>
<td></td>
<td>Register boxes</td>
<td>OE</td>
<td>OBSERVE</td>
</tr>
<tr>
<td>1. Wholesaler (5)</td>
<td>Pack 100 boxes to 1 pallet</td>
<td>AE</td>
<td>ADD</td>
</tr>
<tr>
<td></td>
<td>Register pallet at goods issue</td>
<td>OE</td>
<td>OBSERVE</td>
</tr>
<tr>
<td>2. Carrier (20)</td>
<td>Periodically register pallets on truck</td>
<td>OE</td>
<td>OBSERVE</td>
</tr>
<tr>
<td>2. Wholesaler (7)</td>
<td>Register pallet at goods receipt</td>
<td>OE</td>
<td>OBSERVE</td>
</tr>
<tr>
<td></td>
<td>Unpack pallet</td>
<td>AE</td>
<td>DELETE</td>
</tr>
<tr>
<td></td>
<td>Unpack boxes</td>
<td>AE</td>
<td>DELETE</td>
</tr>
<tr>
<td></td>
<td>Register packages</td>
<td>OE</td>
<td>OBSERVE</td>
</tr>
<tr>
<td></td>
<td>Pack 20 packages per box</td>
<td>AE</td>
<td>ADD</td>
</tr>
<tr>
<td></td>
<td>Pack 100 boxes to 1 pallet</td>
<td>AE</td>
<td>ADD</td>
</tr>
<tr>
<td></td>
<td>Register pallet at goods issue</td>
<td>OE</td>
<td>OBSERVE</td>
</tr>
<tr>
<td>3. Carrier (20)</td>
<td>Periodically register pallets on truck</td>
<td>OE</td>
<td>OBSERVE</td>
</tr>
<tr>
<td>Retailer (4)</td>
<td>Register pallet at goods receipt</td>
<td>OE</td>
<td>OBSERVE</td>
</tr>
<tr>
<td></td>
<td>Unpack pallet</td>
<td>AE</td>
<td>DELETE</td>
</tr>
<tr>
<td></td>
<td>Unpack boxes</td>
<td>AE</td>
<td>DELETE</td>
</tr>
<tr>
<td></td>
<td>Register packages</td>
<td>OE</td>
<td>OBSERVE</td>
</tr>
</tbody>
</table>

select * from pattern [every ObjectEvent{
  a.epList.epc='urn:epc:salmon:123',
  a.readPoint.id='urn:epc:gothenburg',
  a.readPoint.id='urn:epc:gothenburg:goodsIssue'
} ->timer:interval(24 hours) and not ObjectEvent{
  b.epList.epc='urn:epc:salmon:123',
  b.bizLocation.id='urn:epc:rostock',
  b.readPoint.id='urn:epc:rostock:goodsReceipt'}]  

Fig. 6. Example EPL pattern: Shipment duration.

select * from pattern [ObjectEvent{
  a.epList.epc='urn:epc:salmon:123',
  a.bizLocation.id='urn:epc:rostock:goodsReceipt',
  a.readPoint.id='urn:epc:gothenburg',
  and ObjectEvent{
    b.epList.epc='urn:epc:salmon:123',
    b.bizLocation.id='urn:epc:rostock:goodsReceipt',
    b.eventTime < a.eventTime}
}]

Fig. 7. Example EPL pattern: Structural constraints.
We validated our queries by running our queries on the event data stored in the EPCIS repositories and retrieving the notification events expected. Apart from the queries which were supposed to detect product shrinkage there were no problems caused by our monitoring instructions. Therefore, we confirm our assumption of EPCIS events being semantically expressive enough to be a basis for the monitoring of transportation processes and typical SLOs in this area of application. But still, the problems detected by the monitoring of quantities result from the multiple packing and unpacking activities which are common during transportation process execution. Once a package is packed to a box, it is listed in an attribute called childEPCs of any following AggregationEvent. The packing of the box on a pallet results in the box being listed in this attribute until it is unpacked again. Till then, there is no information about the packages contained available in the events captured and thus cannot be validated against expected quantity thresholds. A solution to this might be the limitation of EPL queries which are supposed to evaluate product quantities to QuantityEvents only. Then, they would exclusively process events of this specific type as they occur.

Besides the validation of our queries, we analyzed the performance of the event processing engine by executing our specific queries on the EPCIS events we generated. The tests were run on a standard PC with an Intel Core 2 Duo 6600 processor and a 2.4 GHz, 4 GB RAM and Windows Vista as operating system. We worked with an Event Gathering component which queried all events stored in the EPCIS repositories at one time and sequentially published them in amounts of 500 events per second to the event processing engine. We challenged the event processing engine by increasing the number of queries which were to be executed in parallel. The queries used where always an identical copy of one static test query. The results are given in Fig. 9. They indicate that the number of queries executed by the engine significantly influences its
performance. In particular, the throughput of events halves as the number of queries doubles. It varies from about 23,500 events per second with one query executed to 60 events per second with 1,000 queries executed. We executed the tests several times, each time using a different query. In the sense of relational algebra, our queries exclusively consist of projection and selection statements. Thus, the utilization of different queries did not effectuate different results. Still, we suppose the incorporation of complex set operations in the queries to negatively influence the performance of the event processing engine. An event based system for the monitoring of transportation processes is supposed to process multiple queries on incoming event data at one time without intensively slowing the systems performance. With respect to our experiments it requires the utilization of appropriate mechanisms to filter, separate and route events through the system to limit the amount of event data which is to be processed. The approaches suggested in (Bittner & Hinze, 2004) provide value for the design of such mechanisms to enhance the performance of a system for the event based monitoring of logistics processes.

6. Related work

The monitoring of individually negotiated quality objectives of transportation processes is nowadays practically performed by a multitude of logistics tracking applications (Schmid & Brockmann, 2006). These tracking applications do often require message infrastructures implying immense integration efforts or are proprietary implementations. Thus, they are not applicable for the utilization in dynamic co-operations within complex logistics networks. Furthermore, they are mainly restricted to large enterprises and not affordable by small or medium enterprises (Huvio, Görmvall & Främling, 2002; Karkkainen, Ala-Risku & Främling, 2004; Hillbrand & Schoech, 2007). Research in this area does mainly concentrate on the cool chain industry (Miron & Eisen, 2004). It is often investigated how data could be efficiently captured using sensor or Auto-ID technologies and how it can be stored in software
systems. The correlation of resulting event data to more complex information is not considered. Furthermore, it is often assumed that relevant data is stored centrally and cross-company usage scenarios are not examined.

Already well established approaches to perform long term evaluations regarding the compliance of service providers with concrete Key Performance Indicators (KPIs) are supported by Data Mining mechanisms on data stored in huge Data Warehouses (Immon, 1992; Foerster, Engels, Schattkowsky & Van Der Straeten, 2007; Hornung, 2008). These mechanisms can be applied to RFID based event data. They differ from our approach in their potentially redundant representation of stored data and in their long term character by allowing high response times due to very complex computations. This is mainly due to the long term character of KPI definitions which is unlike the short term intention of SLOs for transportation processes.

Some approaches aim to detect anomalies in distributed event data in near real time (Dada & Thiesse, 2008; Ilic, Andersen & Michahelles, 2009). In this context, anomalies suggest the presence of counterfeit products. Other approaches investigating the monitoring of certain quality objectives do mainly work with fixed policy descriptions (Crisan & Rantzau, 2008; Michlmayr, Rosenberg, Leitner & Dustdar, 2008). They support our architecture design for an event based monitoring system. However, they do not consider the automatic generation of processing instructions like event patterns based on these policies which is essential for practical adoptions. Due to this, current research motivates the investigation on approaches to the automatic generation of event patterns in event processing applications (Wang, Liu, Liu & Bai, 2006; Zang & Fan, 2007; Ammon, Ermersberger & Springer, 2008). Unfortunately, existing work does mainly consider domain specific events which cannot be transferred to the context of our work. In addition, it rather comprises precise problem analyses and research motivations than applicable solutions.

7. Conclusion and future work

In this contribution we argued that current standards-compliant RFID infrastructures, technologies for event correlation, and XML based business document standards enable service oriented logistics monitoring applications that require less integration efforts than existing tracking solutions. This is reflected by our investigation on mechanisms that build upon the EPCglobal Framework to automatically integrate and use distributed RFID based event data for the monitoring of transportation processes. The actual processing of relevant event data to evaluate the compliance with specified SLOs and to monitor process consistence can be performed by modern event processing technologies. These require enhancements with mechanisms to automatically generate event patterns based on objectives which are to be monitored. In Section 2 we have introduced additional requirements a monitoring system needs to fulfill referring to a brief use case. Afterwards, we presented a conceptual design of an architecture (Section 3) addressing these requirements and proposed mechanisms that integrate and correlate event data to perform the monitoring of transportation
processes regarding to specific SLOs. Our architecture design seamlessly integrates into standards compliant infrastructures and thus enables its utilization as well as the monitoring of logistics processes by many industries with minimal integration efforts.

To validate our concepts, an ongoing prototypical implementation of the system components described is presented. The syntax and semantics of the events stored in EPCIS Repositories covers exactly the information needed to evaluate the compliance of a given transportation process with specified SLOs. The monitoring system integrates this data by processing its structure as well as accessing and implementing the interfaces which are specified in the EPCIS Specification (EPCglobal Inc., 2007). We validated the suitability of applying technologies for event processing in the respective application context by successfully realizing a use case scenario. Due to that, the system approach complements the vision of EPCglobal by using the given infrastructure to derive business relevant information and putting cross-company distributed event data in a new context. However, our experiment indicated, that the execution of multiple queries at one time on incoming events can slow down the systems performance significantly. This needs to be appropriately reflected by the systems design. According to the Design Science methodology described in (Hevner et al., 2004) this insight will be reflected in future design and prototyping phases. In addition to this, our future work will focus on the development of an algorithm to automatically generate event patterns based on given SLO descriptions. To support the notification of external business applications as event patterns are detected by the monitoring system, we want to refine our event model by additional types of events which directly indicate certain kinds of notifications. By means of such a data model which has to be exchanged between co-operating companies, external applications will be able to immediately process notifications as they are received. Additionally, we are continuously engaged in developing the prototypical implementation of our concepts. The prototype will be used for further evaluations of our concepts. So far, the evaluation of our work is limited to the utilization of simulated event data. Therefore, we aim to evaluate the systems behaviour by the utilization of event data which was captured during the execution of real transportation processes. Then, we could for example analyze the influence of missing or distorted event data on the monitoring results.

References


System design by simulation – A case study for sensor tags embedded in tyres

Frank Deicke a,*, Hagen Grätz a and Wolf-Joachim Fischer b

a Wireless Communication, Fraunhofer IPMS, Dresden, Germany
b Institut für Halbleiter- und Mikrosystemtechnik, Dresden University of Technology, Dresden, Germany

Received 6 July 2009
Revised 27 September 2009

Abstract. The implementation of ID functions and sensors in a tyre has been discussed intensively for some time past. Such an intelligent tyre is necessary to identify the manufacturer and the type of the tyre. Additionally, physical parameters of the tyre can be measured during use to warn the driver against possible damages or to test different tyres in a lab. The RFID technique is one possibility to realise such an application. During system design, there is a big challenge to answer at least two important questions. The first one is if the system would work with the selected antenna shapes, sizes and positions. And the second one is, which antenna design is more advantageous than others depending on power consumption of the tag, rim shape, size and material as well as using a steel cord in the tyre or not. Answering those questions in a correct way, within an appropriate amount of time and without doing a lot of prototyping is very difficult, because there are relations between electrical and electromagnetic models that must be considered carefully. This paper will focus on these challenges. It will show a way to analyse an inductively coupled transponder system that can be used for such an application. And it presents an approach for modelling and analysing the transmission channel as well as the electrical system behaviour including the influence of a metal rim and the steel cord. Additionally, a discussion is done concerning business value of such a design flow considering different RFID applications with other application specific requirements but finally the some challenges on system design.

Keywords: RFID design, transmission channel modelling, sensor tag, tyre

1. Introduction

RFID transponder systems are used in various applications. There are tags for wireless identification and tags that are able to store extended object information. But there are also tags including a data logging function or a sensor. The design of a transponder system is divided into different parts. These are the design of the transmission channel,
the analogue front ends, the digital protocol units and the application itself. Designing analogue front ends and digital protocol units is very challenging, but it can be done independently of particular applications mostly. There are many vendors providing powerful IPs, ICs or software packages. Designing antennas and optimising the transmission channel are more influenced by particular applications. Thus antenna shapes, sizes as well as antenna positions depend on maximum space available at reader and tag, carrier frequency, requested link distance and antenna material as well as the environment, where the system should be implemented. Because of that, general purpose antennas can not be used in most of these application scenarios. Furthermore, antenna design has very strong impact on system performance like maximum link distance, maximum energy transfer with a fixed link distance or reliable and error free communication between tag and reader. But it is very difficult to find a good solution for the antennas and its positions, because it is not sufficient only to maximise the self and mutual inductances. Instead, it is necessary to find an optimum considering electrical system properties like driver strength and demodulator input sensitivity of the reader as well as minimum transponder voltage and power consumption of the tag besides general requirements of the application.

Today, many solutions are found using a lot of design experience, making numerical simulations for the antennas and verifying it in the lab using prototypes. That standard design flow could be a very time consuming and expensive way because of producing many prototypes and using complex measuring setups in the lab to characterise the transmission channel. Additionally, it is not sure that the best solution found is the optimum available, because the parameter space for optimisation and analysis is very large and multidimensional.

A first system success design approach based on software tools for system analysis and optimisation including automatic parameter variation and model generation seems to be more sufficient. So, important questions like if a specific application would work using RFID technique or how to dimension and position antennas can be answered qualitatively and quantitatively on a virtual level without doing prototyping. This design approach could be less time consuming and less expensive as well as provide better results to work with. To show this, a case study was done to analyse the implementation of an inductively coupled transponder system in a car or truck tyre.

The identification of a car or truck tyre with respect to manufacturer, type and mileage as well as the measurement of physical parameters like pressure, temperature or stress during use to warn against overstraining or damage (Lehmann, 2004) has been discussed intensively for some time past. A passive and inductively coupled transponder system is one possibility to realise that functionality, because it provides wireless energy transfer and wireless data communication, less maintenance and the ability to integrate different sensors. The properties of the transmission channel and the functionality of such a transponder system depend on the rim material and shape as well as the dimensioning and the positioning of both reader and tag antenna. These dependencies will be analysed in the following on a virtual level to evaluate system usability and to derive important design rules concerning this usage scenario.
2. Tag in a tyre

To realise the introduced application, a tag must be integrated in a tyre. The reader is outside the tyre. Therefore, different types of antennas and antenna configurations had been published in the literature. Some examples are Benedict (2003), Lehmann (2004) and Pollack (2000). The used antennas and antenna configurations must ensure the functionality of the tag independent of the size of the tyre, the speed of rotation and the position of the tag.

Besides the optimisation of the transmission channel, a passive tag is needed for identification and the integration of different sensors. Therefore, the ST1 transponder IC is used in a test setup. It provides an analogue 125 kHz RF front-end, a hard coded module to support low level ISO 18000-2 protocol functions, a 16-bit microcontroller core, RAM, flash, EEPROM, timers and several peripheral components to connect, for example, different sensors with an analogue or digital interface. Additionally, analogue and digital signal processing can be done on the tag side (Grätz, Heinig, Deicke & Fischer, 2007). Figure 1 shows the block diagram of a transponder system including various sensors to measure different physical parameters. In the test setup, a combined pressure and temperature sensor MS5541 (Intersema, 2008) is connected to the ST1. Thus, the power consumption of the passive tag can be estimated, to use it for analysing and optimisation of the whole system in the following.

3. Transmission channel modelling

3.1. Antennas

The positioning of both reader and transponder antenna is an important point besides the antenna size, shape and the number of turns. The antennas should be coaxial or at least in parallel for a sufficient data communication and energy transfer with an inductively coupled transponder system. If – in a worst case scenario – the transponder antenna is perpendicular to the reader antenna, there is often no possibility of data and energy transfer. Considering the current application, the tag must be implemented in a wheel with different size and rotation speed. So, antennas and

![Block diagram of a transponder system for measuring different physical parameters.](image-url)
antenna positions that are changing their orientation to the reader antenna while turning the wheel do not seem sufficient. Because of that, an annular transponder antenna is assumed to be for example under the tread (Fig. 2). The wheel and the transponder antenna are co-axial. The annular antenna can be placed in the middle of the tyre, nearby the sidewall or the bead as well as on the rim or directly on a run-flat system (Continental, 2005; Rodgard, 2008).

The transponder circuit can also be placed under the tread or inside the tyre. The reader antenna is outside and in parallel with the wheel. It is smaller than the transponder antenna. So, the reader antenna can be positioned on the axle or on an advantageous position in the wheel case.

3.2. Rim model

A very simple model approximation of a rim is a round plate. It represents general eddy current losses in the system and it can be used to analyse basic influences on

---

**Fig. 2. Cross section of a wheel with integrated transponder antenna and external reader antenna.**
the transmission channel dependent on link distance, antenna size, radial shift of the reader antenna or rim materials. But the quantitative results do not agree with many practical applications. So, an improved model is used in the following. In addition to the round plate, it includes an annular rim and a rim flange on both left and right sides (Fig. 3). In general, the model is symmetrical, but the round plate can also be moved to the left or right side. The rim diameter, the rim width, the height of the rim flange, the thickness and the used material can be adjusted. Optionally, if a steel cord is implemented in a tyre, it can be modelled with a thin annular belt. The width, thickness, material and the height are adjustable.

The annular transponder antenna surrounds the rim. Its horizontal position can be changed. So, the antenna can be positioned in the middle of the rim or above the right or left rim flange using an offset. The advantage of an asymmetric antenna position is a shorter distance to the reader antenna if the rim width is large. The coupling can be improved. In that connection, the aspect ratio

$$AR = \frac{H_{AT}}{RW}$$  (1)
is another important parameter. In this paper, it is defined in relation to the aspect ratio of a tyre with the quotient of the antenna height $H_{AT}$ above the rim and the rim width $RW$. The steel cord is above the transponder antenna. The gap between antenna and steel cord is also adjustable.

4. Used tools for system analysis and optimisation

The software tool TransCal (Deicke, 2009) is used for analysis and simulation-based optimisation of transponder systems. It was developed by the IPMS and is written in C++. TransCal combines different modelling domains such as electrical circuits and electromagnetic antenna models to form a system simulation. The analyser/optimiser module (Fig. 4) analyses and optimises different transponder systems using parameter variations and search algorithms. Furthermore, an automated model generator reorganises and adapts imported user defined netlists and generates antenna models as well as the rim model and steel cord for the current task. The capability of the model generator depends on the used internal or external solver. To consider different application scenarios, it could be necessary to extend the model generator for the electromagnetic domain. A library including basic as well as complex geometrical structures supports that process to reduce setup time. The model coupling module controls and synchronises the simulations of internal and external numerical solvers selected by user (Deicke, Grätz & Fischer, 2008). For the current task proven external simulators like Spice (Quarles, Pederson, Newton, Sangiovanni-Vincentelli, Wayne, 2005) and FastHenry (Kamon, Smithhilser, White, 1996) are used.

5. System analysis

5.1. System setup

For system setup, the general input parameters of Table 1 are used. The reader and transponder antenna are optimised for maximum link distance in free air. Then, this

![Diagram](image-url)
Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Reader</th>
<th>Tag</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Antenna parameters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$r_i$</td>
<td>31 mm</td>
<td>243 mm</td>
</tr>
<tr>
<td>$b$</td>
<td>10 mm</td>
<td>11 mm</td>
</tr>
<tr>
<td>$N$</td>
<td>56</td>
<td>33</td>
</tr>
<tr>
<td><strong>Type</strong></td>
<td>MLC</td>
<td>TWS</td>
</tr>
<tr>
<td><strong>Electrical parameters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_0$</td>
<td>6.0 V</td>
<td>6.0 V</td>
</tr>
<tr>
<td>$V_{T,min}$</td>
<td>5.0 V</td>
<td>5.0 V</td>
</tr>
<tr>
<td>$\Delta V_{RR}$</td>
<td>0.01 V</td>
<td>0.01 V</td>
</tr>
<tr>
<td>$f_0$</td>
<td>125 kHz</td>
<td>125 kHz</td>
</tr>
<tr>
<td>$R_L$</td>
<td>14 k\Omega</td>
<td>14 k\Omega</td>
</tr>
<tr>
<td>$R_{L,Mod}$</td>
<td>30 k\Omega</td>
<td>30 k\Omega</td>
</tr>
</tbody>
</table>

An optimised non-varying antenna setup is used to analyse and compare different rim configurations with and without steel cord. Later, both antennas can be optimised dependent on particular rim shape, size and material. The reader antenna is a multi-layer coil (MLC) and it is smaller than the transponder antenna that is a thin-walled solenoid (TWS). Additionally, Table 1 lists important electrical parameters of the reader and the tag. $V_0$ is the amplitude of the driver, $\Delta V_{RR}$ is the minimum input voltage of the demodulator, $V_{T,min}$ is the minimum transponder voltage, $R_L$ is the load resistance and $R_{L,Mod}$ the load resistance during modulation. The resonance circuits and the quality factor are adjusted automatically by TransCal dependent on the used antennas and the influence of the wheel.

5.2. Parameter variation

Two parameters are very important for system evaluation if a transponder system is analysed within a tyre. The first parameter is the minimum load resistance $R_{L,min}$ with a defined transponder voltage and link distance. Therewith, the maximum power consumption can be calculated to estimate which sensors and signal processing functions for measuring physical parameters can be implemented into the tag. The second parameter is the demodulator input voltage $\Delta V_{RR}$ to determine if data communication is possible from the tag to the reader.

For the first analysis below, an antenna configuration is used without a steel cord. Thereby, the rim width is varied to analyse different aspect ratios. Additionally, the reader antenna is moved in radial direction starting from a co-axial position. Figure 5 depicts a FastHenry model of the transmission channel including the rim and the antennas. With this example, the reader antenna is on a non-coaxial position with an offset of 15 cm. The link distance is also 15 cm. The tag antenna is above the left rim flange. The rim width is 10 cm and the aspect ratio 0.43. The diameter of the rim is 40 cm and the round plate of the rim is centred. The rim material is aluminium.

The diagrams of Figs 6 and 7 show the minimum load resistance and the demodulator input voltage of the current setup with a link distance of 7.5 cm. The rim width is varied from 1 cm to 10 cm. That corresponds to an aspect ratio from 4.3 to 0.43.
including the range of most used car and truck tyres. The reader antenna is moved in radial direction beyond the tag antenna. The extremes of $R_{L,min}$ and $\Delta V_{RR}$ are not with a co-axial antenna configuration. They are at a radial shift of 19.3 cm approximately. If the reader antenna is moved beyond the tag antenna, the load resistance increases sharply. $\Delta V_{RR}$ has the same behaviour in the opposite direction.

The diagrams also show, that $R_{L,min}$ and $\Delta V_{RR}$ do not depend strongly on high rim widths. As a result, low aspect ratios are not really an influencing factor with that configuration and it can be assumed that the system would also work on lower values and flatter tyres respectively. If a low rim width is considered, the distances between
Fig. 6. $R_L$ [kΩ] vs. rim width and radial shift of the reader antenna.

Fig. 7. $\Delta V_{RR}$ [mV] vs. rim width and radial shift of the reader antenna.
the round plate and the antennas are smaller. So, the influence of the plate is bigger and for example on a co-axial antenna configuration, the load resistance is bigger as on larger rim widths.

The diagram of Fig. 8 depicts the minimum load resistance versus the radial shift of the reader antenna with different link distances and a constant rim width of 5 cm. The absolute minimum value decreases and moves radially outwards with reducing link distance. Thus, it is above the rim flange for very small distances. For example considering a link distance of 2.5 cm, the minimum load resistance is at a radial shift of 21.8 cm approximately. If the link distance increases, the absolute minimum also increases and moves towards the centre of the rim. At a link distance of, for example, 15 cm, the minimum is at a radial shift of 13.3 cm. At very high distances, the curve corresponds qualitatively to a free air configuration without a metal rim. If the curve with a link distance of 2.5 cm is considered, the minimum of $R_{L_{\text{min}}}$ is 1.3 kΩ. For a link distance of 15 cm, the minimum is 11.3 kΩ. Thus the maximum power consumption of the tag is 19.1 mW and 2.2 mW respectively if a transponder voltage of 5 V is considered. This is sufficient to power the introduced passive tag for measuring pressure and temperature. Considering the difference of $R_{L_{\text{min}}}$ between the centre position of the reader antenna and the position of the absolute minimum value, it increases with reducing the link distance. If the link distance is small, the correct position of the reader antenna is more important than at higher link distances. The load resistance increases sharply if the reader antenna is moved beyond the tag antenna.

Figure 9 depicts the simulated results of the demodulator input voltage for different link distances and a constant rim width. The curves have in general the same

![Figure 8: $R_{L_{\text{min}}}$ vs. radial shift of the reader antenna for different link distances and a constant rim width.](image-url)
Fig. 9. $\Delta V_{RR}$ vs. radial shift of the reader antenna for different link distances and a constant rim width.

![Graph showing $\Delta V_{RR}$ vs. radial shift](image)

behaviour as for the load resistance but in opposite direction. For example, the maximum demodulator input voltage for a link distance of 2.5 cm and 15 cm is at a radial shift of 21.8 cm and 13.4 cm, respectively. Thus, the position of the reader and the tag antenna has the same influence on both parameters.

With a second analysis, the same configuration is considered with a steel cord, like it is shown in Fig. 10. The steel cord is as wide as the rim and 1 cm above the tag antenna. The thickness is 2 mm. The diagram of Fig. 11 depicts the minimum load resistance versus the radial shift of the reader antenna with different link distances like it was done in the analysis before. In comparison to Fig. 8, the curves are steeper and the range of radial shift, where the tag would work, is smaller. Additionally, the minimum load resistance is higher than on the results without a steel cord. With a link distance of 15 cm, the tag can not be powered from the RF field of the reader.

6. Practical test setup

A demonstrator was created in the lab, to verify the simulated behaviour qualitatively. Therefore, a 20 inch bike wheel was used. It is fixed in a wheel truing stand (Fig. 12). The tag antenna is mounted on the tyre. The aspect ratio is approximately one. The transponder circuit is located in the inner of the tyre. It contains the transponder IC as well as the pressure and temperature sensor. So, pressure and temperature can be measured in real time and independent of rotation speed. The reader antenna is mounted on a fixture device that can be moved in two directions to change the link distance and the radial shift of the antenna.
Finally, general results of the simulations correspond to the test results in the lab. Additionally, the maximum link distance for measuring pressure and temperature was determined. It is 13 cm approximately using the current setup and the ISO 18000-2 protocol. The maximum link distance for a standard ID application is 22 cm approximately.

7. Discussion and usability

On summarising the analysis, questions on system design and usability can be answered for the current application qualitatively and quantitatively without doing
Fig. 11. $R_{\text{min}}$ vs. radial shift of the reader antenna for different link distances and a constant rim width including a steel cord.

Fig. 12. Test setup of a tag in a bike wheel.

prototyping. Thus the current system setup would work at different link distances using different radial shift for the reader antenna depending on rim shape, size and material as well as on using a steel cord in a tyre or not. Finally, the right position of the
reader antenna is very important and it varies with system setup and tyre properties. If such a comprehensive tool for system analysis and optimisation like TransCal is used, the antenna positions and the correct dimensioning of the antennas itself can be defined easily for maximising system performance for particular car and truck tyres.

If calculation time for the results of Figs 6 and 7 are considered for example, 400 calculation steps are needed. Using current computer technologies the overall calculation time is 14.76 hours approximately. That corresponds to 2.13 minutes for the calculation of each step including the calculation of the electromagnetic model, importing the transmission channel parameters to the electrical level, matching antennas and calculating the electrical circuit. In addition to that, it is possible to change the general system setup or to change the variation parameters or its range and repeat calculation to evaluate slight different usage scenarios. Considering that, the capabilities and the efficiency of using such a design tool become clear. In contrast, using a standard design flow introduced above, the time to get the same results with respect to quantity and quality will take days or maybe weeks, because prototypes and measuring setup must be changed more often. The basic setup time and costs needed for model generator extension of TransCal and to build up the measuring setup in the lab are neglected here, because these costs were incurred only once.

If one looks at the design of inductively coupled transponder systems in general, there are a lot of systems that must include different functions besides simple identification or it must work in special environments with conductive structures influencing the RF field. From this it follows that the design of each application means maybe starting design from scratch. So, the TransCal framework or something like that can be used advantageously if:

- Possible antenna shapes and sizes are different from general purpose antennas.
- The antenna configuration is non-coaxial. (If there is for example an arbitrary translation or rotation.)
- The transmission channel is influenced by several structures with different shapes, sizes and conductivities.
- A large and multidimensional parameter space must be considered.
- The tag implements more complex functions than simple identification. Implementing additional sensors or signal processing in a passive tag result in bigger power consumption and maybe a worse communication between tag and reader.

The benefits are that each system can be analysed and optimised in a less time and cost consuming way. Thus, the idea of a first systems success design approach could be realised.

8. Conclusions

In this paper the behaviour of an inductively coupled transponder system within a wheel setup was discussed. Such a transponder system including different sensors can be used to measure different physical parameters like temperature, pressure or
stress to warn the driver of a car or truck against overstraining or damage of tyres. Additionally, a better identification of tyres with respect to manufacturer, type and mileage can be done. The paper focused on the analysis of the transmission channel including a standard shaped metal rim with different aspect ratios to consider most used tyres for cars and trucks. Additionally, the position of the reader antenna is varied to find the best position for wireless data and energy transfer dependent on link distance and rim width. Therefore, the TransCal tool is used. This framework consists of an analyser/optimiser module, an automatic model generator and a model coupling module to use different internal and external solvers for the calculation of both electrical and electromagnetic models. Thus the transmission channel can be optimised. In addition, the impact on the whole transponder system can be analysed considering a large and multidimensional parameter space. As a result, less prototyping steps are needed and the idea of a first system success design approach could come true. So in many different application scenarios, the implementation of the RFID technique will become a less time and cost consuming process.

References


Preliminary analysis of warehouse localization systems based on RFID technology

Giada La Scalia*, Giuseppe Aiello, Mario Enea and Rosa Micale
Dipartimento di Tecnologia Meccanica, Produzione ed Ingegneria Gestionale, Università degli studi di Palermo, Palermo, Italy

Abstract. In the industrial warehouse design domain, today’s computerized information systems have gained a relevant interest due to the issues related to asset tracking and traceability. In such context, the employment of new information technologies on warehouse management systems has opened new business opportunities due to the sensible price reduction in the last years. This paper focuses on the technical issues related to the realization of wireless localization systems for warehouses, which are necessary for the implementation of random allocation policies, and in particular investigates the opportunities offered by RFID technology in such context. The enforcement of random allocation policies allows to increase the utilization coefficient of warehouses which is a critical issue, for example in refrigerated warehouses for perishable products. In particular, the development of localization systems based on trilateration is here considered, and an experimental model which links the received signal strength to the reading distance has been determined in order to take into account the specific features of the technology employed. A methodology is hence proposed to overcome the simplifying assumptions theoretical attenuation models rely on, by fitting a mathematical model on experimental observations. The problem of the accuracy level required to locate Stock Keeping Units (SKUs) of fixed dimensions is also considered, resulting in the evaluation of the maximum allowed reading distance. On the basis of the obtained results, the optimal configuration of the fixed infrastructure in terms of the number of antennas and their position is finally defined.

Keywords: Warehouse management, RFID, localization accuracy, design optimization

1. Introduction

Radiofrequency Identification (RFID) technology is recognized as a revolutionary innovation in retailing operations, however its penetration is still quite limited, probably due to the perception of a high cost of implementation. The potential benefits of this technology in fact are still poorly exploited and there is the possibility of significantly improving the Return On Investment (ROI) by implementing innovative features and capabilities. In particular, this paper refers to the context of warehouse management and on the implementation of wireless localization systems for asset tracking, which are currently under development in several industrial contexts (Sanpechuda & Kovavisaruch, 2008). One of the main benefits of automatic localization systems in...
warehousing operations is related to the possibility of implementing optimal allocation policies, which directly influence the required storage capacity (Lee & Elsayed, 2005). For example, shifting from a dedicated storage policy to a random storage policy has been demonstrated to increase the utilization coefficient of warehouses, therefore allowing a reduction in the overall storage volume (Hausman, Schwarz & Graves, 1976). This is a critical issue in the design of refrigerated warehouses for perishable products. The corresponding potential economic benefit related to the reduction of the refrigeration costs depends upon the number of different products stored and the storage conditions. However, the optimized design of the RFID infrastructure is a key factor to maximize the ROI and achieve the highest economical benefit. The basic motivation of this research, hence, is to investigate the technical issues related to the implementation of the RFID technology for localization purposes, considering the optimized design of warehouse infrastructures.

In particular, the development of localization systems based on trilateration is here considered, and a reliable mathematical model, which links the Received Signal Strength (RSS) to the reading distance, is proposed.

An optimized attenuation model is a fundamental requirement for an effective trilateration algorithm. In fact the main obstacle to the practical application of wireless based localization systems is related to their poor precision (Sanpechuda & Kovavisaruch, 2008). The problem of the accuracy level required to locate stock keeping units (SKUs) of fixed dimensions is therefore investigated, resulting in the evaluation of the maximum allowable reading distance corresponding to the required precision. In addition the simplified assumptions theoretical models are based upon, generally prevent the model from being employed in the development of real-life applications. To overcome such limitations, suitable models should be developed taking into account real technological features such as the emission curves of antennas.

According to such considerations, this research refers to the development of a distance attenuation model based upon experimental data, involving the evaluation of localization accuracy and the comparison with theoretical results. The experimental analysis has been performed employing active IDENTEC ILR tags and omnidirectional antennas. The attenuation model thus obtained has been implemented in the trilateration algorithm for the localization system. By means of the proposed methodology it is therefore possible to determine the maximum allowable reading distance, once the required precision is established, according to the technology employed. On the basis of this result the optimal configuration of the fixed infrastructure, in terms of the number of antennas and their position, can be eventually determined.

2. RFID based indoor localization systems

Indoor location systems have become very popular in recent years in providing a new layer of automation called automatic object location detection. Localization is a technique to find the spatial relationship among different objects, and the process of determining the location of an object in space is defined radiolocation if it uses
wireless technologies. Almost all the localization methods require the observation of a
direct or reflected ray or wave to deduce distances. Such observations can be gathered
by different measuring techniques such as Time-Of-Arrival (TOA), Time Difference
of Arrival (TDOA), Angle-Of-Arrival (AOA), and Received Signal Strength (RSS),
etc. The TOA and TDOA techniques refer to signal propagation time for determining
the distance, while AOA is based on the estimation of the relative angles between
the neighbors to detect the position of the nodes (Savarese, Rabacy & Langendoen,
2002). RSS based localization refers to the technique of estimating the position of a
transmitter by measuring the intensity attenuation of the signal. RSS is hence based on
either theoretical or empirical calculations to convert the signal strength measurements
to distance estimates.

Automatic indoor object localization has been approached by means of different
types of wireless technologies such as Infrared radiation, Ultrasonic, and Radio-
frequency. Infrared Radiation and ultrasonic technologies have been employed in the
past and the drawbacks that prevent their employment in cost effective localization
systems for warehouses are well known (Bahl, Padmanabhan & Balachandran, 2002).
Depending on the type of frequency range used, Radio Frequency can be categorized
into RFID (Radio-Frequency IDentification), WLAN (IEEE 802.11), Bluetooth (IEEE
802.15) and Ultrawideband (UWB). UWB, WLAN and Bluetooth are unpractical on
small, power constrained devices and/or they do not deliver enough range, accuracy
or cost effectiveness to be practicable for warehouse and logistic applications (Gezici,
Tian, Giannakis, Kobayashi, Molisch, Poor & Sahinoglu, 2005). RFID, contrarily, is
now being seen as a radical means of enhancing material handling processes. The
basic components of a RFID system are the readers and the tags. The RFID tag is a
low functionality microchip that stores an unique identification number.

Although RFID technology has the required potential to be employed for indoor
localization purposes, using radio communications for positioning poses several prac-
tical problems: signals attenuation and fading from obstacles in the transmission path,
reflections off surfaces and relative antenna orientation. In particular, in logistics appli-
cations, the presence of the storage infrastructures and the high humidity content or
even ice present in the products generally results in high signal attenuation. In this
paper, the RSS technique is employed for the estimation of the distances between
the tags and the antennas. It is well known that the signal attenuation is linked to
the transmission path through the mathematical relation defined attenuation model
or path loss model. According to traditional path loss models, the signal strength
decreases uniformly as a function of distance \( d \):

\[
\frac{p_r}{p_0} = \left( \frac{d_0}{d} \right)^\alpha
\]

(1)

where \( p_r \) is the received power at distance \( d \), \( p_0 \) is the normalized received power a
reference distance from the transmitter (typically \( d_0 = 1 \) m) and \( \alpha \) is the distance power
gradient, which is highly dependent to the geometry and physical characteristics of the
environment (Pahlavan & Levesque, 2005). In ideal conditions (indoor environment is homogeneous and errors due to reflections, interferences, etc. are negligible), α = 2 and in this situation the received power in dBm is defined as:

\[ P_r = 10 \log_{10} \left( \frac{p_r}{p_0} \right) = 10 \log_{10} (p_0) - 10 \alpha \log_{10}(d) + X \]  (2)

where \( X \) is a normally distributed random variable expressing the attenuation (in decibel) caused by log-normal shadow fading effects. This random variable is considered zero-mean, that is, \( X \sim \mathcal{N}(0, \sigma_X^2) \), while the value of the standard deviation \( \sigma_X \) depends on the characteristic of a specific multipath environment (Pahlavan & Levesque, 1995). We define the total path loss \( L_p \) (i.e. the difference between the power of the signal transmitted and received in decibel) as:

\[ L_p = P_t - P_r \]  (3)

where \( P_t \) is the signal transmitted expressed in decibels. Substituting (2) in (3) we obtain:

\[ L_p = P_t - 10 \log_{10} (p_0) + 10 \alpha \log_{10}(d) + X \]  (4)

or

\[ L_p = L_0 + 10 \alpha \log_{10}(d) + X \]  (5)

where \( L_0 = 10 \log_{10}(p_t/p_0) \) represents the path loss in decibels at one meter distance.

A reliable mathematical model which establishes a relation between reading distance and signal attenuation, such as the one represented in eq. 5, is required in order to develop an effective RSS localization system. The specific technology employed and the environment where localization is performed (storage area), however influence the signal attenuation making theoretical model inadequate in practical applications.

Finally, the present approach relies on trilateration as a localization method. Trilateration is a technique to compute the position of an object in a 2D space by means of Cartesian coordinate system \( \{x, y\} \), given its distances from three fixed non-collinear reference nodes. Trilateration hence requires the measurement of distances between the tag and the reader which can be determined by the RSS. In order to be located, therefore, a tag must fall within the reading range of at least 3 nodes, which means the whole storage area must be 3-covered. This introduces the problem of \( k \)-coverage which consists in determining, given a set of nodes deployed in a target area, if every point in the target area is covered by at least \( k \) nodes. The problem of selecting the layout that requires the minimum number of nodes and ensures the expected precision in the storage area can ultimately be tackled. This problem can be solved optimally in a 2D plane, but it is NP-hard when extended to a 3D space. The number of nodes needed to cover an area, depends on the power ranges of the nodes. In order to determine a closed form solution of the \( k \)-coverage problem in 2D spaces, the sensing region of every node is considered circular with a radius of \( r \). If the generic circle \( C(n, r) \) is the sensing circle of node \( n \), it is said to cover a point \( p \), if the distance \( d(p, n) \) between \( p \)
and $n$ is less or equal than $r$. An optimal layout results in minimum overlap satisfying a $3$-coverage constraint, and the optimal area coverage is obtained when nodes are posed such that they form equilateral triangles with sides equal to their power ranges (Fig. 1a/b). In this case, the number of nodes needed to cover a square of $L \times L$ is:

$$N = \left\lceil \frac{(2L/r + 3) \cdot (L/h + 1)}{2} \right\rceil$$

(6)

where $\lceil \rceil$ indicates the ceiling function, $r$ is the power range of the nodes, and $h$ is the height of the verification triangle (Capkun & Hubaux, 2004).

In localization systems, however, the maximum allowed reading distance is generally limited by the system accuracy rather than the power of antennas. The accuracy of a location sensing system must hence be linked to the specific applications considered and the existence of various applications with different accuracy requirements increases the need for proper approaches to the design of optimized indoor location systems. The need for more precise indoor localization systems has stimulated interest in accurate modeling of the propagation environment, developing novel technologies (Bahl & Padmanabhan, 2000; Fontana, 2001; Wang, Norman & Rajgopal, 2007) and in comparative performance evaluation of different technologies (Pahlavan, Krishnamurthy & Beneat, 1998; Krishnamurthy & Pahlavan, 1999; Alavi & Pahlavan, 2005). Finally, the accuracy of Signal-strength-based trilateration is related to the signal strength/distance relation. This relation either approximately obeys a quadratic decrease or the precise signal strength map must be known. In such sense, once the technologies related features are known, ray tracing technique can be employed to take into account environment specific issues. Ray tracing (Schaubach, Davis IV & Rappaport, 1992; Anderson, 1993; Stutzman & Thiele, 1998) is a commonly used computational method for site-specific prediction of the radio channel characteristics of wireless communication systems. Recent development of software to predict the area coverage on the basis of ray-tracing algorithm should be employed in order to obtain realistic area coverage maps (Bach, Stantchev, Lederer, Weigh, Herbst & Kunze, 2005; Aikaterini, Koutsoul, Secol, Jimenez, Roua, Ealo, Prieto & Guevaral, 2007; Bekkali & Matsumoto, 2008).

Fig. 1. The $k$-coverage problem.
3. Experimental analysis

A warehouse localization system must be supported by a reliable attenuation model in order to link the RSS measured to the distance between the tag and the reader. As stated before, theoretical signal attenuation models are generally inadequate for practical applications, since they are based on extremely simplifying assumptions. To be sufficiently reliable, hence, an empirical model must be determined taking into account the specific features of the technology employed and the characteristics of the storage area considered. The main element which affects the performance of wireless localization systems is their accuracy, hence, the experimental analysis, is focused on determining the variation in the accuracy of RSS measurement with the reading distance, rather than the maximum attenuation level allowed for the reader to detect the tags.

The experimental system is based on IDENTEC ILR (Intelligent Long Range) technology and it is constituted by a set of active tags (i-Q), a reader (i-PORT 3 Interrogator), an elliptically polarized antenna and a workstation connected to the reader with standard Ethernet connection. The following Fig. 2 depicts the experimental system. The experimental configuration involved a power emission level of 4 dBm at UHF (868/915 MHz) frequency, a received signal power of –10 dBm and sensitivity of –85 dBm. This configuration is supposed to achieve reading ranges of up to 100 meters and a large reading zone due to the wide apex angle of 120°. The elliptical antenna polarization (Fig. 3), makes the system robust towards the direction of the tag relative to the antenna.

The storage area considered is a square area of 25 × 25 m², for refrigerated perishable products that are piled up with no significant storage infrastructures.

The experimental analysis has been initially focused on the establishment of a mathematical relation to link the reading distance to the attenuation level measured. In order to determine the experimental signal attenuation curve, the received signal strength was measured at different (known) distances starting from 1.2 m to 40 m and 50 replicates were taken for each point. The average percent RSS value of the replicates is given in the following Fig. 4. Also the theoretical curve based on the previous Eq. 1 (free space model) was evaluated, considering an \( L_0 \) value of –38.078 dBm.

![Fig. 2. The experimental system.](image)
Elevation Azimuth

Fig. 3. Antenna polarization diagram.

140
120
100
80
60
 RSS %

Distance (m)
40
20
0
0 1 2 3 4 5

experimental free space exponential model

Fig. 4. The experimental and the theoretical attenuation model.

and $\alpha = 2$. The experimental attenuation curve has been obtained as an exponential regression model fitted to the experimental data. The value correlation coefficient obtained ($r = 0.984$) confirms that the mathematical model obtained well fits to the experimental data, as given in eq. 7 and in Fig. 4.

$$\%\text{RSS} = 1.26 e^{-0.14d}$$  \hfill (7)

The superiority of the exponential regression model compared to the free space model is confirmed by the absolute and percent error calculated according to the equations below and given in Figs 5 and 6.
\[ e = \left| \text{RSS} - \hat{\text{RSS}} \right| \quad (8) \]

\[ e_{\%} = \frac{\left| \text{RSS} - \hat{\text{RSS}} \right|}{\text{RSS}} \quad (9) \]

where RSS is the experimental measure and \( \hat{\text{RSS}} \) is the value calculated according to either the exponential or the free space model.

Considering that as the distance increases the RSS goes asymptotically to zero, percent error values increase with the distance although absolute errors decrease. This means that as the distance increases, the RSS measured is affected by a higher percent error, which ultimately lessens the accuracy of the localization. It is therefore necessary to evaluate the effect of the measurement error on the overall accuracy of
the localization system. The measurement error is a consequence of the fact that the RSS signal measured is affected by a random error, expressing the effect of non-systematic causes which originate a difference between the measured value and the real value. Such error is assumed to be distributed as a Gaussian probability function with null average value: 
\[ \varepsilon = \mathcal{N}(0, \sigma) \] 

It is therefore necessary to assess how the measurement error reflects in the localization accuracy. For each set of replicates the \( \chi^2 \) test with critical value of 0.01 has been calculated confirming the hypothesis of a random error affecting the measures, however the normal probability hypothesis weakens as the measurement distance decreases. For small distances the measurement error is generally negligible compared to the dimensions of the objects to be located, therefore the precise distribution of the measurement error is not important. Clearly, RFID technology is unpractical for the localization of extremely small objects, which however is not generally the case of industrial warehouses. For example, Figs 7 and 8 give the (A) histograms and (B) the normal probability plots corresponding to the experiments at 13 and 36 m.

Coherently with the normal probability functions above reported, and establishing a confidence value \( \beta \), it is possible determine the confidence interval [\( \text{RSS}_L, \text{RSS}_U \)]
expressing the condition that the measured RSS value belongs to the interval \([\hat{RSS}_l, \hat{RSS}_u]\) with a probability \(\beta\).

\[
\text{prob}(\hat{RSS}_l \leq \text{RSS} \leq \hat{RSS}_u) = \beta
\]  

(11)

Being RSS(d) monotonically decreasing, according to eq. 7, the following conditions hold:

\[
\text{prob}(f^{-1}[\text{RSS}(d)]_l \leq f^{-1}[\text{RSS}(d)] \leq f^{-1}[\text{RSS}(d)]_u) = \beta
\]  

(12)

\[
\text{prob}(d_l \leq d \leq d_u) = \beta
\]  

(13)

where \(f^{-1}[\text{RSS}(d)]\) represents the inverse function of RSS(d).  

Which results in a confidence interval \([d_l, d_u]\) upon the distance \(d\) as the image of RSS through \(f^{-1}(\text{RSS})\). In other words, it can be stated that when the distance of the tag is unknown and the RSS attenuation is measured, the position of the tag can be approximately determined with a certain confidence level (Fig. 9). Clearly, the higher the confidence, the wider the interval. The existence of a random measurement error on the RSS value measured by the antenna when the tag is at an unknown distance ultimately means that the distance of the tag cannot be determined exactly by the straightforward application of the attenuation model (eq. 7). On the contrary, once the standard deviation of the error affecting the RSS measured is determined, a confidence interval can be assigned with a confidence level \(\beta\). The exponential attenuation model can finally be employed to determine the corresponding confidence interval on the distance of the tag. The distance measurement error, however is not a random error,

Fig. 9. Localization intervals at fixed accuracy.
since it is not distributed according to a normal distribution, due to the non-linearity of the exponential curve. The distance between the tag and the reader can hence be approximately determined according to a fixed confidence level, once the attenuation model is known and the influence of the measurement error at the calculated distance is known.

For example at 13 m distance, the percent RSS measured is a normal variable with average value and standard deviation of 18 and 2.47 respectively. This means the confidence interval at level 98% is [12.37; 23.87]. According to the attenuation model this results in a distance range of $f^{-1}(12.37) = 11.88$ m and $f^{-1}(12.37) = 16.57$ m. The asymmetry of this interval is due to the non-linearity of the attenuation model, however the confidence level is preserved due to the strict monotonicity of $f$.

According to the considerations above, the relation between the localization interval and the distance for different fixed values of $\beta$ is given in Fig. 10. For example, if a 4 m accuracy is requested at 95% confidence, meaning that the probability locating the tag within an interval of 4 m is 95%, the maximum reading range is approx. 13 m.

Finally, the localization system is based on trilateration (Fig. 11), hence three RSS measures and corresponding distance estimations are required in order to locate an SKU in the warehouse. The presence of a confidence interval on the distance measure from each access point allows to approximately locate the tag within a circular crown rather than on an exact circle.

Therefore the tag will be approximately located into an area whose dimensions depend upon the confidence level considered. This approximated location area is

![Fig. 10. Reading interval as a function of the distance at different confidence levels.](image-url)
directly related to the dimensions of the SKUs at a fixed confidence level, therefore according to the dimensions of the SKUs to be located and to the confidence level established, it is possible to determine the optimal number of access points required.

For example if a $3 \times 3 \text{ m}^2$ SKU must be located with a maximum ranging accuracy of 92% for each reader, the maximum allowed distance from the antennas, from Fig. 10, is 9 m, while the maximum allowed range drops to 3 m if the ranging confidence requested is 98%. Consequently, the required number of access points will be 11 and 26 respectively (eq. 6).

4. Conclusions

This research discusses the issues related to the practical application of RFID based localization systems for warehouses and falls within the broader framework of RF based asset tracking systems which are currently gaining interest in several industrial contexts. In warehouse management systems, in particular, the establishment of wireless localization technology enables the implementation of advanced traceability systems and random allocation policies. In order to fully exploit the benefits of this technology, however optimized system design is mandatory. In this paper this issue is considered according to the maximum reading range which ensures the required measurement accuracy for locating the SKUs. According to this purpose, the distance between the tag and the fixed antenna is evaluated by measuring the RSS and referring to a suitable attenuation model. The establishment of a reliable attenuation model is hence crucial, and it is well known that theoretical signal attenuation models based on the power loss gradient are inadequate for practical applications since they are based on over-simplifying assumptions. In this research, therefore, a
suitable methodology has been proposed to determine the optimal placement of the
nodes of an RFID network deployed within a warehouse, considering the specific
attenuation model fitted on experimental data referred to a commercial technology.
This can be the first design stage, prior to a detailed optimized layout which can be
obtained by means of RF signal coverage simulations. Although there are commer-
cial software packages to support the design phase detailed layout, considering the
effects of obstacles and reflections and real emission curves of antennas, this activ-
ity is generally time consuming, hence a preliminary design can be helpful in such
context.

In addition the measurement error in the evaluation of the RF signal attenuation
has been considered and the resulting effect on the distance approximation has been
evaluated. The experimental analysis allowed to link a localization interval with the
distance, at fixed confidence levels, demonstrating that such interval widens with
the distance. The definition of the optimized design is finally based on the tradeoff
between maximum allowable reading range and accuracy, and the proposed method-
ology ultimately allows to determine the optimal configuration of the fixed Rfid
infrastructure. In other words, given the dimensions of the SKUs, the minimum num-
ber of antennas required to ensure the requested accuracy over a 3-covered area is
calculated.

In general RSS based localization systems require a reliable mapping of the atten-
uation level over the covered area. In such sense, the specific characteristics of the
technology employed and the environmental features, such as reflections and refrac-
tion caused by the walls and the obstacles or storage infrastructures play a fundamental
role. The methodology proposed in the research aims at supporting the designer in
the preliminary design phase where the designer is most interested in roughly esti-
mating the number of required antennas in order to establish an approximated cost for
technical/economical feasibility analysis. Such objective can be achieved by means
of the proposed methodology with a limited experimental campaign. In spite of its
simplicity, the proposed approach suffers some limitations due to several simplifying
assumptions such as constant power range of the readers, no interposed obstacles, etc.
in a general 2D context. The exact number of antennas, and their position is generally
established afterwards in detailed design phase, and in order to take into consider-
aton the specific application features, different methodologies (e.g. simulation) are
generally employed in such context.

The implementation of RFID infrastructures for warehouses is still quite limited,
and this is generally due to the apparent high implementation cost. However the gen-
eral perception is that real life applications generally are not based on well optimized
infrastructures and/or do not fully exploit the multiple opportunities offered by RFID
technology. In the case here proposed the experimental test have been carried out in
an empty warehouse, however the methodology here proposed could allow to take
into account real situation by properly modifying the attenuation model. For exam-
ple refrigerated warehouses for perishable products will have significantly different
attenuation curves due to the high percentage of humidity.
References


