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RFID in the warehouse: A literature analysis (1995–2010) of its applications, benefits, challenges and future trends

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ABSTRACT

Radio Frequency Identification (RFID) has been identified as a crucial technology for the modern 21st century knowledge-based economy. Some businesses have realised benefits of RFID adoption through improvements in operational efficiency, additional cost savings, and opportunities for higher revenues. RFID research in warehousing operations has been less prominent than in other application domains. To investigate how RFID technology has had an impact in warehousing, a comprehensive analysis of research findings available from articles through leading scientific article databases has been conducted. Articles from years 1995 to 2010 have been reviewed and analysed with respect to warehouse operations, RFID application domains, benefits achieved and obstacles encountered. Four discussion topics are presented covering RFID in warehousing focusing on its applications, perceived benefits, obstacles to its adoption and future trends. This is aimed at elucidating the current state of RFID in the warehouse and providing insights for researchers to establish new research agendas and for practitioners to consider and assess the adoption of RFID in warehousing functions.

1. Introduction

Radio Frequency Identification (RFID), one of the Automatic Identification and Data Capture (AIDC) technologies (Wamba and Boeck, 2008), has attracted significant attention in the fields of supply chain and manufacturing, and more recently, in various service sectors. As the name implies, RFID transmits information through radio waves between RFID tags (or transponders) and readers (interrogators) (Hunt et al., 2007). The collected information is passed on to RFID middleware for processing, for use in business applications. Each tag consists of unique identification information about the item to which it is attached, e.g. item ID, date of production, shipping detail, expiry date, etc. depending on the intended uses.

As a means of collecting, transmitting and utilising data, RFID offers many advantages over other AIDC technologies such as barcodes (Baker, 2005; Brown et al., 2007). The benefits of RFID are well-perceived by industry, including retail, logistics, manufacturing, the military, healthcare, pharmaceuticals and the service sector (Oztaysi et al., 2009; Ngai et al., 2008). A substantial range of RFID applications have been implemented; different industries may have different interest in the technological benefits. These benefits include unique identification of each tagged item and status monitoring, improved stock visibility and traceability at any stage in the supply chain, increased data accuracy and sharing, automated inventory counts, automated receiving and scanning, reduced shrinkages, and so on (Ngai et al., 2008; Brown et al., 2007; Anonymous, 2005; Baker, 2005; Luckett, 2004).

As pioneers of RFID adoption, Wal-Mart and the US Department of Defence carried out trials on RFID application in their supply chain and reported promising outcomes. Mandates were issued in phases for their suppliers to apply RFID tags on their shipments (O'Connor, 2008). Other early adopters include Procter & Gamble, Gap, Tesco UK, and Marks & Spencer UK (Collins, 2006a, 2006b, 2004b; Bacheldor, 2006). More recently, large-scale RFID projects have been implemented. DHL has tagged 1.3 m pallets for its delivery operations to all 89 Metro Cash and Carry in France (Wessel, 2008), and Sam's Club (wholesales retail stores owned by Wal-Mart) has issued mandates for all their suppliers to apply RFID tags in stages (Burnell, 2009). There is evidence showing an increase of pilot trials and implementations (Roberti, 2006).

Due to its well-perceived capability and popularity in the business world, there has been a rapid growth of interest in RFID in the academic community across different disciplines.

In order to ascertain the extent of RFID coverage in the logistics literature, a preliminary bibliographic search was conducted using

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the ISI Web of Knowledge database, considered as a primary source for citation studies (Roth, 2005; Meho and Yang, 2007). Results of the query are illustrated in Fig. 1, which shows the rapid growth of RFID publications from 1995 to 2010. The growing trend coincides with the forecast put forward by Ngai et al. (2008) and Chao et al. (2007). It can be noted in Fig. 1 that, since the reviews on RFID literature up to 2005 (Chao et al., 2007; Ngai et al., 2008), the number of publications from 2005 to 2010 has continued to grow rapidly, indicating a need to review this new literature.

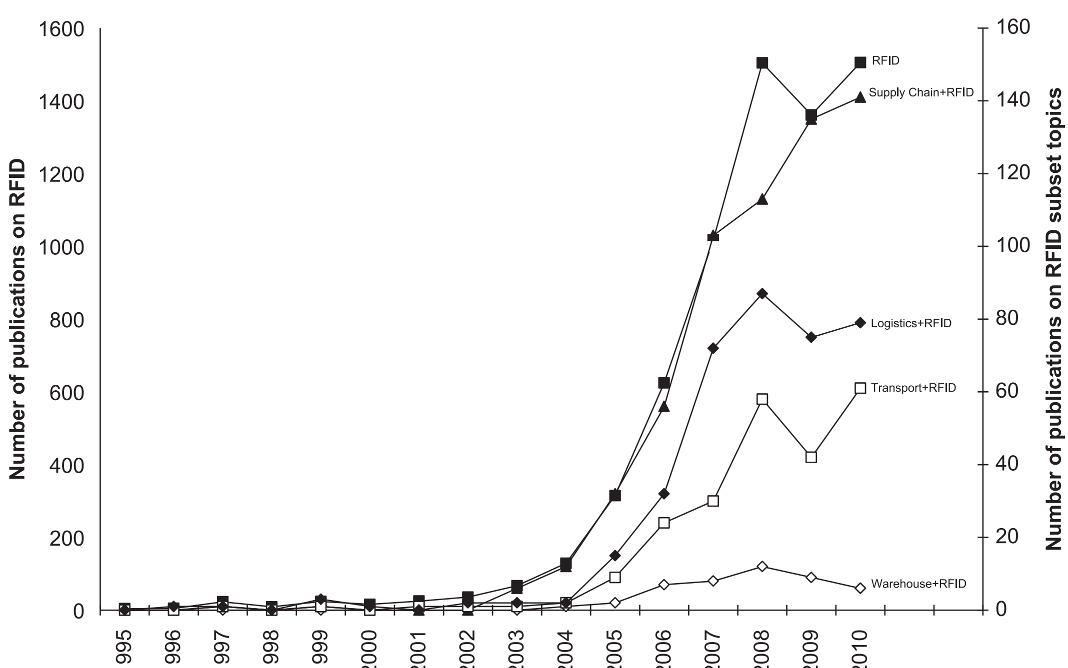
As Fig. 1 shows, the increasing number of RFID publications in the domains of transport, logistics and supply chain follows the growing trend of overall RFID research. However, it can also be seen that interest in RFID in warehousing is rather stagnant and relatively small in comparison to other research domains. Warehousing is a critical supply chain function and such an outlook (in Fig. 1) suggests a need to review this under-focused domain comprehensively. This is corroborated by Curtin et al. (2007). They stated that amongst many domains in RFID research, warehousing comes as one of the key domains to greatly benefit from RFID adoption. Moreover, in the RFID literature warehouse application is mainly discussed as a subset. The relatively few publications focusing solely on RFID applications in warehousing include the use of RFID case-based reasoning for managing different warehouse operations (Poon et al., 2009; Chow et al., 2006a, 2006b, 2006c), investment in improving inventory accuracy (Uckun et al., 2008), RFID adoption issues and implementation challenges in warehouses (Bahr and Lim, 2009), and an empirical study of RFID in the warehouse industry evaluating its costs and benefits (Vijayaraman and Osyk, 2006).

This paper reviews research on RFID in warehousing applications. It aims to identify the gaps not explored in previous works that have general or supply chain management scope. In other words, the reader can learn which benefits and applications of RFID in warehouses are strongly linked to identification and which associated benefits of RFID are seldom examined in the warehousing literature. The current status of RFID solutions for warehousing is evaluated against previous recommendations. Moreover, potential RFID obstacles and future trends are examined from the warehousing perspective.

The paper contributes to knowledge by providing a comprehensive review of the academic literature on RFID in warehousing, considering its application and influence on warehouse operations. The research questions addressed are: what is the state of RFID application in warehousing as presented in academic literature and what are the perceived benefits? Are the RFID benefits interlinked and could this help academics and practitioners to build a stronger case for the technology adoption? In order to answer these questions the following objectives were set:

- Develop a framework to classify RFID literature, focusing on its warehousing subsets,
- Review and analyse the literature within the classification framework on how RFID has been applied and the added value obtained in the warehouse,
- Examine the benefits of RFID in warehouse operations and rank them according to their perceived gains,
- Study future trends to provide insights for academics to establish new research domains and for practitioners to examine associated benefits to provide business case for RFID adoption.

This paper is organised as follows: Section 2 describes the methodology used in analysing the academic literature and the four discussion topics that have been identified. Section 3 discusses topic one, which is the framework to analyse the literature based on RFID application domains. Section 4 (topic two) uses a benefits matrix to analyse the correlation between the benefits and warehouse operations and application domains for all the articles studied, so as to identify both the popular and under-focused (but potentially value-added) benefits which could draw the attention of researchers and practitioners. Obstacles to RFID adoption in the warehouse (topic three) are discussed in Section 5 and the future trends of using RFID (topic four) are analysed in Section 6. Finally, concluding remarks are given in Section 7.



Note: The left x-axis is for RFID publication in general and on the right is for RFID subset topics

Fig. 1. Publications from 1995 to 2010 on RFID and subset topics.

2. Methodology

Up to 2010, there were two major literature reviews analysing the state of research on RFID technology: Ngai et al. (2008) and Chao et al. (2007). They presented the scientific literature from 1991 to 2005 and 1995 to 2005 respectively. By means of bibliometric analysis, Chao et al. (2007) documented the number of publications per year, type, country and language and divided the RFID literature into two categories: (1) technological innovation and organisational adoption, and (2) new challenge and diffusion. The literature review by Ngai et al. (2008) utilised a different approach, based upon content-oriented classification, and divided the literature into the following categories: RFID technology, its applications, and its policies and security. The authors also provided a discursive analysis on future research directions.

As noted in Section 1, there is a need to conduct a comprehensive literature review of the current state of research related to RFID in warehouse operations, and an analysis to explore the future trends of RFID in warehousing in order to identify the new research directions and value-added applications for the academics and practitioners. In contrast to the general RFID literature reviews by Chao et al. (2007) and Ngai et al. (2008) this paper analyses the literature that pertains to the applications of RFID technology specifically in warehouse operations.

2.1. Timeline of research literature analysed

This study analyses the literature in consecutive years from 1995 to 2010. The choice of 1995 as a start of literature search follows the reasoning from Ngai et al. (2008) and is also justified by the results of bibliographical query as shown in Fig. 1.

2.2. Literature search

The academic literature reviewed in this study was obtained from the leading databases of scholarly articles in order to review the field as comprehensively as possible. The scholar databases used in this study are:

1. ABI/Inform Complete
2. ACM Digital Library
3. EBSCO Business Source Complete
4. SCOPUS
5. Emerald
6. IEEE Xplore
7. Science Direct
8. Springer Link
9. Taylor & Francis

2.3. Database query

Despite the differences between the databases in performing literature searches, in each case the following generic query was used: «(Title OR Abstract) CONTAINS ("radio frequency identification" OR rfid) AND (Title OR Abstract) CONTAINS (warehouse NOT "data warehouse") AND (Timespan)=1995–2010 AND (Article Type)=(Peer Reviewed)». It was necessary to exclude the phrase "data warehouse" as it does not refer to an operational warehouse in a supply chain context. The search query resulted in 403 articles. Articles with duplicate entries due to database overlap, news articles from trade magazines and articles in languages other than English were discarded. The process of categorising and analysing the remaining 253 articles was modelled after practice outlined by Ngai et al. (2008), whereby two authors autonomously analysed the articles and discrepancies between authors' judgement were reconciled by discussion, with the input and agreement from the third author, until a unanimous decision was made whether to include articles in the set. As a result, an additional 195 articles were rejected because they matched the query but did not focus on RFID research work in the warehouse (e.g. they only mentioned warehouse as an example for RFID application but did not actually conduct research in the domain). This left 58 articles to be analysed in this paper.

2.4. Limitations

This study is subject to a number of limitations. First of all, despite using nine leading scholarly databases, there is a possibility of some scientific articles not being covered as they are not indexed in any of them. The second limitation is related to the dynamic nature of online publication databases. As the articles become available from the publishers, some of them might have been added at a later stage and backdated. Therefore, the authors of this paper recognise that some articles may not have been included as they were not available on the databases at the time of writing. The last limitation is that this study is only focused on articles published in the English language. Despite these limitations, it is believed that this study has achieved reliable comprehensiveness and can benefit academics and practitioners in establishing new research directions and evaluating their assessment of applying RFID in the warehouse.

2.5. Analysis

Many academic literature reviews focus on bibliographical/statistical analyses that revolve around the categories, e.g. by type of journal, country, most cited institutions/individuals, etc. However, this study analyses the use of RFID technology in the warehouse, considering how and where it is applied to improve warehouse efficiency, what are the important benefits gained and its future trends to provide insights for new research scope and value-added business applications. This study area has been identified by Ngai et al. (2008) and Chao et al. (2007) as the next movement for researchers focusing on RFID business value and organisational applications when the technology is reaching its maturity stage. The framework developed in this research builds upon the theoretical foundations from the strategy and information systems disciplines. These fields contributed significantly to the understanding of processes involved in the implementation of new technology, analysis of challenges to its adoption and benefits thereof (Whitaker et al., 2007; Dutta et al., 2007). To facilitate the analysis, the paper is divided into four discussion topics as follows:

- *Discussion one*: The application domains of RFID in different warehouse operations.
- *Discussion two*: A matrix to examine the benefits perceived.
- *Discussion three*: A discussion of the potential obstacles in adopting RFID in the warehouse.
- *Discussion four*: An analysis of the future trends that could further benefit the use of RFID in the warehouse.

In order to help academic and practitioners to better comprehend the key findings of the literature reviewed in this article, an RFID framework was developed (see Fig. 2). It shows the application of the RFID in the warehouse, its benefits as well as the implementation obstacles related to this technology. Its categories are based on the analysis of the literature reviewed and the foundation of warehouse research. The framework is also aimed at facilitating the aforementioned four discussion topics.

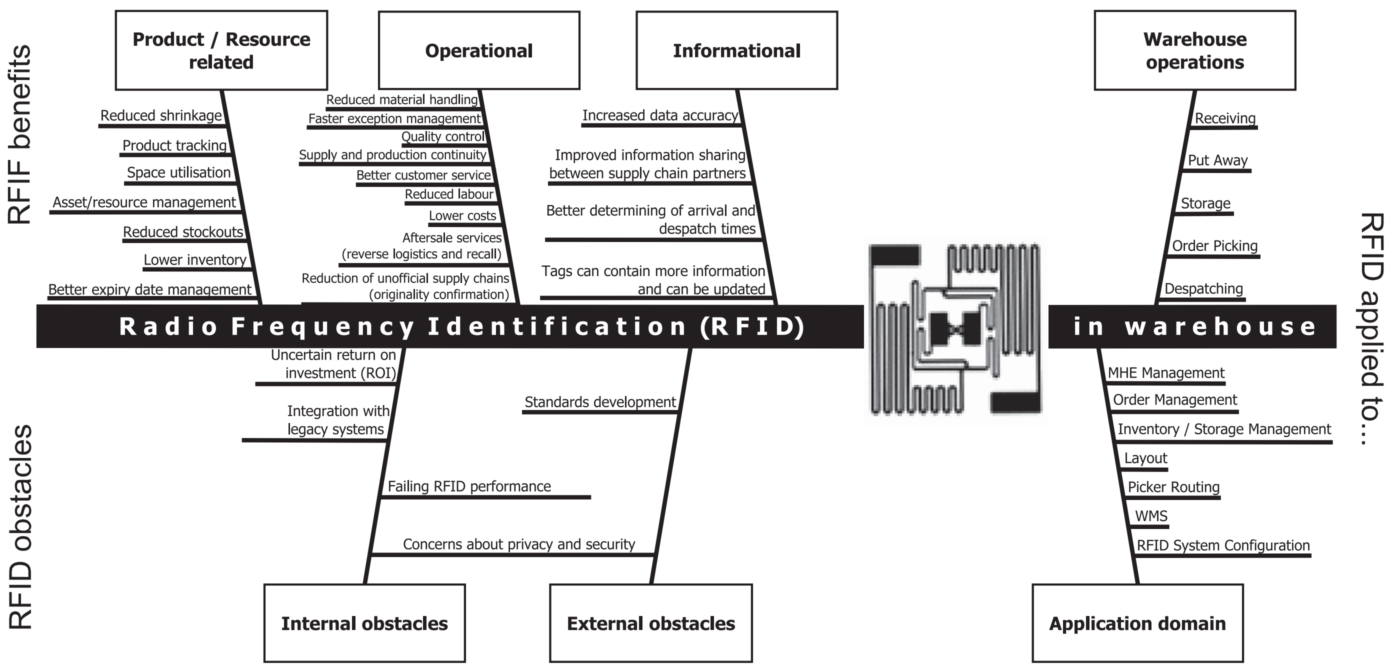


Fig. 2. RFID in the warehouse framework.

Fig. 2 shows that there are several factors to consider during RFID implementation in the warehouse. RFID technology can be implemented in all or only selected warehouse operations and there are several application domains to choose from. Furthermore, RFID benefits and implementation obstacles can also be identified at first glance. The framework presented in Fig. 2 provides a reference guide for both academic researchers and practitioners in considering RFID in warehouse operations. The framework differs from the RFID frameworks for other supply chain functions in terms of its scope as it is solely focused on warehousing. Nonetheless, the authors envisage that the result of this study will be of great benefits for a more general supply chain context in RFID research.

3. Discussion one: application of RFID in warehousing operations

3.1. Warehousing operations and their importance in the supply chain

The efficiency and effectiveness of a supply chain network is dependent on the performance of its functional elements, in particular, warehousing operations (Rouwenhorst et al., 2000). They facilitate storage and buffer functions between upstream and downstream points of the supply chain (De Koster et al., 2007). The core warehouse operations revolve around the flow of materials in the facility, which are receiving, put away, storage, order picking and despatching (Gu et al., 2007; Berg and Zijm, 1999). Receiving is the start of the warehousing process, in which the arriving items are unloaded from the transport carriers. Their identity, quantity and condition is checked at this stage, and items may be repacked to different stock keeping units, i.e. put into stillages, palletised or de-palletised, after which they await for the next process called put away. Put away is the process of physical moving of the received goods from the staging area to the locations in the warehouse, where they can be stored. Storage is the placement of goods in the facility for the purpose of safe keeping, protection and retrieval as required by the next activity. Order fulfilment or order picking refers to the removal of items from the storage locations for the purpose of fulfilling customer orders. Completed orders are checked to ensure picking accuracy and may be sorted or consolidated before despatching. Consolidation refers to grouping multiple orders for the same destination. Despatching is the last warehousing activity, in which goods are loaded onto a transport carrier.

In addition to the aforementioned activities, warehouses may also offer a cross-docking function that coordinates products movement between receiving and despatching activities. Inbound cargo is sorted, combined with other inbound deliveries and despatched without being put to storage. Cross-docking operations serve the purpose of holding fewer inventory items, reducing storage costs and improving service times (Maknoon and Baptiste, 2009). Furthermore, warehouses may also perform a range of value-added processes, such as break-bulk, unpacking, testing, assembling, labelling and repacking.

Warehouse operations are critical in the supply chain management context (Lambert et al., 1998; De Koster et al., 2007). Through their operations they address changing market conditions and the uncertainties of production and demand fluctuations. Moreover, they are capable of taking advantage of transportation and production economies, as well as allowing bulk quantity purchases to reduce procurement costs. Warehouses also serve as a buffer for activities like cross-docking, direct deliveries as well as reverse logistics in which materials are collected for disposal or recycling. Additionally, warehouses create important links between suppliers and customers by overcoming space and time distance between them, ensuring the maintenance of the desired customer service levels, consolidating multiple orders into one delivery and supporting just-in-time agreements between suppliers and customers.

3.2. RFID literature analysis

This paper performs an analysis on RFID publications corresponding to their application of the technology in the warehouse, which was a basis for the classification framework. In the first step of this classification, based on the content of the articles, two categories were identified: conceptual and implementation-focused application. The distinction between them is based on

Table 1
Literature category based on application domain and warehouse operation.

Operation	Application domain						
	MHE management	Order management	Inventory/Storage man	Layout	Picker routing	WMS	RFID system configuration
Receiving	Wang et al. (2010a) Chow et al. (2006a) Chow et al. (2006b) Chow et al. (2006c)	Wamba and Chatfield (2010) Zeimpekis et al. (2010) Bendavid et al. (2006) Wamba et al. (2006) Rizzi et al. (2008)	Wang et al. (2010a) Zeimpekis et al. (2010) Kwok and Wu (2009) Bendavid et al. 2006 Wamba et al. (2006) Lao et al. (2010) Wang et al. (2008) Rizzi et al. (2008) Lu et al. (2007) Wang et al. (2007)		Chow et al. (2006a) Chow et al. (2006b) Chow et al. (2006c)	Wang et al. (2010a) Zhang et al. (2009) Chu and Li (2008) Tan (2008) Yan et al. (2008) Qiu et al. (2005)	Modrak et al. (2010) Anssens et al. (2010) Ross et al. (2009) Rizzi et al. (2008)
Put away	Wang et al. (2010a)	Zeimpekis et al. (2010) Rizzi et al. (2008)	Wang et al. (2010a) Zeimpekis et al. (2010) Kwok and Wu, 2009 Cheung et al., 2009 Rizzi et al. (2008) Chuan et al. (2007)		Berenyi and Charaf (2008b) Berenyi and Charaf (2008b)	Wang et al. (2010a) Qiu et al. (2005)	Ross et al., 2009 Rizzi et al. (2008)
Storage	Wang et al. (2010a) Liu et al. (2006)	Zeimpekis et al. (2010) Rizzi et al. (2008)	Wang et al. (2010a) Zeimpekis et al. (2010) Kwok and Wu (2009) Gandino et al. (2007) Liu et al. (2006) Cheung et al. (2009) Hariharan and Bukkapatnam (2009) Muguira et al. (2009) Wang and Bao (2009) Ding et al. (2008) Ho and Sarma (2008) Rizzi et al. (2008) Chuan et al. (2007) Ong et al. (2007) Wang et al. (2007) Zhang et al. (2007) Naohisa et al. (2006)	Wang et al. (2010b)	Muguira et al. (2009)	Wang et al. (2010a) Tan (2008) Yan et al. (2008) Qiu et al. (2005)	Ross et al. (2009) Rizzi et al. (2008)
Order picking	Wang et al. (2010a) Poon et al. (2009) Poon et al. (2008) Prause et al. (2009) Liu et al. (2006)	Poon et al. (2009) Rizzi et al. (2008)	Wang et al. (2010a) Zeimpekis et al. (2010) Kwok and Wu (2009) Liu et al. (2006) Hariharan and Bukkapatnam (2009) Muguira et al. (2009) Ding et al. (2008) Ho and Sarma (2008) Rizzi et al. (2008) García et al. (2007) Naohisa et al. (2006)		Prause et al. (2009) Muguira et al. (2009) Berenyi and Charaf (2008b) Berenyi and Charaf (2008b) Faschinger et al. (2007)	Wang et al. (2010a) Qiu et al. (2005)	Ross et al. (2009) Rizzi et al. (2008)
Despatching		Wamba and Chatfield (2010) Zeimpekis et al. (2010) Bendavid et al. (2006) Wamba et al. (2006) Rizzi et al. (2008)	Zeimpekis et al. (2010) Kwok and Wu (2009) Bendavid et al. (2006) Wamba et al. (2006) Rizzi et al. (2008)			Zhang et al. (2009) Chu and Li (2008) Tan (2008) Qiu et al. (2005)	Modrak et al. (2010) Anssens et al. (2010) Ross et al. (2009) Rizzi et al. (2008)

Table 1 (*continued*)

Operation	Application domain						
	MHE management	**Order management**	**Inventory/Storage man**	**Layout**	**Picker routing**	**WMS**	**RFID system configuration**
			Lu et al. (2007) Wang et al. (2007)				
Others (general use)	Jeon et al. (2010)	Rizzi et al. (2008)	Rizzi et al. (2008)			Choy et al. (2008)	Choy (2009)
	Rizzi et al. (2008)		Lu et al. (2007)			Zhang et al. (2008)	Li and He (2009)
						Yang and Zou (2005)	Reza and Geok (2009)
							Singh et al. (2009) Hoong (2008) Rizzi et al. (2008) Singh et al. (2008) Kabadurmus et al. (2007) Son et al. (2007) Bosselmann and Rembold (2006) Leong et al. (2006) Porter et al. (2004)

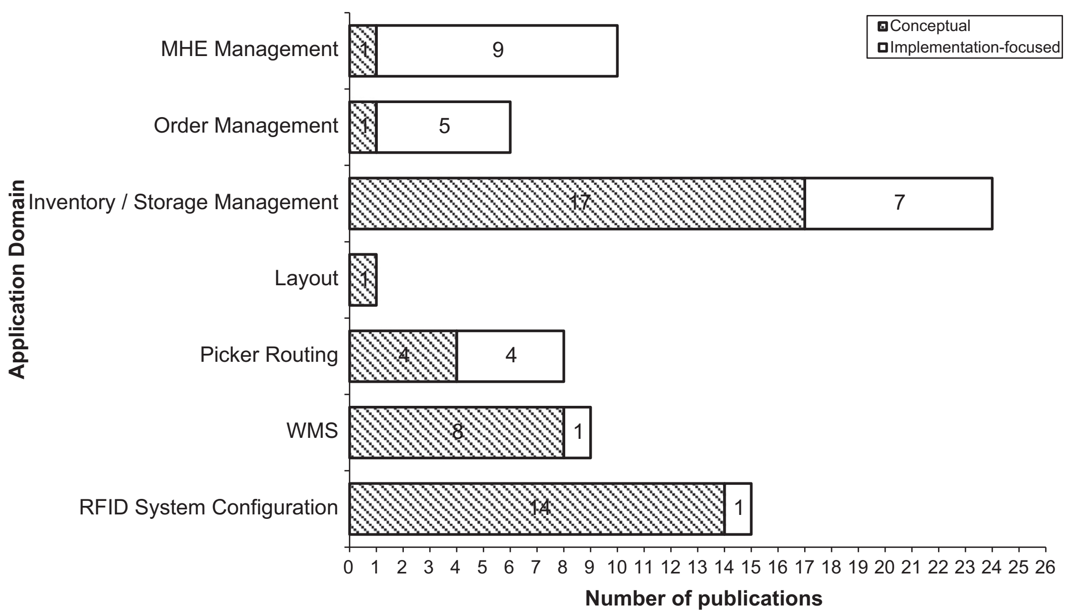


Fig. 3. Number of RFID publications in different application domains.

how the authors applied their research and findings. Articles demonstrating RFID application in warehouse environment at a company or laboratory facility were classified as “implementation-focused application”, whereas articles based on the results of software simulation, theory or proof of concepts, which did not state unambiguously any application or test in a warehouse were placed in the “conceptual” category. 16 articles were identified as implementation-focused applications and 42 articles were identified as belonging to the conceptual category. This in itself highlights the lack of implementation-focused applications and the gap forming between these two categories.

By thoroughly analysing the articles, they were further grouped by their application domain and warehouse operation; some of them belong to more than one category (see Table 1). As depicted in Table 1, seven application domains were identified and, in addition to the five typical warehouse operations, a category “others” was included for articles where the focus is on the general use of the technology in the warehouse. The 58 articles were then mapped with the appropriate RFID application domains and warehouse operations.

To distinguish between implementation-focused application and conceptual articles in each application domain, Fig. 3 was produced. It can be noted that the domain of inventory/storage management has received the most attention with 24 articles having been published (17 being conceptual articles and 7 implementation-focused applications). This is then followed in sequence by RFID system configuration (15 articles), MHE (material handling equipment) management (10 articles), WMS (warehouse management system) (9 articles), picker routing (8 articles), order management (6 articles), and lastly, layout with only 1 article. Table 1 can be further analysed with Fig. 4 showing the number of research works in each warehouse operation. It can be seen in Fig. 4 that most works (22 articles each) are related to receiving and storage operations, which coincide with Fig. 3 where

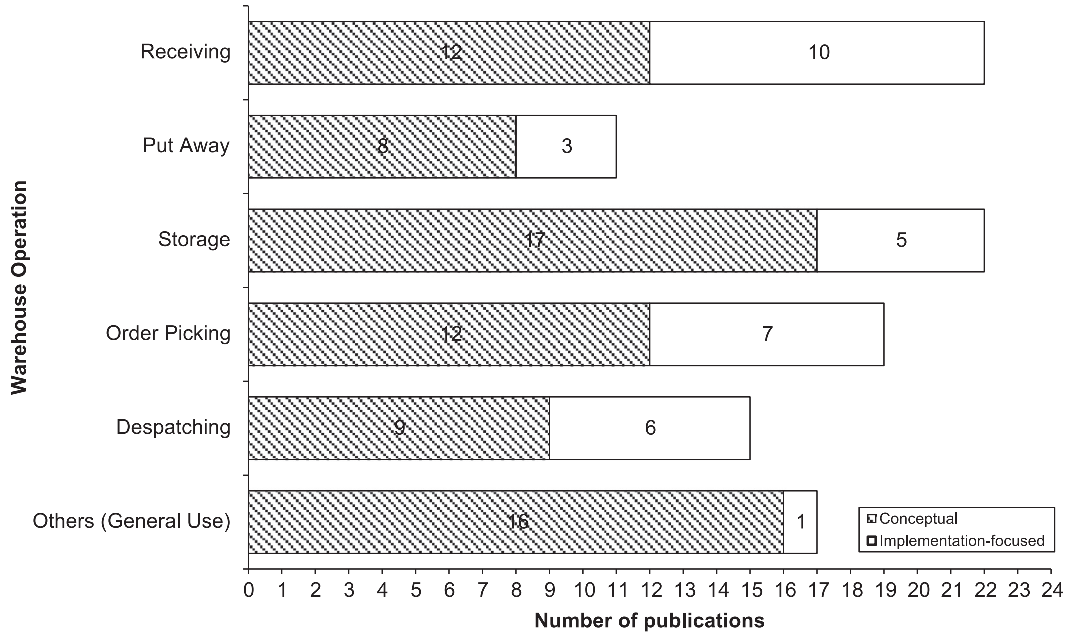


Fig. 4. Number of RFID publications in different warehouse operations.

the largest RFID application domain is inventory/storage management. The following subsections analyse the conceptual and implementation-focused categories based on RFID application domains.

3.3. Inventory/storage management

From Fig. 3, it is evident that the majority of authors focus on the use of RFID in inventory/storage management, which is an inherent part of the core warehouse operation. It can be seen that the number of conceptual articles has outgrown the number of implementation-focused articles. The literature studied shows how RFID systems can benefit the warehouse in inventory and storage management, especially in the effort to resolve inefficiencies such as poor storage space utilisation, misplaced stocks, and errors in inventory records.

The conceptual articles present ideas or methods, some supported with simulation results, to envisage how RFID can be used in the warehouse. For instance, Ho and Sarma (2008) proposed an optimal methodology to solve the problem in relation to storage location assignment and used RFID to facilitate storage in a random and fragmented manner (i.e. enhancing the use and taking advantage of the benefits of employing random storage policy). Hariharan and Bukkapatnam (2009) proposed a Partially Observable Markov Decision Process model to enable quick detection of misplaced items in the warehouse using portable RFID devices or RFID-enabled forklift trucks. This helps to avoid errors in storage location that lead to inventory inaccuracy, incomplete orders and may lead to subsequent lost sales. Prior to implementation, it is common to use simulation software to evaluate new ideas. Rizzi et al. (2008) and Lu et al. (2007) used simulation approaches to redesign and test warehouse processes of a FMCG company and pallet movement systems, respectively. Wang et al. (2008) and Wang and Bao (2009) analysed processes in mail and vegetable distribution centres respectively, pointing out how the introduction of RFID will impact the operations in these facilities.

As the technology has advanced, applications have been found incorporating RFID with other technologies/systems, on both software and hardware aspects. Software applications include a multi-agent system used in the warehouse for controlling inventory and communicating with suppliers (García et al., 2007), rule-based autonomous storage planning (Cheung et al., 2009), an RFID-based fuzzy storage assignment system (Ho et al., 2010), and a case-based reasoning using RFID to provide decision support system for food receiving operations assignment (Lao et al., 2010).

The hardware aspect of RFID applications includes a unique method of material tracking (using RFID and IR) in the warehouse proposed by NEC (Naohisa et al., 2006). Other examples include Wang et al. (2010b) combining RFID with a novel design of a conveyor belt system for storage and picking of items to fulfil customer orders and enable enhanced storage utilisation. Chuan et al. (2007) proposed a warehouse robot that uses RFID to identify objects and places in the warehouse by reading their tags and is able to navigate to designated locations. Furthermore, there are other creative proof of concept models, such as an unmanned air vehicle (UAV) flying in warehouse aisles for stock taking (Ong et al. 2007), an RFID-enabled hand glove for locating lost items and counting inventory (Muguira et al., 2009) and tracking frequent walks of warehouse operatives or retail customers to reveal frequently visited points in a facility (Berenyi and Charaf (2008b).

The research work in implementation-focused articles has predominantly on developing RFID software/infrastructure. Wang et al. (2010a) developed a Digital Warehouse Management System (DWMS), which consists of RFID-embedded pallets and shelves to provide real-time visualised inventory control and automatic storage and retrieval, and Liu et al. (2006) developed a resource management system to select the most suitable MHE to perform loading/unloading tasks in a lab-based warehouse facility.

Since its introduction to the logistics field, RFID has been considered a promising technology that could improve operations not only within a company, but as a wider system connecting businesses. A number of implementation-focused articles presented such business-to-business (B2B) e-commerce with sharing RFID-collected inventory data. Bendavid et al. (2006) built a proof of concept model in the laboratory demonstrating inventory data collection from the process of despatching cargo to receiving at distribution centre. Other authors were also using similar B2B approach for inventory management in their respective supply chains, such as in the beverage industry (Wamba et al., 2006), the textile industry (Kwok and Wu, 2009), and the agricultural industry (Gandino et al., 2007; Zeimpekis et al., 2010).

3.4. RFID system configuration

Several studies were conducted to evaluate the configuration of RFID systems in warehousing applications. All the articles studied in this context belong to the conceptual category, mainly focusing on testing models to find the best system configuration that hopefully can be applied in implementation-focused applications. A general description of RFID system set up for warehouse consisting of tags, readers, middleware and WMS was provided by Li and He (2009) and Modrak et al. (2010). The system configuration can be tuned depending on the specific requirements. For example, Choy (2009) presented a mathematical model for reconfiguring RFID systems, which takes into account warehouse policies at pallet, case and combined levels. With this model decisions can be made regarding the hardware requirements for RFID to be used in different warehouse applications. A variety of possible configurations has been considered by Ross et al. (2009) where six scenarios are analysed and simulated, from barcode only to full RFID roll-out. The factors considered are labour utilisation, personnel and warehouse activity costs. While considering implementation strategies, it is important to reflect on the problems emerging during RFID roll-out at the warehouse. There are several factors influencing the feasibility of RFID systems in warehouse operations that were tested by Porter et al. (2004), which included capture zone, orientation requirements, performance with MHE, performance when attached to different containers and content.

Another technical problem for RFID set up in the warehouse is in regard to the entire facility coverage within the reader's range. A solution was proposed by Reza and Geok (2009) who developed square and hexagonal grids that ensure adequate coverage of desired areas with appropriate RFID signal. Similar radio waves propagation within the facility was also undertaken by Bosselmann and Rembold (2006) where a ray tracing model was developed to visually show the areas where the RFID signal was weak, so that tuning to ensure full coverage can be done. In order to be able to obtain the functionality of an RFID system despite incomplete readings, Hoong (2008) designed an experiment to find the least possible area for obtaining a full read rate of stacked cartons, which can prove useful in setting up antenna and tag reading positionings. Likewise, the study on tagged cartons containing metal and water moving on conveyor belt was conducted by Kabadurmus et al. (2007). It was found that product type is a major factor contributing to RFID tag readability and fast conveyor speed is a crucial reason for tag misreading. This finding coincides with the studies by Singh et al. (2008, 2009) on palletised consumer goods, such as paper rolls, soda cans and water bottles. The variables identified were product type, pallet stacking pattern and forklift truck speed. Another factor impeding tag readability is the proximity of readers in a dense warehouse environment (Leong et al., 2006). A possible solution to this issue is proposed by Anssens et al. (2010) suggesting to synchronise readers' beams.

3.5. Warehouse management systems (WMS)

There has been considerable interest in investigating how RFID influences WMS and the effective methods of integration between them. Fig. 3 shows 8 conceptual articles and one implementation-focused application article related to RFID-assisted WMS. Generally, WMS and RFID technology are integrated at three levels: data collection, data movement and data management (Tan, 2008). Data collection is realised by RFID readers communicating with WMS via an IT network, and is analysed and used by the WMS as part of data management. However, continuous streaming of data in regard to identification and location of tags puts a strain on the WMS causing long processing times. In order to alleviate this issue at a conceptual level, Yang and Zou (2005) proposed an event-driven RFID reader management whereby data is sent to WMS on event triggered basis. This means that readers are only activated in the occurrence of detecting stock movements, and hence, only meaningful data is sent to WMS.

In addition, WMS may not be readily able to communicate with an RFID system. Thus it may be necessary to add an additional software layer that will enable data exchange. Chu and Li (2008) proposed a way to integrate RFID middleware with WMS based on service-oriented architecture (SOA), converting RFID data to a recognisable format. Zhang et al. (2009) implemented procedures for reader management in the Java programming language. According to Choy et al. (2008) another way to bring efficiency in WMS is to optimise database management with embedded procedures for handling queries efficiently, so as to enhance the performance of the entire system. Qiu et al. (2005), proposed an RFID-driven information flow system to address inefficient cycle counting, inaccuracy and costly labour. The one implementation-focused article is from Wang et al. (2010a) proposing DWMS which has been introduced in previous subsection.

3.6. MHE management

In contrast to previous application domains, there are more implementation-focused articles reported in MHE management. The only conceptual article is by Rizzi et al. (2008) developing business intelligence modules that execute rules for measuring key performance indicators and tracking of MHE activities in an FMCG company. In the implementation-focused use of RFID for tracking and routing MHE around the warehouse facility, there are several approaches proposed in the literature. Chow et al. (2006a) used ultra wideband (UWB) RFID system on forklift trucks to collect information about the state of the MHE, the problems with orders handling and the performance of warehouse resources. Similarly UWB was used in Chow et al. (2006b, 2006c). Liu et al. (2006) applied WiFi-based RFID system on the floor aisles to track cargo and MHE in real time in order to formulate an optimal strategy for order picking.

In order to ensure a smooth operation flow, the MHE must follow selected paths and all deviations from the routes must be recorded in order to improve future plans. Such systems to manage MHE during order picking were developed by Poon et al. (2008), consisting of RFID-tagged forklift trucks and a network of readers covering the entire warehouse. The later work by the same authors (Poon et al., 2009) proposed an RFID case-based logistic resource management system to improve order picking by formulating appropriate material handling solutions based on triangular localisation scheme. In contrast to expensive real-time locating systems or embedding RFID tags in the warehouse flooring, Jeon et al. (2010) suggested attaching tags to the warehouse ceiling in order to provide guidance for MHE. Guided maps for navigating MHE in order to improve routing and navigation around the facility were introduced by Prause et al. (2009) and Wang et al. (2010a).

3.7. Others (order management, picker routing and layout)

There are six articles from the set of articles considered reported contributing to improving order management, five of which are implementation-focused articles. These include the B2B models proposed by Bendavid et al. (2006) and Wamba et al. (2006), discussion of preliminary results of RFID pilot in Wamba and Chatfield (2010), logistics management of dried figs (Zeimpekis et al., 2010), and three dynamic methodologies of order fulfilment introduced by Poon et al. (2009). Only 8 articles reported on facilitating picker routing, i.e. RFID-enabled gloves (Muguira et al., 2009), an UWB system on forklifts (Chow et al., 2006a, 2006b, 2006c) and tracking of warehouse staff movement (Berenyi and Charaf, 2008a, 2008b), mobile assistance for warehouse workers (Prause et al., 2009) and RFID based system for solving optimal picking problems (Faschinger et al., 2007). The only article found for layout improvement is by Wang et al. (2010b) to fulfill customer orders efficiently through an RFID-enabled conveyor belt system.

3.8. *Types of RFID system in implementation-focused applications*

As part of the discussion, it is necessary to understand the type of RFID systems used in implementation-focused applications. To facilitate this understanding, Table 2 has been populated. It describes the implementation and application domains, and gives an overview of the type of frequency and communication protocol used, type of tags, and Electronic Product Code (EPC) compliance.

The UHF frequency has been a long standing choice for supply chain applications due to its long reading range and standardised protocol. This popularity is reflected in Table 2, where only two applications use HF tags. In Gandino et al. (2007), HF tags were used to identify fruit bins. Despite the unclear justification for this choice of frequency in the paper, it can be suggested that the HF property of working well around water contained in fruits could well be the reason. In addition, Liu et al. (2006) used HF tags placed on the floor aisles for MHE positioning. In this case the short reading range of HF tags was more suitable for this application to create more accurate paths for MHE, and to avoid interference with tags identifying stock.

Most implementation-focused application articles use passive tags in their applications. The rationale for their choice is that they

Table 2
Types of RFID system in implementation-focused category.

Article	Application domain	Brief description	Frequency LF, HF, UHF	Tag type: passive (P), active (A)	Comm. protocol	Compliance with EPC
Jeon et al. (2010)	MHE management	Localisation system for MHE based on the RFID tags attached to the ceiling of warehouse as the alternative for under flooring and expensive RTLS solutions. Real time MHE localisation and tracking of cargo/pallets realised	UHF	P	Wi-Fi	Yes
Modrak et al. (2010)	RFID system configuration	Laboratory study on optimal tag positioning on the inbound and outbound goods. Materials did not cause the considerable signal loss and tags were responding at longer distances, even if surrounded by pallets with raw materials	UHF	P	Not mentioned	Not mentioned
Wamba and Chatfield (2010)	Order management	Pilot project where RFID led to optimisation of warehouse processes. Picking and despatching were changed. Warehouse control improved. Real-time verification of shipments reduced shipping errors and lowered costs.	UHF	P	Not mentioned	Yes
Wang et al. (2010a)	MHE management, inventory/storage management WMS	Digital warehouse management system (DWMS) based on RFID. System tested in the tobacco warehouse.	UHF	P	Wi-Fi	Not mentioned
Zeimpekis et al. (2010)	Order management, inventory/storage management	Design and implementation of an intelligent RFID-based information system for supply chain management of fruits. Capable of capturing product history and quality, tracing it across distribution channels (i.e. for recall purposes).	UHF	P	Wi-Fi	Yes
Kwok and Wu (2009)	Inventory/storage management	RFID based intra-SC designed to link textile supply chain from dyeing, spinning, knitting manufacture and retail.	UHF	P	Not mentioned	Yes
Poon et al. (2009)	MHE management	RFID case-based logistic resource management system (R-LRMS) to improve order picking by formulating and suggesting the appropriate material handling solutions in a warehouse.	UHF	P	LAN	
Prause et al. (2009)	MHE management, picker routing	A mobile assistance for warehouse workers guides to picking locations using RFID. Results in reduced picking errors, shorter training for new staff, overall decrease of costs and increase of customer satisfaction.	Not mentioned	Not mentioned	Not mentioned	
Poon et al. (2008)	MHE management	Localisation system for warehouse forklift trucks based on the RFID	UHF	P	LAN	
Gandino et al. (2007)	Inventory/storage management	Inexpensive warehouse management system designed for traceability of products at small and medium food businesses	HF, UHF	P	Not mentioned	Not mentioned
Bendavid et al. (2006)	MHE management, inventory/storage management	Shows how RFID systems present at supplier at DC enable more automated e-commerce between supply chain partners	UHF	P	Not mentioned	Yes
Chow et al. (2006a)	MHE management, picker routing	RFID-RMS (Resource Management System) for selecting most suitable resource for material handling using case-based reasoning	UHF	P, A	UWB/Wi-Fi/LAN	Not mentioned
Chow et al. (2006b)	MHE management, picker routing	Knowledge-based Logistics Management System with integrated RFID, online analytical processing, case-based reasoning and optimisation models for supporting logistic decision making in planning and operation	UHF	P, A	UWB/Wi-Fi/LAN	Not mentioned
Chow et al. (2006c)	MHE management, picker routing	Real time knowledge-based system with integrated RFID, online analytical processing, case-based reasoning and optimisation models for supporting logistic decision making in planning and operation	UHF	P, A	UWB/Wi-Fi/LAN	Not mentioned
Liu et al. (2006)	MHE management, inventory/storage management	Resource management system for the real-time tracking the position of goods and equipment in the warehouse, also selecting suitable resource for package handling operation	HF, UHF	P	Wi-Fi	Not mentioned
Wamba et al. (2006)	MHE management, inventory/storage management	Presents the RFID EPC network as the opportunity to realise the B2B eCommerce supply chain management. Field study with beverage company	UHF	P	Not mentioned	Yes

are inexpensive due to simpler tag design and components, and their appropriate reading range for the applications. Moreover, passive UHF tags can be standardised with ISO/EPC protocols. However, some applications may require active tags, e.g. in Chow et al. (2006a, 2006b, 2006c) these tags were used to identify forklift trucks because of stronger signal and longer read range. The signal that is emitted by an active tag is strong to withstand interference from metal on forklift truck and provides a stable way for localising it during movement. As to the way readers communicate data from the tags to the middleware and WMS, several research works have been conducted based on LAN network (Poon et al., 2009, 2008; Chow et al., 2006a, 2006b, 2006c). The use of Wi-Fi networks was also investigated (Jeon et al., 2010; Wang et al., 2010a; Zeimpekis et al., 2010; Chow et al., 2006a, 2006b, 2006c; Liu et al., 2006) as it can cover warehouse space with minimum investment (i.e. using existing infrastructure). Additionally, solutions offered by the market that have embedded LAN and Wi-Fi capabilities make it a viable way for transferring RFID-generated data. As far as the standardisation is concerned, only six articles mentioned the compliance with EPC standards, but it may be suggested from the widespread use of UHF passive tags that other applications in Table 2 would also comply with EPC standards.

4. Discussion two: RFID benefits matrix

In order to provide an insight for warehouse researchers and practitioners to assess the value of using RFID, scientific articles were analysed to understand how RFID benefits were perceived. First, the articles were reviewed carefully to map with a list of benefits, as well as warehouse operations and application domains as previously discussed, so that a benefits matrix could be formed, as seen in Table 3. Table 3 shows that majority articles reviewed in this study acknowledge more than one benefit of RFID and relate to more than one warehouse operation and application domain. The matrix was further analysed by means of associating the benefits with relevant warehouse operations and applications domains as shown in Tables 4 and 5 respectively. The benefits in the tables were ranked according to their perceived popularity based on the articles analysed. This analysis approach is aimed at emphasising the high value benefits in the relevant warehouse operations and application domains, as well as highlighting the under-focused benefit areas that may lead to undertaking new research and developing new applications and solutions to improve warehouse operations.

There are a number of scholarly works discussing RFID achievements in the supply chain, identifying and assessing technology benefits. Tajima (2007) and Li and Visich (2006) proposed an extensive list of envisaged benefits within the supply chain context. Baars et al. (2009) suggested three key dimensions in which such benefits are realised: automation, information and transformation. These benefits can be direct or indirect and affect both operational and managerial areas. The list of RFID benefits compiled was derived from the previous works and was categorised into three warehouse-relevant groups of benefits: product/resource related, operational and informational. The category of benefits was developed by the authors based on the analysis of RFID benefits by their properties and categorisation by a common affiliation. Product/resource related benefits refer to the ones that impact on warehouse resources: storage space, equipment and handled products. Operational benefits refer to the ones achieved in warehouse activities. Informational benefits are derived from the informational capabilities of RFID technology. These three main categories summarise areas where RFID has its impact on the warehouse.

In order to give a more thorough analysis, Table 3 also shows the percentage of the number of articles (from conceptual and implementation-focused applications categories) reported achieving the benefit in each benefit area. It is worth noting that we have mapped the benefit only if it is clearly stated in the article as achieved, and have avoided making assumptions predicting what benefits could have been attained in the work reported in each article. This is to ensure the quality and reliability of the analysis without prejudice.

Based on Table 3, it is clear that many articles acknowledged more than one benefit received from a single RFID system implementation. This implies that the gains obtained from using RFID are interconnected between (and spread across different) operations/domains, and hence a number of benefits may be achieved simultaneously. For example, product tracking affects various areas providing more benefits within the warehouse. Product tracking realised with RFID allows for reduced shrinkages and better expiry date management. Additionally, knowing the location of the items helps to improve space utilisation and increase accuracy in product records, thus reducing inventory levels. Instant product identification realised with the RFID also helps to reduce the amount of manual labour, material handling and allows better exception management. Lastly, more accurate information about the products may enhance information sharing between the supply chain partners, helping in better determining arrival and despatch times.

In the early RFID literature the technology was argued to lower costs. This benefit resulted from using RFID to reduce product shrinkages and stock-outs, to improve space utilisation and asset/resource management and to lower the inventory. Moreover, lower costs are also the outcome of reduced material handling and reduced labour through the use of the technology. Analysing the link between the reduced labour and other RFID benefits, it can be realised that it is a direct result of product tracking that gives increased data accuracy. This means that picking routes can be planned more efficiently and less time is spent on identifying items and their locations. Furthermore, reduced labour is also linked to improved asset/resource management, where less time is spent on locating MHE equipment within the warehouse, as well as reduced manual labour as breaking pallets is no longer required to identify items. These benefits may also result in offering better customer services, such as no stock-outs, better expiry date management for quality products, and product authentication.

Table 3 also points out that the top benefits for implementation-focused application articles are lower costs (58%), reduced labour (50%), asset/research management (50%), and increased data accuracy (50%), whereas for conceptual articles they are product tracking (52%), asset/resource management (40%), reduced labour (19%) and material handling (17%). These results provide support for the relationship between identification as an essence of RFID technology and the benefits received. Recognising the unique identity of each object plays a crucial role in achieving the associated benefits above. For instance, with RFID in place, each pallet can be easily tracked and traced (i.e. product tracking), and warehouse operatives do not need to break down pallets to establish identity and or perform quantity checks (i.e. reduced labour time and cost). This also leads to facilitating material handling operations (i.e. good asset/resource management), and ensuring this information can be stored automatically on the back-end system/WMS eliminating laborious and error-prone manual data entry (i.e. increased data accuracy).

Tables 4 and 5 reveal the association between the benefits and warehouse operations and application domains, respectively. The tables serve a dual purpose. Firstly, they show the well-perceived benefits and the most applied warehouse operations and application domains. This helps warehouse practitioners to identify a basis to consider investment justification. For instance, based on

Table 3
RFID benefits based on application domain and warehouse operation.

Article	**Operation**						Application Domain						
	Receiving O1	Put away O2	Storage O3	Order picking O4	Despatching O5	Others (General use) O6	MHE management A1	Order management A2	Inventory/Storage management A3	Layout A4	Picker routing A5	WMS A6	RFID system configuration A7
Implementation-focused articles													
Bendavid et al. (2006)	X				X			X	X				
Chow et al. (2006a)	X						X				X		
Chow et al. (2006b)	X						X				X		
Chow et al. (2006c)	X						X				X		
Gandino et al. (2007)			X						X				
Jeon et al. (2010)						X	X						
Kwok and Wu (2009)	X	X	X	X	X				X				
Liu et al. (2006)			X	X			X		X				
Modrak et al. (2010)	X				X								X
Poon et al. (2008)				X			X						
Poon et al. (2009)				X			X	X					
Prause et al. (2009)				X			X				X		
Wamba and Chatfield (2010)	X				X			X					
Wamba et al. (2006)	X				X			X	X				
Wang et al. (2010a)	X	X	X	X			X		X			X	
Zeimpekis et al. (2010)	X	X	X	X	X			X	X				
% of number of articles on each benefit													
Anssens et al. (2010)	X				X								X
Berenyi and Charaf (2008b)		X		X							X		
Berenyi and Charaf (2008b)		X		X							X		
Bosselmann and Rembold (2006)						X							X
Cheung et al., 2009		X	X						X				
Choy et al. (2008)						X						X	
Choy (2009)						X							X
Chu and Li (2008)	X				X							X	
Chuan et al. (2007)		X	X						X				
Ding et al. (2008)			X	X					X				
Faschinger et al. (2007)				X							X		
García et al. (2007)				X					X				
Hariharan and Bukkapatnam (2009)			X	X					X				
Ho and Sarma (2008)			X	X					X				
Ho et al. (2010)		X							X				
Hoong (2008)						X							X
Kabadurmus et al. (2007)						X							X
Lao et al. (2010)	X								X				
Leong et al. (2006)						X							X
Li and He (2009)						X							X
Lu et al. (2007)	X				X	X			X				
Muguira et al. (2009)			X	X					X		X		
Naohisa et al. (2006)			X	X					X				
Ong et al. (2007)			X						X				
Porter et al. (2004)						X							X
Qiu et al. (2005)	X	X	X	X	X							X	
Reza and Geok (2009)						X							X
Rizzi et al. (2008)	X	X	X	X	X	X	X	X	X				X
Ross et al. (2009)	X	X	X	X	X								X
Singh et al. (2008)						X							X
Singh et al. (2009)						X							X

Table 3 (*continued*)

Article	**Operation**						Application Domain						
	Receiving O1	Put away O2	Storage O3	Order picking O4	Despatching O5	Others (General use) O6	MHE management A1	Order management A2	Inventory/Storage management A3	Layout A4	Picker routing A5	WMS A6	RFID system configuration A7
Son et al. (2007)						X							X
Tan (2008)	X		X		X							X	
Wang and Bao (2009)			X						X				
Wang et al. (2007)	X		X		X				X				
Wang et al. (2008)	X								X				
Wang et al. (2010b)			X							X			
Yan et al. (2008)	X		X									X	
Yang and Zou (2005)						X						X	
Zhang et al. (2007)			X						X				
Zhang et al. (2008)						X						X	
Zhang et al. (2009)	X				X							X	
% of number of articles on each benefit													

	Benefit						
	Product/Resources						
	Reduced shrinkage	Product tracking	Space utilisation	Asset/resource management	Reduced stockouts	Lower inventory	Better expiry date management
	A	B	C	D	E	F	G
Implementation-focused articles							
Bendavid et al. (2006)		X					
Chow et al. (2006a)				X			
Chow et al. (2006b)		X		X			
Chow et al. (2006c)		X		X			
Gandino et al. (2007)		X					
Jeon et al. (2010)				X			
Kwok and Wu (2009)				X	X	X	
Liu et al. (2006)			X				
Modrak et al. (2010)		X					
Poon et al. (2008)				X			
Poon et al. (2009)				X			
Prause et al. (2009)							
Wamba and Chatfield (2010)							
Wamba et al. (2006)							
Wang et al. (2010a)			X	X			
Zeimpekis et al. (2010)		X					X
	0%	38%	13%	50%	6%	6%	6%
Conceptual articles							
Anssens et al. (2010)		X					
Berenyi and Charaf (2008b)		X					
Berenyi and Charaf (2008b)		X					
Bosselmann and Rembold (2006)			X	X			
Cheung et al., 2009							
Choy et al. (2008)				X			
Choy (2009)		X		X			
Chu and Li (2008)		X		X			
Chuan et al. (2007)				X			
Ding et al. (2008)							
Faschinger et al. (2007)		X					
García et al. (2007)		X		X			

Hariharan and Bukkapatnam (2009)			X	X			
Ho and Sarma (2008)			X				
Ho et al. (2010)							
Hoong (2008)		X					
Kabadurmus et al. (2007)		X		X			
Lao et al. (2010)							
Leong et al. (2006)		X					
Li and He (2009)							
Lu et al. (2007)		X					
Muguira et al. (2009)		X	X				
Naohisa et al. (2006)		X					
Ong et al. (2007)							
Porter et al. (2004)		X		X			
Qiu et al. (2005)		X		X			
Reza and Geok (2009)		X		X			
Rizzi et al. (2008)		X		X			
Ross et al. (2009)		X					
Singh et al. (2008)		X					
Singh et al. (2009)							
Son et al. (2007)							
Tan (2008)							
Wang and Bao (2009)		X		X			
Wang et al. (2007)				X			
Wang et al. (2008)							
Wang et al. (2010b)		X					
Yan et al. (2008)				X			
Yang and Zou (2005)		X		X			
Zhang et al. (2007)				X			
Zhang et al. (2008)							
Zhang et al. (2009)	0%	52%	10%	40%	0%	0%	0%
% of number of articles on each benefit							

	Benefit													Specific benefits of RFID not discussed
	Operational									**Informational**				
	Reduced material handling	Faster exception management	Quality control	Supply and production continuity	Better customer service	Aftersale services (reverse logistics and recall)	Reduced labour	Reduction of unofficial supply chains (originality confirmation)	Lower costs	Increased data accuracy	Improved information sharing between supply chain partners	Better determining of arrival and despatch times	Tags can contain more information and can be updated	
	H	I	J	K	L	M	N	O	P	Q	R	S	T	X
Implementation-focused articles														
Bendavid et al. (2006)		X										X		
Chow et al. (2006a)	X				X				X	X				
Chow et al. (2006b)	X				X				X	X				
Chow et al. (2006b)	X				X				X	X				
Gandino et al. (2007)	X						X		X					
Jeon et al. (2010)									X					
Kwok and Wu (2009)				X			X				X			
Liu et al. (2006)	X						X		X					

Table 3 (*continued*)

	Benefit													Specific benefits of RFID not discussed
	Operational									**Informational**				
	Reduced material handling	Faster exception management	Quality control	Supply and production continuity	Better customer service	Aftersale services (reverse logistics and recall)	Reduced labour	Reduction of unofficial supply chains (originality confirmation)	Lower costs	Increased data accuracy	Improved information sharing between supply chain partners	Better determining of arrival and despatch times	Tags can contain more information and can be updated	
	H	I	J	K	L	M	N	O	P	Q	R	S	T	X
Modrak et al. (2010)														
Poon et al. (2008)							X							
Poon et al. (2009)							X			X				
Prause et al. (2009)					X		X		X	X				
Wamba and Chatfield (2010)									X	X				
Wamba et al. (2006)		X					X			X	X	X		
Wang et al. (2010a)							X			X				
Zeimpekis et al. (2010)					X				X		X			
	31%	13%	0%	6%	31%	0%	50%	0%	56%	50%	19%	13%	0%	0%
Conceptual articles														
Anssens et al. (2010)														X
Berenyi and Charaf (2008b)														
Berenyi and Charaf (2008b)														
Bosselmann and Rembold (2006)														
Cheung et al., 2009							X							
Choy et al. (2008)		X								X				
Choy (2009)														
Chu and Li (2008)														
Chuan et al. (2007)														
Ding et al. (2008)	X									X				
Faschinger et al. (2007)							X							
García et al. (2007)									X	X				
					X									

Hariharan and Bukkapatnam (2009)														
Ho and Sarma (2008)														
Ho et al. (2010)														
Hoong (2008)	X													
Kabadurmus et al. (2007)														
Lao et al. (2010)					X									
Leong et al. (2006)														X
Li and He (2009)							X		X	X				
Lu et al. (2007)	X						X							
Muguira et al. (2009)	X													
Naohisa et al. (2006)														
Ong et al. (2007)														
Porter et al. (2004)														X
Qiu et al. (2005)	X						X							
Reza and Geok (2009)														
Rizzi et al. (2008)														
Ross et al. (2009)							X		X					
Singh et al. (2008)														
Singh et al. (2009)														
Son et al. (2007)														X
Tan (2008)										X				
Wang and Bao (2009)							X		X					
Wang et al. (2007)	X					X								
Wang et al. (2008)														
Wang et al. (2010b)	X				X		X							
Yan et al. (2008)														
Yang and Zou (2005)														
Zhang et al. (2007)														
Zhang et al. (2008)														
Zhang et al. (2009)									X					
% of number of articles on each benefit	17%	2%	0%	0%	7%	2%	19%	0%	12%	12%	0%	0%	0%	10%

Table 4
RFID benefits by the number of publications categorised by warehouse operations.

Benefit		Operation						Total
		Receiving O1	Put away O2	Storage O3	Order picking O4	Despatching O5	Others (General use) O6	
B	Product tracking	12	7	13	10	8	7	57
D	Asset/resource management	12	7	12	10	6	6	53
N	Reduced labour	6	5	9	9	5	2	36
P	Lower costs	7	2	5	5	4	2	25
H	Reduced material handling	6	1	7	4	3	2	23
Q	Increased data accuracy	7	1	3	5	3	2	21
C	Space utilisation	1	3	5	4	0	0	13
L	Better customer service	5	1	3	3	1	0	13
R	Improved information sharing between supply chain partners	3	2	2	2	3	0	12
I	Faster exception management	2	0	0	0	2	1	5
K	Supply and production continuity	1	1	1	1	1	0	5
E	Reduced stockouts	1	1	1	1	1	0	5
F	Lower inventory	1	1	1	1	1	0	5
G	Better expiry date management	1	1	1	1	1	0	5
X	Specific benefits of RFID not discussed	1	0	0	0	1	3	5
S	Better determining of arrival and despatch times	2	0	0	0	2	0	4
M	Aftersale services (reverse logistics and recall)	1	0	1	0	1	0	3
A	Reduced shrinkage	0	0	0	0	0	0	0
J	Quality control	0	0	0	0	0	0	0
O	Reduction of unofficial supply chains (originality confirmation)	0	0	0	0	0	0	0
T	Tags can contain more information and can be updated	0	0	0	0	0	0	0
	Total	69	33	64	56	43	25	

Table 5
RFID benefits by the number of publications categorised by application domains.

Benefit		Application domain							Total
		MHE management A1	Order management A2	Inventory/storage management A3	Layout A4	Picker routing A5	WMS A6	RFID system configuration A7	
B	Product tracking	3	3	13	0	5	3	9	36
D	Asset/resource management	8	2	12	0	3	5	4	34
N	Reduced labour	5	2	8	1	2	2	2	22
Q	Increased data accuracy	6	3	4	0	4	3	1	21
P	Lower costs	6	2	5	0	4	1	2	20
H	Reduced material handling	4	0	6	1	4	1	1	17
L	Better customer service	4	1	3	1	4	0	0	13
C	Space utilisation	2	0	6	0	0	1	0	9
I	Faster exception management	0	2	2	0	0	1	0	5
R	Improved information sharing between supply chain partners	0	2	3	0	0	0	0	5
S	Better determining of arrival and despatch times	0	2	2	0	0	0	0	4
X	Specific benefits of RFID not discussed	0	0	0	0	0	0	4	4
G	Better expiry date management	0	1	1	0	0	0	0	2
K	Supply and production continuity	0	0	1	0	0	0	0	1
E	Reduced stockouts	0	0	1	0	0	0	0	1
M	Aftersale services (reverse logistics and recall)	0	0	1	0	0	0	0	1
F	Lower inventory	0	0	1	0	0	0	0	1
A	Reduced shrinkage	0	0	0	0	0	0	0	0
J	Quality control	0	0	0	0	0	0	0	0
O	Reduction of unofficial supply chains (originality confirmation)	0	0	0	0	0	0	0	0
T	Tags can contain more information and can be updated	0	0	0	0	0	0	0	0
	Total	38	20	69	3	26	17	23	

Tables 4 and 5 it can be identified that the benefits in the first third of the list are of high value and in addition, the storage operation (depicted in Table 4) and inventory/storage management (Table 5) have also received the most attention for RFID implementation/exploitation. Additionally, the less popular or overlooked benefits (especially the bottom third of the benefit list) and the under-focused warehouse operations and domains can also be identified. It was shown in earlier discussion that the RFID benefits are interconnected. This provides insights for academic researchers to form new research agendas and for practitioners to explore the potential value-added benefits of RFID adoption.

5. Discussion three: RFID obstacles in the warehouse

Despite the successful applications of RFID technology in the warehouse reported in industrial media (e.g. RFID Journal) and the promising academic research, there are a number of issues hindering the widespread adoption of RFID technology in warehousing. Within the context of general application of RFID, Bose et al. (2009) suggested that issues impeding technology impact are related to adoption/acceptance, privacy/security, problem solving and contingency factors. Focusing on the echelons in the supply chain, Kapoor et al. (2009) discussed a number of RFID adoption obstacles related to the supply chain relationship (e.g. information ownership transfer, sharing cost of infrastructure and lack of economic incentives for information sharing) and technology specific (e.g. system bottlenecks due to data volume, risk of obsolescence of installed RFID solution, read errors and evolving standards).

Similarly, RFID obstacles in warehousing are also related to the adoption process, integration and technology performance. These obstacles can be classified into internal and external categories (see Fig. 2). Internal obstacles refer to the problems encountered within the warehouse, starting with the decision to install RFID systems based on satisfactory return on investment (ROI), through to the concerns about integration with existing company legacy systems. RFID performance in the warehouse environment expands beyond an internal issue, as it is also depending upon the properties of the technology (which is considered to be an external obstacle). Matters of privacy and security are both internal and external, as on the one hand they involve the warehouse management and employees and on the other, they involve legislators and the like. The solely external obstacle affecting the RFID adoption in the warehouse is the issue of standardisation.

5.1. Uncertain return on investment

Return on investment (ROI) is one of the crucial criteria for companies to consider when introducing a new technology as this will point to their expectation on quantifiable benefits (Collins, 2004a).

Several studies have reported concerns of some industries with lack of confidence that RFID could bring a satisfactory ROI (White et al., 2008; Attaran, 2007; Vijayaraman and Osyk, 2006; O'Connor, 2005). In order to justify the ROI for RFID implementation in the warehouse, the industry will need to assess what is critical to their businesses that will lead to maximum gains. Tables 4 and 5 provide a list of benefits together with their application domains and operations that can be used as a reference. For instance, achieving lower inventory combined with compact space utilisation may open a possibility for additional gains from renting out the freed storage space. Furthermore, reduced demand for labour along with reduction in material handling may lead to additional savings as a consequence of lower staff requirements. The more positive outlook on ROI was verified in a recent study of the use of RFID in three echelon supply chain, which has illustrated the highest cost savings and satisfactory ROI in the warehouse (Giusto et al., 2010). The perception of unclear ROI and hesitance to invest in RFID may be changed by thorough evaluation of the application domains that will benefit the most in a warehouse facility, which will then create an opportunity for practitioners and researchers to identify new ways for efficiency enhancement, cost reduction and ROI improvement.

5.2. Integration with legacy systems

Another challenge to RFID adoption is the complexity of integration with the company's legacy systems, such as WMS, Enterprise Resource Planning (ERP), and Customer Relationship Management (CRM) (Vijayaraman and Osyk, 2006). This is also associated with the issue of handling the magnitude of data created by the integrated system. Without a common platform for exchanging data in different formats and high costs of system integration restrict the popularisation of the technology (Rim and Park, 2008). For example, the RFID Journal reported on the problems International Paper encountered whilst rolling out RFID at one of its warehouses (Fleet, 2004). The company's legacy systems were written in COBOL, one of the oldest programming languages, and were not able to interact with the data generated by the new RFID system. The problem was solved using a layer interface that converted RFID data and presented it to the legacy systems as barcode data. RFID may have a major impact on business IT systems and its seamless integration with legacy systems may require an enormous amount of planning in order to adapt the new integrated system with meaningful data in a reliable manner (Williams, 2005). The provision of such seamless integration is a great challenge; however it has the capability to significantly benefit a wide range of business operations.

5.3. Failing RFID performance

Another often mentioned obstacle to the widespread adoption of RFID is its performance (Wu et al., 2006). Several studies suggested that RFID does not provide 100% reliability of results in industrial settings (Collins, 2006b; Porter et al., 2004). In most cases, the reliability problems are related to the location of tags (Wu et al., 2006), signal distortions due to dense reader set up (Leong et al., 2006) and warehouse characteristics like metal parts and moving objects (Kabadurmus et al., 2007; Bosselmann and Rembold, 2006), as well as type of handled products (Singh et al., 2009).

Deficient performance of the technology directly affects warehouse operations like receiving, picking and despatching, as these are the areas that require absolute confidence in product identification. Errors at each stage lead to discrepancies in WMS and inventory management, more time spent on order picking and disruption in service to customers; all resulting in more enquiries, investigations, returns, credit notes etc. Understandably, the practitioners have a 100% reliability expectation on RFID. However, some researchers have suggested that reading performance at each stage of the warehouse operations does not always have to be 100% and a combination of actual and implied reads are sufficient to meet some purposes (Hardgrave and Miller, 2006). Ongoing improvements in the hardware aspect of RFID increase its capabilities and minimise deficiencies, but the perception of poor performance from earlier RFID experiences among practitioners may need time to overcome.

5.4. Concerns about privacy and security

The capability of RFID technology stimulated interest not only from academics and practitioners but also general public. The popular understanding of the technology suggests that RFID can continuously track people and objects anywhere and anytime, which created resistance and opposition to the technology (Hardgrave and Miller, 2006).

For companies the question of privacy may be a concern in case of shared storage facility and when open loop RFID solutions are considered. It is reported that companies see a threat of industrial espionage through unauthorised tags reading (Roussos and Kostakos, 2009). Furthermore, as the RFID technology is affecting employees' roles it is perceived as a threat to job security (Curtin et al., 2007). Therefore, it is important to emphasise to the workforce that RFID adoption is to help workers in their tasks and improve productivity, not to cause redundancies or increase workload. Kwok and Wu (2009) suggested that inviting employees to participate in the RFID roll-out plan at early stages minimises their resistance to changes in company operations and may also result in better solutions. The privacy and security issues may be solved by increasing the protection measures embedded in the RFID hardware and software, while public privacy concerns about RFID may be alleviated by education and legislation.

5.5. Standards development

Early articles and studies about RFID noted the lack of unified global standards as an obstacle to widespread adoption of the technology (Vijayaraman and Osyk, 2006). However, existing RFID standards are now more established (Hunt et al., 2007; Ahson and Ilyas, 2010; Finkenzeller, 2010). The International Organization for Standardization (ISO) created standards for several RFID applications, such as animal tracking (ISO 11784 and 11785), contactless payments (ISO 14443), and vicinity cards (ISO 18047). Standards for testing conformance (ISO 18407) and performance (ISO 18046) of RFID tags and readers were issued. Additionally, a global standard for supply chain has also been developed. Electronic Product Code (EPC) is the core element of EPC Global Network proposed by GS1. Its second-generation protocol (Gen-2) was developed and approved by ISO, within ISO 18000 series. Although many RFID vendors are now complying with Gen-2 standard in order to promote wider adoption, some vendors are still using their proprietary protocol for specific purposes/applications. It is also important to note that power regulations and certification procedures are still varied from country to country.

6. Discussion four: future trends

This section aims to explore the potential future trends and highlights a roadmap for the future through a set of questions that need to be addressed, so as to expand the current RFID research scope and the commercial use of the technology in the warehouse. The topics for future trends presented in this section are based on the analysis above and the recent movement in the RFID market. This movement is realised based on invaluable insight from the practitioners' perspective which was gained through commercial literature, especially the recent reports in the *RFID Journal*, as well as conversations with industry experts. Based on the extensive analysis of literature review and practitioners' input, the authors of this study identified four areas that could be valuable domains for conducting RFID research from a warehousing perspective. They are open systems, data sharing, integration with other technologies and Internet of Things. All of these four areas are connected through the use of RFID, not as a single point solution to solve operational problems within one organisation, but as a technology that spans across the domains and links entities due to its informational and data sharing capabilities and thus potentially creating more closely linked and interconnected logistic systems. The following are some of the research questions on using the RFID technology based on the four areas:

- Considering warehouses as a part of the open supply chains based on RFID, what are the technological and operational implications for warehouses that need to be facilitated? What about other echelons in the supply chain? What models or theories on supply chain and warehousing designs, applications and benefits assessment would help logistics practitioners?
- Which technological platforms could achieve seamless integration of RFID data across the supply chain? What would be the operational implications? How can supply chain members be encouraged to engage in wider data sharing? What could be done to alleviate security threats and privacy concerns? Which models and theories could help in evaluating and quantifying the benefits of data sharing across the supply chain?
- Which technologies currently used in warehouses could be enhanced with RFID? What could be done in order to ensure cost effectiveness of such integration? What would be the impact of RFID integration with other technologies on warehouse operations, productivity and costs? Would that meet the needs of warehousing practitioners?
- With the increase in popularity of the Internet of Things, what could be done to make warehouses part of this integrated system? What new models and practices could be developed? How can the benefits of such integration be evaluated and conveyed to practitioners?

The following sub-sections explore potential future trends based on the analysis of literature in this article and the current situation in the RFID market.

6.1. Open systems

It can be seen that majority of the research in the existing literature has been conducted focusing on the benefits achieved in a single operation or operations within a warehouse (i.e. a closed loop system), without expanding the research to consider how the technology could potentially benefit other supply chain partners (i.e. open system). The *RFID Journal* has reported a range of cases deploying RFID as an infrastructure to bring greater improvements in the wider supply chain (RFIDJournal).

As one of the core functions of RFID is unique identification of goods, more value can be achieved through close collaboration between supply chain partners as the goods move along the chain. For example, the downstream partners (e.g. retailers) can easily trace the status and location of their goods in the upstream supply chain and any discrepancy can be rectified immediately, in order to avoid stock-outs and hence increase sales and customer services. It can also prevent counterfeit products entering their supply chain. A further example is during the time of product recalls. Using RFID technology can make the process of recalling items faster and more efficient, as well as foster trust from the consumers, e.g. the application of RFID in tyre tracking during production, and in inventory management and aftermarket services (Wang et al., 2007). Kumar and Budin (2007) presented an approach for product recalls in food industry. Such solutions not only have the potential to provide the necessary identification in the case of product recalls but also to provide increased efficiency in supply chain operations such as resource management in transportation and warehousing facilities.

By opening up the view of using RFID in the supply chain, it can help practitioners to see more value that can be achieved by collaborating with supply chain partners and the potential to reduce the overall cost of RFID investment, and hence develop stronger business cases for technology adoption. From the academic perspective, more research could be conducted focusing on the wider aspect supporting the technology applied in the supply chain and the technological and operational implications that need to be facilitated.

6.2. Data sharing

The ability to share RFID data is the key success of the technology. Data sharing is critical for applications in closed and open systems (Kwok and Wu, 2009; Wamba et al., 2006). Within a warehouse it can be used for different departments/operations to achieve their purposes, e.g. quality control and expiry date management. These have been identified in Tables 4 and 5 as less popular but value-adding benefits, which in this case, can be delivered. For an open system, the warehouse operator will need to know the manufacturer's production status in order for them to prepare the storage facility needed, so does the transportation to ensure their service availability. Irregularities in the supply can be immediately detected.

Another benefit closely connected to data sharing is exception management. Swift identification with RFID enables alerting warehouse staff to expected special (urgent despatching) products, which in other cases would not be given the priority. Sharing data about stock between warehouses and supply chain partners helps to avoid high inventory (safety stock) levels. Moreover, better determination of stock arrival and despatch times can also be realised, resulting from the ability of reading RFID tags at different stages in the supply chain (Bendavid et al., 2006).

To enhance data sharing across the supply chain, practitioners could utilise a central data sharing system such as EPC Information System (Osinski, 2009). With EPCIS, each supply chain partner can easily access the collected data. However, much research will be needed focusing on a common (technical) platform whereby each key operation at the supply chain partners can be seamlessly incorporated, e.g. to create a communication channel for instant notification of action.

6.3. Integration with other technologies

As with any emerging technology, more features will be expected by the users. This can be seen when one technology integrates with another so that better features can be introduced and less infrastructure changes can be made possible. In the RFID market, to enhance its adoption there are integrations with Wi-Fi, GPS and infrared for various applications. In warehousing, RFID integration with, e.g. pick-to-light and voice-assisted picking systems, will lead to more efficient storing and order picking. New ways of integrating different technologies should be explored in warehousing facilities in order to maximise operational efficiency and much research should be conducted to address the technical and operational challenges for such integration solutions.

6.4. The Internet of Things

The Internet of Things (IoT) has been a popular topic in recent years (Atzori et al., 2010), significantly supported by many governments. Within the Seventh Framework Programme, the European Commission is supporting a number of research projects on IoT. In China, Wuxi City is named as the National Innovation Demonstration Zone of IoT (Iera et al., 2010). In essence, IoT consists of a network of autonomous nodes (e.g. systems, technologies, applications) but yet connected through a common platform and that are capable of communicating with each other to provide a wide range of services. RFID can play an important role in this network as a means of communication and data provider. In terms of warehouse/RFID research, there is a range of domains worth exploiting, such as data interchange mechanisms, compatibility between different systems/Internet technologies, adaptable B2B models, and so on.

7. Concluding remarks

This paper has provided a comprehensive analysis of the academic literature published from 1995 to 2010 pertaining to the application of RFID technology in warehouses based on the perceived benefits, application domains and the types of warehouse operations.

The paper was organised into four discussion topics, aiming to analyse the current state of RFID application in warehousing, to provide insights for researchers to establish new research domains and for the practitioners to consider their assessment of adopting RFID in the warehouse. To the best of authors' knowledge, this study is the first detailed review of academic literature about RFID application in warehouse functions. Previous work has included an overall reviews of the RFID literature (Ngai et al., 2008; Chao et al., 2007) or has been specifically focused on supply chain management (Sarac et al., 2010). It is important to focus solely on warehousing functions as they are complex in themselves and play important roles within the supply chain. Moreover, limiting the research scope to warehousing functions has facilitated the identification of gaps that have not been explored in previous supply chain focused works, as well as generating findings relevant to warehouse operations. The paper has discussed the benefits and applications of RFID in warehouses, how they are strongly linked to identification and the associated benefits of RFID that are seldom examined in the warehousing literature. Additionally, the current status of RFID solutions for warehousing was presented and evaluated against previous recommendations. Furthermore, potential RFID obstacles and future trends were examined from the warehousing perspective.

Ngai et al. (2008) predicted the future increase in the amount of the published literature on RFID and this study confirmed the continuation of this trend (see Fig. 1), but it was found that particular interest in RFID in warehousing is rather stagnant and relatively small in comparison to other research domains. Ngai et al. (2008) noted that the RFID research focuses on internal operations (i.e. closed loop system) and has given a recommendation for opening it up to include a wider scope of benefits that may be achieved in the value chain. It emerged that the majority of articles reviewed in this study also focused on the benefits achieved in a single operation or operations within a warehouse. Therefore, the authors of this study would like to stress the recommendations, given in previous section, for expanding the research to how the technology could potentially benefit other supply chain partners.

As for the reasons impeding RFID applications, technical and economic difficulties discussed in Sarac et al. (2010) were also confirmed by in this study. Despite the similarity of insights with general and supply chain management RFID reviews of the scientific field, this article identified the gaps and findings that are specific to the warehouse research. The prior RFID warehouse research reviewed in this study was divided to two categories: implementation-focused applications and conceptual papers. Articles in the first category showed how RFID is applied in the various warehouse functions, and specifically dealt with practicalities of the application. Conceptual papers proposed ideas for improvements and extended the use of the technology with findings based on computer simulation, theory or proof of concept.

This study identified several key findings/gaps that could be covered in future warehouse research. First of all, it was pointed out that researchers' focus is revolving around the applications and benefits that are closely linked to “identification”, which is the core function of RFID technology. This study has also revealed various associated benefits of RFID that are scarcely examined in the literature. It is envisaged that studies showing linkage between RFID benefits could strengthen the case for RFID adoption. Secondly, RFID solutions are treated as a closed loop system and its benefits are less exploited across the supply chain, in spite of recommendations in the earlier works. To facilitate the exploration of wider adoption in the supply chain, this study discussed the potential RFID obstacles that could hold up the adoption decisions. Furthermore, this study also indicated and discussed the potential future trends that could lead to further research directions and new, creative applications for commercial use.

The study also offers lessons for practitioners. The study can be used as a reference library to identify specific RFID warehouse applications, which have been classified by warehouse operation, application domain and benefits discussed. The analysis of the implementation-focused RFID applications may be of interest to industry executives, as it not only provides a summary of how the RFID technology is used in warehouses, but also points out technical details of each application. This may serve as guidance for plans to implement RFID and business cases may be strengthened by considering the inter-related RFID benefits that could be achieved in the warehouse. Lastly, the discussion on RFID obstacles in the warehouse may help to avoid pitfalls en route to successful RFID adoption.

Building a strong business case for RFID adoption in the warehousing industry requires moving from the current state to more value-added applications in emerging technologies. There are several ways for the data generated by RFID to benefit warehouse operations. One of them is to use the data for cost analysis of the performed operations. The authors of this paper are currently developing a dynamic cost optimisation framework for WMS that will evaluate all associated costs of warehouse operations based on RFID data, so as to fulfill customers' order requirements more efficiency and cost-effectively. In conclusion, the authors would like to encourage academics and industry researchers to look beyond the core applications for RFID and consider more overarching applications that will take RFID benefits beyond the current state, e.g. being able to support the up and coming realisation of IoT.

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