INTELLIGENT CONSTRUCTION COMPONENTS FOR INTEGRATING PRODUCT DESIGN, DELIVERY PROCESS, AND LIFE-CYCLE PERFORMANCE

Nuno Gil, Hilary Kahn

Manchester Centre for Civil & Construction Engineering, UMIST and University of Manchester, PO Box 88, Manchester, M60 1QD, nuno.gil@umist.ac.uk
Department of Computer Science, University of Manchester, Oxford Road, Manchester, M13 9PL, hkahn@cs.man.ac.uk

Information and communication technology (ICT) can enable high-value delivery, performance, and maintenance of components for engineering and construction projects. This work presents a literature review on the capabilities of Radio Frequency Identification (RFID) tagging — a technology increasingly applied in various industrial sectors though in a limited way in the construction sector. This review looks at how, in theory, RFID tagging can add 'intelligence' onto construction components to, first, enable companies involved in a supply chain to access more accurate information about product demand, inventories, and production and distribution capacities; and second, to help suppliers gain insights into actual usage patterns, and the life-cycle maintenance and servicing needs of the products they design and manufacture. Further, we detail specific real-world problems, unearthed after conducting preliminary empirical research with a glass manufacturer, which reveal opportunities to which RFID tag-sensor technology capabilities may provide effective solutions. Consideration is also given briefly to a formal, information model-based approach to providing effective IT solutions to applying RFID tag-sensor technology to construction components.

Keywords: RFID tagging, sensors, construction supply chain, information modelling

INTRODUCTION

Two interrelated problems motivate this work: first, the noticeable inefficiency of the supply chains for components that integrate engineering and construction projects, in which non-value added time can amount to more than 90% in the case of engineered components (Elfving et al. 2002, Arbulu et al. 2003); and second, the inadequate information flows – when not missing entirely – between product developers/manufacturers, user-customers, and maintenance and serviceability divisions (Tsao et al. 2004). Supply chain systems encompass material and equipment suppliers, production facilities, distribution services, and customers, linked together via the feed forward flow of materials and the feedback flow of information (Towill 1996). Supply chain management is complex whenever product demand is hard to predict due to expanding product variety, short-product life cycles, and variety of selling channels (Christopher and Towill 2002, Lee 2002). In particular, demand is hard to predict with supply chains serving the engineering and construction industry, first because of the project-based nature of the markets, and second, because of the industry's fragmented nature that offers suppliers limited visibility of the flow of their products down the supply chain (Vrihhoef and Koskela 2000). These are significant

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problems because, where supply chains are long and unreliable, lead times make it harder to compress project delivery times and to finish projects on time (Tommelein et al. 2004). The problem is getting increasingly significant as labour shortages force the industry to use more pre-fabricated and pre-assembled components (Gibb 1999).

The fragmented nature of the construction industry and the lack of appropriate methods and tools, make it hard for customers and suppliers to know, in the course of the operating life cycle of the components, the actual component performance in terms of robustness and reliability to usage patterns, and the actual maintenance and servicing requirements (Shohet et al. 2002). Occasionally, components may be installed in locations that are hard to reach or that require extra health and safety precautions from operators, and monitoring their performance is a costly and time-consuming process. As a result, components may be used and perform differently from product developers- and user-customers' design intent but this remains ignored by suppliers. This problem matters to suppliers, who identify here potential business opportunities and competitive advantages, and to customers, who are primarily concerned with escalation of maintenance and serviceability costs and with being given levels of service that meet their expectations (Dainty et al. 2003, El-Haram and Horner 2003).

Information and communication technology (ICT) is increasingly seen as an enabler of high-value delivery, performance, and maintenance of construction components (Feeser 2001). ICT can enable supply chain participants to integrate and gain better access to information about demand, inventories, and production and distribution capacities (Choi and Liker 2002). Information visibility can help companies to eliminate non-value added activities, optimize capacity utilization, pursue economies of scale, reduce excessive inventories, and design supply chains that are flexible and sufficiently responsive to variability in demand (Alshawi 2001, Koutsakas et al. 2002, Shankar and O'Driscoll 2002). Information visibility can also help suppliers gain insights, which otherwise would be hard to get and sustain, into actual usage patterns and into the maintenance and servicing needs of their components. These insights can help suppliers design and manufacture better products. Access to information also matters to customers who invest upfront in components, bear the cost of their maintenance and serviceability, and wish to be provided with levels of service that meet their expectations.

RFID TAGGING AND SENSOR TECHNOLOGY

Radio Frequency Identification (RFID) tagging, unlike bar coding, is a non line-of-sight technology that uses radio waves to identify individual items. RFID technology consists of two main components: a reader and a transponder (or RFID tag which is a microchip attached to an antenna). A reader converts the radio waves emitted by the RFID tag into a form readable by computers. There are two varieties of tags: active and passive. Passive tags are small, approximately a centimetre square, and thin and light enough so that the electronic circuit can be printed on flexible plastic; they are inexpensive (as little as 25p and likely to fall further) but hold a limited amount of information and can only be detected when they are in close proximity to a reader. In contrast, active tags can carry more information and incorporate a battery that runs the chip's circuitry and broadcasts a signal to the reader; active tags may measure a few centimetres across and are more expensive. State-of-the-art RFID tagging technology offers increasing capabilities such as (1) extended communication ranges, up to 50 m or more, (2) fast tag read/write rates, (3) enhanced programmable storage capacity, (4) selective addressing (i.e., reader's ability to communicate with an individual tag); and (5) extended battery life (Ashton 2003).

Initiatives to exploit RFID technology have emerged in various sectors. Some investigate the usefulness of RFID technology to improve the performance of closed-loop systems, i.e., systems in which the data regarding the attributes of the tagged object is stored in a common database under the control of a single owner, such as systems for supporting factory automation, asset and human tracking during military operations, automatic vehicle identification systems, and library systems (AIM 2003). Other initiatives investigate the applicability of RFID technology to support open-loop systems that involve several companies exchanging electronic data, such as cargo shipment and livestock tracking. In the engineering and construction sector, research has applied RFID tagging technology to support the delivery of products to construction sites, including structural steel members (Furlani and Pfeffer 2000), engineered pipe supports and hangers (Jaselskis and El-Misalami 2003), and stonework pallets (BRE 2003). Recent figures indicate that RFID technology is the basis of 6,000 patents filed and suggest that today's almost £1 Billion worth of RFID technology sales could hit £10 Billion in a decade (Booth-Thomas 2003).

The applicability of RFID tagging technology for supporting supply chain management was the focus of the Auto-ID Center's work (Auto-ID Center 2003) – a research initiative that evolved into the EPCglobal Network, a not-for-profit organisation entrusted by industry to promote standardization and interoperability between RFID tag systems for supporting supply chain processes. EPCglobal Network's initial work on standardisation has started to handle identification of tags and communication with tags (EPCglobal 2004). EPCglobal work uses passive tags (primarily attached to cases or pallets) to track the whereabouts of low-value goods as they pass from the factory floor to the warehouse, through the distribution chain to the retailer and the point of sale. The data generated by the RFID system, once interpreted by a decision-support system, gives manufacturers detailed information on the quantity and location of product inventories and helps to monitor product delivery. This data also helps retailers to guard against stock shortages and monitor better sales systems. While the results from pilot projects are promising (Ashton 2003), more research is needed to understand how to implement RFID tagging systems in ways that are economical, that do not infringe consumers' privacy rights, and that are practical (Kärkkäinen and Holmström 2002, Rae-Smith and Ellinger 2002).

In contrast, less work has been done on how to exploit RFID tagging technology for managing the delivery of high-value components. Here, the cost of the tag is negligible in relation to the cost of the component. This allows for investigation of the use of active, read-write tags integrated with sensors and with extended functionality and communication range. Read-write capabilities can be useful for monitoring and recording the operating performance and usage patterns of high-value components, thereby binding performance data with the physical object. Further, the technology can potentially help to provide feedback to product developers and manufacturers on product performance, on usage patterns, and on maintenance, servicing, and operating needs. Recent industry initiatives indicate that suppliers are increasingly interested in offering customers improved visibility on product performance and service history. For example, OTIS' E*Service uses the Internet to provide customers with round the clock access to maintenance records and performance history of their lifts and escalators (OTIS 2003). Likewise, Pepperl+Fuchs commercializes a wireless-based identification system for supporting preventive maintenance and problem forecasting on roller coasters (Hornis 2004).

Few research studies have, however, investigated, the benefits of integrating sensors with RFID tagging technology within the built environment. While integrated RFID tags-sensors offer great promise, they are only beginning to be commercially available; in contrast, research applying sensor technology to the physical environment is not new (Akinci et al. 2003). For example, two initiatives ─ 'Smart Office Spaces' by the Berkeley Sensor and Actuator Center and 'Wireless Measurement and Control of the Indoor Environment in Buildings' by the Berkeley Wireless Research Center —exploit sensors (of temperature, humidity, levels of light, and air quality) to develop more energy efficient and comfortable buildings (CBE 2004). Active RFID tagging technology when integrated with sensors promises to be useful in addressing the aforementioned problems. However, the extent to which RFID tag-sensor technology can deliver technically feasible, economically viable, and practical intelligent components remains to be proved.

PRELIMINARY EMPIRICAL FINDINGS

Jointly with three British manufacturers of construction components (Pilkington, Kingspan, and Intelligent Modular Solutions) and a British information systems company specialising in the design and supply of software driven item or asset tracking and recording systems (Intellident) ─ we identified specific real-world problems and limitations that suggest the existence of opportunities to which RFID tagging-sensor technology capabilities may provide effective solutions.

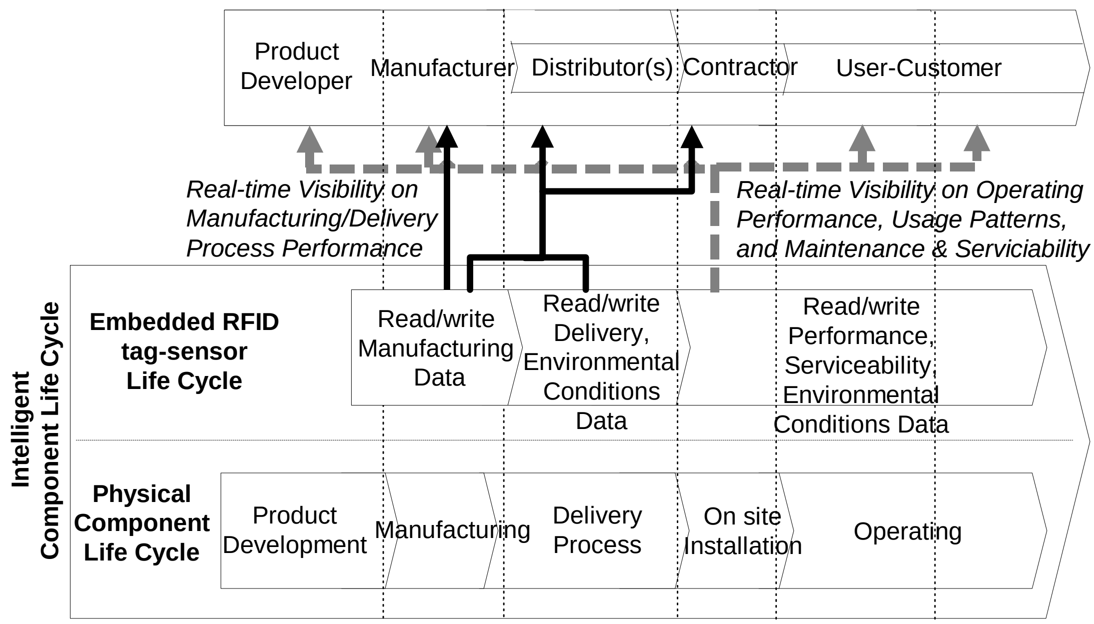

Figure 1 –'Intelligent' Component Life-Cycle

These opportunities, conceptually depicted in Figure 1, fall into three main categories: (1) facilities management and preventive maintenance: the lack of systems that generate alerts should engineering and construction components start to show evidence of performance deterioration (e.g., unusual temperatures and vibration modes) prevents timely repair/replacement before potentially disastrous breakdown; (2) life-cycle monitoring: the absence of monitoring of e.g. temperature or humidity means that extreme ambient conditions at any point in the product lifecycle may result in damage to components that goes unnoticed; and (3) product traceability: difficulties in matching components with their respective factory batches, and consequently with manufacturing and delivery information, undermine the confidence of both user-customers and manufacturers in the quality of the products, cause delays in product delivery, increase risks associated with product warranties, and contribute to augmenting the cost of insurance premiums. As an example, the next section focuses on one of the cases investigated, that of Pilkington.

THE CASE OF PILKINGTON

Empirical Research Approach

An empirical research study was carried out in collaboration with managers and staff from Pilkington's factories in St Helens, UK (Green Gate and Cowley Hill). Between October 2003 and April 2004, seven people at Pilkington with job responsibilities in technology research and development, customer service and logistics, stockroom management, and production management were interviewed. The operations manager for Nijman/Zeektank (the company responsible for transporting Pilkington's glass) was also interviewed. These interviews together with archival documentation from Pilkington (e.g., operations procedures/manuals, printouts of the computerized logistic system, business reports) form the basis of our understanding of opportunities for applying RFID-sensor technology to Pilkington's float glass business.

Float Glass Manufacturing Process

Pilkington is one of the four world's largest manufacturers of glass and glazing products for the building and automotive markets, each market being responsible for approximately half of the sales. At the heart of Pilkington's business is the float process which manufactures clear, tinted and coated glass. The process produces large glass plates that are perfectly flat and free from optical distortion and flaws. Succinctly, the process consists of first mixing together, refining, melting, and homogenising fine-grained ingredients (high quality sand, soda ash, limestone, salt cake, and dolomite) at 1,500^{o}C to make a molten glass batch. Then, the molten glass is poured continuously, at approximately 1000ºC, from the furnace onto a shallow bath of molten tin, where it spreads out and forms a level surface. After annealing (controlled cooling), a solidifying glass ribbon is drawn off from the bath at 600^{o}C to emerge as a polished product with virtually parallel surfaces. The glass thickness is controlled by the speed at which the glass ribbon is drawn off. Automated on-line inspection reveals upstream process faults that can be corrected, and enables computers to steer cutters round flaws. Glass can then be processed into products with additional properties through large-scale coating, laminating and silvering processes. These are usually carried out in different factories although multiple coatings can be deposited on-line as the ribbon of glass is being formed.

The global market for flat glass is around 34 million tonnes a year, of which around 70 per cent is consumed in windows in buildings (Pilkington 2003). Pilkington controls 15 per cent of the world's flat glass production capacity. It operates 25 plants and has an interest in another nine, making around 6000 kilometres of glass a year in thicknesses of 0.4mm to 25mm and in widths up to 3 meters (Pilkington 2004). Pilkington's central planning department schedules the manufacture of glass considering four main factors: order book, stock levels, transport availability, and sale forecasts.

Glass is either made to stock or to order. A main factor driving the need for making glass to stock is the fact that a float glass plant is designed to run non-stop, 24 hours/365 days per year, throughout each campaign life of between 10 and 15 years. Float lines are normally capable of several campaigns following major repair/upgrade programmes (Pilkington 2003). Float glass can be of different colors (e.g., green, bronze, grey), each involving a different batch composition. The transition product after changing batches, which can amount to as much as seven day's production, is 'set to crush,' i.e., will be sent to the waste glass section waiting to be recycled as raw material in a later batch. A float glass factory typically makes large quantities of glass to stock before changing the float composition as a function of demand forecasts.

Float Glass Delivery Process

Pilkington's customers include glass merchants and distribution outlets that cut the glass and sell it to other customers in custom sizes, secondary process plants and automotive glass manufacturers (some of which are Pilkington associates), and window manufacturers. Float glass is sold by the square metre. Glass is relatively heavy and comparatively cheap, making distribution costs significant (Pilkington 2004). Computers translate the customer's requirements into patterns of cuts designed to minimise wastage. Diamond wheels trim off the selvedge and cut the ribbon to size dictated by the computer. The glass sheets are then stacked together usually in packs of 50 sheets and placed on special glass handling steel crates called 'stillages'. These stillages are used both as storage devices and to transport glass to the clients.

The minimum order of glass is 20 tonnes, which equates to approximately 100 sheets of 6m by 3m sheets of glass. Stillages are usually full and carry up to 5 packs of the same type of glass. While large merchants typically order only one type of glass per stillage, small merchants may order different glass types to be transported on the same stillage. Stillages have various forms and are designed to carry different glass types. Figure 2 shows an 'LE' and a 'CB' stillage. Pilkington estimates that they have approximately 7,000 stillages in circulation: 10% of the fleet are 'LE' type stillages, which is one of the largest types, and 15% are 'CB' stillages, the smallest of the stillages which Pilkington uses to supply glass to the automotive industry.

Figure 2 – LE (left) and CB (right) Stillages (reprinted with courtesy of Pilkington)

Most of the larger stillages used by Pilkington can only be carried by a special truck and trailer system called a Floatliner, which is unique in the fact that it loads itself without the use of a forklift. The truck backs the trailer onto the stillage and the trailer's in-built hydraulic equipment enables it to lower itself and pick up the stillage. A system of radio tracking is used to pinpoint accurately any truck anywhere in the UK at any time.

Opportunities for Applying RFID tags

Pilkington uses a standard software application developed by SAP[1] to schedule the manufacture of the glass. Pilkington produces and places barcode labels on the side of each pack of glass to allow the packs to be identified by the warehouse and transportation staff. The barcode information allows Pilkington to identify each individual pack of glass and store this information on the SAP system, including type of glass in the pack, glass features (colour, quality category, size, thickness), and number of glass sheets in a pack. Hence, the SAP system can offer Pilkington real-time visibility on the glass stock levels, provided that employees reliably scan the glass packs as they enter and leave the stockroom, but does not provide information on the location of the glass in the stockroom nor on which stillage the glass is on. As a result, there is some difficulty in having real time data on knowing which stillages are available and their whereabouts; typically, locating free stillages is done manually. The problem is compounded however because different Pilkington factories, and even some competitors, use each other's stillages. Stillages supposedly should be brought back to the factory from where they originally left once they are empty. Some merchants unload the glass once a full stillage arrives whereas other merchants may keep the stillages to store the glass. In practice, however, a stillage may be picked up by a truck en route to another factory. This practice may be explained by the need to minimize transportation costs: trucks should not be in transit unless they are carrying a stillage. In extreme cases, a stillage may be picked up by a truck operating for a competitor and Pilkington will lose track of the stillage.

The lack of information on the location of the stillages is detrimental to the performance of Pilkington's glass delivery process: shipments may have to be delayed until the required stillages are located and moved with the help of forklifts through rows of closely packed stillages; manufacturing schedules may have to be altered because stillages with the required glass packs cannot be found on time; incorrect stillages may have to be used or appropriate stillages may have to be requested from another factory; glass packs placed on stillages that remain stored for over long periods may become unfit for sale or for further processing e.g. coating.

Technology involving RFID tagging could help Pilkington track the location of glass packs and stillages. One possible solution would involve tagging stillages and glass packs and readers equipped with antennae could be located at the entrance of the stockroom bays. The RFID readers would identify each transponder as it passes thorough the bay entrance and send the information to the host computer, which would track the objects' movements. Alternatively, a reader could be placed onto each of the forklift trucks that move the stillages around the factory and transponders would be placed at the entrances to each of the storage bays and on the glass packs and stillages. Further, by placing transponders on the Floatliners, embedding antennae into the tarmac at the entrance of Pilkington sites and at delivery locations, and linking customers to a central operations computer, the RFID system could track the movements of registered stillages and glass in the supply chain. Such a system would provide Pilkington with real-time information about which truck is distributing which

[1] SAP is one of the world's largest independent suppliers of standard software applications for real-time enterprise data processing.

stillage, with what glass (if any), to which location. This would help Pilkington to know the number and type of stillages that remain in stock fully loaded, how many are on-site and empty, and the whereabouts of stillages not on site.

Opportunities for Applying RFID tags Integrated with Sensors
One limitation experienced by Pilkington relates to their current inability to monitor and control the environmental conditions experienced by the glass during storage, transportation, and once installed on-site. Research at Pilkington has demonstrated that excessive temperatures or humidity levels can damage coated glass. Further, excessive levels of vibration during transportation may cause the glass packs to rub against the steel structure of the stillage and damage the coating of the glass sheets. A system that integrates sensors (of temperature, humidity, vibration) with RFID tags could allow environmental conditions to be monitored during glass delivery. Further, if tag-sensors remained embedded on glass after its installation on site, they could help to monitor and provide a better understanding of glass performance in relation to the conditions *in situ*, and so help Pilkington develop products that better meet customers' needs.

FUTURE RESEARCH STEPS

At present, 30% of the global output of float glass is produced in China, albeit that only 11 of the 92 float lines in China are as yet capable of producing glass with quality comparable with that produced by western lines (Pilkington 2003). Pilkington's ability to develop new glass products ─ which generate higher profit margins ─ will be increasingly important for sustaining its commercial leadership position. Recent research and development initiatives for the building sector, such as Pilkington Activ™ dual-action self-cleaning glass and Pilkington K G1ass™ energy-saving glass, demonstrate that Pilkington is aware of the importance of new product development. RFID-sensor technology will undoubtedly have an even greater impact on the effective management of these advanced products throughout their life cycle.

The introduction of RFID tags, possibly in combination with sensors, offers the opportunity to gather a great deal of new data relating to all aspects of the lifecycle of construction components. This new data in turn can provide new insights from which manufacturers and customers can learn. However, there is one strong *caveat* that must be given – and that is, that just getting new data is not the key goal; to be of real benefit, that data must be understandable and meaningful (i.e. its semantics must be clear) so that it provides a genuine information resource, and it must be possible to integrate that information with the company's existing information systems. This level of integration cannot be achieved, nor can it be maintained and extended, through *ad hoc* software development. Formal specification techniques must be leveraged.

Future research will use formal specification techniques based on the ISO standard modelling language EXPRESS (EXPRESS 1994). As far as tags and sensors are concerned, EXPRESS models will capture the details of what data can be held on RFID tags of all kinds and what types of data different kinds of sensors can deliver. In addition, from a user standpoint, EXPRESS models will be developed to capture a full understanding of what information is to be extracted from the data on the tags and sensors and then define how that data links into the wider information support environment that a given company is using.

However, it is not sufficient just to capture these specifications - though they are useful in their own right because they provide readable and explicit definitions of what the tags can do for a company and how the tag/sensor capabilities relate to the company's needs. The empirical research studies carried out indicate that even greater value will accrue if these models can be used as the basis for generating software tools that can support the application of RFID tags and sensors both generally and in the construction domain in particular. Example software tools that the studies identified as particularly useful include an RFID tag/sensor system simulator that will allow users to investigate the effectiveness of different tag/sensor technologies in terms of information carrying capability, and an activity model simulator that will provide the platform to support simulation of RFID tag-sensor use cases derived from the construction industry.

In addition, the viability and practicality of developing 'intelligent' construction components will be investigated using computer-based simulation models to compare the performance of existing supply chains with that of hypothetical supply chains using 'intelligent' construction components. Detailed case studies on new products will also be conducted to provide information about the key factors that determine the commercial success or failure of marrying emergent technologies with traditional engineering and construction components.

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