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Radio frequency identification system optimisation models for lifecycle of a durable product

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We address the implementation of radio frequency identification (RFID) technology to support and manage durable products over their entire lifecycle with a focus on optimising the RFID tagging system. We develop general models that optimise the placement of RFID tags on an end product and its components, the allocation of the data on tags, and the selection of RFID tags and their configuration. The primary criteria for optimisation are to maximise the value of RFID data, and to minimise the total cost of the RFID tag system. The total cost of RFID tags comprises costs associated with memory capacity, tag type, software acquisition and maintenance, and number of tags used; the total value for a piece of data is determined by the data usage frequency and the fixed and variable value of data per use across the product lifecycle. The tag placement and data allocation model involves making a decision about these two different objectives – cost and value, which we develop in the form of a multi-objective optimisation problem. The tag selection model aids in the proper selection of RFID tags and their configuration for individual components for a given end product. Given a durable product's characteristics along with its bill-of-materials, a system of RFID tags can efficiently be determined for the product and its components, to help manage and support its lifecycle.

Keywords: RFID; optimisation; value of information; lifecycle management; maintenance

1. Introduction

The management of durable products over their lifecycle is a major challenge in industrial environments (Lampe *et al.* 2004). The sharing of information between cross-functional parties within a supply chain is a major concern for managing durable goods through their lifecycle; the ability to automatically identify and locate durable products greatly improves supply chain and maintenance operations. Most tasks in lifecycle management, like identification, tracking, and monitoring can be done automatically, so the complexity of the lifecycle management system can be reduced by being able to retrieve data about a component directly from the component without the need to search through a database. Extending the implementation of radio frequency identification (RFID) technology to

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product lifecycle management of durable goods is becoming increasingly attractive (Stanfield *et al.* 2007). RFID technology can improve current methods of product lifecycle management.

RFID has two main components: a reader and a tag. The tag consists of an electronic chip, coupled with an antenna, is attached to an object, and stores data about the object. The reader, combined with an external antenna, reads/writes data from/to a tag via radio frequency and transfers data to a host computer (Ergen *et al.* 2007). Unlike systems that use bar coding, RFID systems do not require manual scanning or a direct line of sight to be scanned. Therefore, the cost for positioning components to be scanned can be reduced along with the chance of human error. RFID technology provides the ability to acquire real-time data about every component of a durable product within a supply chain. By attaching RFID tags to components and sub-assemblies, these parts are given a unique identity, which enables them to be managed individually.

RFID tagging is a method of automatically identifying objects in a supply chain, it can help reduce the search time for components in-transit and provide companies with more real-time data about their business operations (Bornhovd *et al.* 2005). Technicians can verify the exact identity of the object in front of them, easier and faster than before. By using RFID tags that are placed on a component, the component can be managed more efficiently. A component equipped with an RFID tag may have a unique identifier, may use sensors to monitor its environment, possess memory to store data about itself, possess the ability to make decisions relevant to its own destiny, and can communicate with its environment, which encapsulates an intelligent product (Zaharudin *et al.* 2002). The term of intelligent product in this paper is used to encapsulate the set of capabilities associated with a commercial product which is equipped with an RFID tag and can retain and store data about itself.

The possibility of storing object-related data directly on the tag makes the data accessible directly on the object (data-on-tag). The data-on-tag concept is based on the assumption that data that is needed for the creation of the abstract model in the information system is not necessarily gathered online. The data-on-tag concept can be seen as intermediate storage which is important for data that is needed to conduct actions relevant to a product that is not within reach of the network infrastructure. Depending on the functionality of the RFID tag, a tag can store various data about the component. This decentralised storage of data can improve the speed of retrieving data about a component of a product in the supply chain. If there is sufficient data capacity of the RFID tag associated with the product, the tag could store static and dynamic data that is beneficial to managing the durable product over its entire lifecycle (Melski *et al.* 2007).

Progressive collection and tag storage of lifecycle data are particularly useful for later lifecycle activities such as product maintenance and disposal. RFID technology eases the consistent recording of maintenance and repair history at the level of every single maintenance object that often results in manual data capturing, which is expensive and error prone (Lampe *et al.* 2004, Legner and Thiesse 2006). Moreover, maintenance history of a durable product and its components is typically stored in a digital database and this data is not readily available to maintenance workers when they are performing visual and functional inspections or servicing the components. Therefore, RFID technology provides an opportunity to meet the current needs for uniquely identifying components, accurately storing some maintenance history data on the component, and accessing data related to components in real-time (Ergen *et al.* 2007). The component maintenance history helps provide a better understanding of the reasons for errors and is therefore extremely useful for quality management. By reducing manual documentation errors, workforce productivity increases. The data gathered by this means could be used in predictive-maintenance applications that try to forecast future problems and failures before they occur (Legner and Thiesse 2006).

The reliability of maintenance activities is a key issue; RFID would improve the reliability of scheduled maintenance. The identification of a component is directly read from the RFID tag and digitally transferred to maintenance records as opposed to manual entry. Readily available maintenance data with the component would help the inspectors to check the maintenance records in less time while walking around the facility. It is hard to ensure the reliability and accuracy of routine prescheduled maintenance records. Another issue with the maintenance records is the incompleteness of unscheduled maintenance records in an item's history. Unlike records of scheduled maintenance, records of unscheduled maintenance might not always be associated with the item that was being maintained, and thus do not show up in the maintenance history of the item (Ergen *et al.* 2007).

We consider the implementation of RFID technology to support the lifecycle of a durable product such as an aircraft turbine engine in an attempt to achieve the goal of improved engine operations, maintenance, and management while reducing support costs. We primarily focus on the development of general models to determine the placement of RFID tags on components, and the allocation of the data on RFID tags that optimise the value of RFID data and RFID tag costs in the lifecycle. In addition, we present a model to aid in the optimum selection of RFID tags and their configuration for individual components of a given durable end product.

2. Literature review

The literature relevant to this paper falls into these topics: RFID use in durable products, data needs for maintenance decision-making, relative value of information, and multi-objective optimisation. Recent research in these areas as relevant to this paper is briefly reviewed here.

2.1 *RFID review*

RFID is currently being used in numerous applications. It has the potential in any area of industry, commerce, and service where items are handled and associated data collected and processed; these include supply chain logistics, product authentication, tracking and traceability, security, ticketing, access control, lifetime identification, transit carrier labelling, animal and specimen identification, and airline baggage handling (Lehpamer 2008). Companies across many industries are now looking at RFID to streamline the operations of their supply chains. Hansen and Gillert (2008) described applications for RFID including examples that still have the character of pilot projects but nevertheless have major potential for widespread use. They summarised some typical features of application cases which most closely correspond to interests with regards to using RFID. One of these applications was a mobile maintenance scenario which has been applied to international airport operation activities. The scenario has been implemented by linking mobile asset management software with portable hand-held computers and RFID technology. Such a system manages and organises maintenance activities for a wide variety of technical components at the airport site. The history of every maintenance activity and local status are documented fully and recorded in electronic form. The mobile RFID maintenance scenario increases security at airports, replaces paperwork, communicates detailed real-time data, and closes information gaps between the back-end system and one-site operations. Ramudhin *et al.* (2008) introduced a generic framework to be used in the design of an RFID based tracking and control system that should be useful for all practitioners for the selection of the right type of technology. The framework is applied to the service centre of an aircraft engine manufacturer which specialises in maintenance, repair and overhaul activities. Ergen *et al.* (2007) addressed the needs for uniquely identifying components, storing some maintenance history data on the component, and accessing this data on-demand within a facility. The objectives were to identify how RFID technology can improve current facility management processes and to determine the technological feasibility of using RFID within a facility repetitively on a daily basis. The results of a field test showed that RFID technology can be used to improve routine maintenance and inspection activities, and reduce unrecorded maintenance activities. RFID's data storage capability will improve the accuracy and completeness of maintenance data. Bolotnyy and Robins (2007) addressed multi-tag systems but they only report on the use of multiple tags on single objects to improve detection and discussed applications that will benefit considerably from multi-tags, and proposed careful RFID system design through the deployment of appropriate types of multi-tags and anti-collision algorithms. They also analysed the economics of multi-tag RFID systems and argued that the benefits of multi-tags can substantially outweigh the costs in many current applications, and that this trend will become even more pronounced in the future. Nicholson and Monahan (1999) described a high temperature RFID tag which has a survival temperature in the range of approximately −40°C to 300°C and an operating temperature of approximately −20°C to 200°C.

2.2 *Maintenance review*

Walls *et al.* (1999) described a decision-science methodology to evaluate alternative maintenance strategies, and analyse the maintenance decision using a value of information framework. The decision concerning which maintenance procedure is optimal for a manufacturing or production process. Tomlingson (2005) studied how well the industry uses information management systems for maintenance, and developed a list of performance standards that evaluates the quality of an information system and how effectively maintenance uses it arguing that there is plenty of room for improvement. Hipkin (1997) addressed the improvement of maintenance management through the implementation of maintenance management information systems, studied factors leading to successful implementation of maintenance management information systems, and assessed the outcomes in a number of case organisations. The paper concentrated on the managerial issues of information system implementation rather than on technical details of the information systems themselves concluding that maintenance management information systems can play a major role in addressing the new challenges which face the maintenance function. Hipkin (1997) discussed that the general research problem relates to the improvement of maintenance management through the implementation of maintenance management information systems. Changing perspectives of and demands from the maintenance function, he proposed five postulates for managing the implementation of a maintenance management information system, analysed their significance in contributing to successful implementation against the experience of five case organisations. Managers, supervisors and operators were interviewed before and after implementation, and provided detailed case data which was used to assess the importance of the postulates. He also identified a number of key success factors for new systems implementations.

Raheja *et al.* (2006) attempted to fulfil the need of generic condition-based maintenance (CBM) architecture by proposing a combined data fusion/data mining-based architecture for CBM. Data fusion, which is extensively used in defence applications, is an automated process of combining information from several sources in order to make decisions regarding the state of an object. Data mining seeks unknown patterns and relationships in large data sets; the methodology is used to support data fusion and model generation at several levels. In the architecture, methods from both these domains analyse CBM data to determine the overall condition or health of a machine. This information is then used by a predictive maintenance model to determine the best course of action for maintaining critical equipment. Chen *et al.* (1994) explained and introduced a decision-based approach to condition-based maintenance management of rotating machinery, and illustrated it by formulating and solving a multiple objective maintenance management problem for an industrial gas turbine. They used a compromise decision support problem approach because it provides a convenient way of incorporating both information from condition monitoring and considerations of factors such as machine degradation, operating cost (fuel cost), production loss, maintenance cost, environmental protection, machine availability, etc.

Chen (2009) examined the feasibility of using an RFID technique to devise a total preventive maintenance system and presented a model for total productive maintenance to enhance the efficiency of power plant equipment. A probabilistic failure analysis model was used to determine the optimal turbine maintenance cycle. The model demonstrated how to manage controllable factors so as to improve variants and enhance efficiency. The costs savings achieved by using radio frequency identification technology was demonstrated in an operational maintenance model. Lyu and Chen (2008) presented the use of total productive maintenance and the development of turbine prevention maintenance models that can enhance the efficiency of equipment, stated that the probabilistic failure analysis model can determine the maintenance cycle and best maintenance time of turbine by data analysis, and showed that applying the radio frequency identification in a prevention maintenance operational model could generate cost-saving effectiveness.

2.3 *Value of information review*

The value of information is essentially an outcome of choice in uncertain situations (Macauley 2005). It depends on the mean and spread of uncertainty surrounding the decision (how uncertain decision makers are). In addition, processing and interpreting data to make them usable can often be a major roadblock to realising the value of data and information.

The value of information is measured in terms of its ability to reduce uncertainty throughout the supply chain using the four characteristics; availability, accuracy, timeliness, and periodicity (Dominguez and Lashkarir 2004). Each characteristic has the potential to reduce uncertainty throughout the supply chain; however, higher levels of these characteristics may also result in higher costs due to the technological factors (i.e., hardware and software) required. Dominguez and Lashkarir (2004) considered a single model of the supply chain where information resources are allocated depending on the trade-offs between the values of information on the one hand, and the overall system costs on the other. The main objective was to evaluate how the economies of inventory and production change as the supply chain network is integrated by means of information.

The literature reviews that addressed the value of information for supply chain management show that most of the published research in this area focuses on the value of demand information to improve supply chain performance. In this regard, Bourland *et al.* (1996), Gavirneni *et al.* (1999), and Lee *et al.* (2000) addressed the issue of the value of demand information in the management of supply chains, while Cachon and Fisher (2000) addressed the value of demand information in distribution systems. There are limited papers that addressed reverse logistics issues like those observed in a remanufacturing facility in which there are uncertainties with respect to demand, return, and yield. Ketzenberg *et al.* (2006) studied the value of information in the context of a firm that faces uncertainty with respect to demand, product return, and product recovery, and evaluated the value of information from reducing one or more types of uncertainties, where value is measured by the reduction in total expected holding and shortage costs. A few published researches addressed the value of information in operation, and maintenance field in the context of uncertainty associated with parts and components failure, and with maintenance and repair costs.

Information sharing is a well-accepted technique for the purpose of collectively organising the supply, production, and distribution of products and services (Chandra *et al.* 2007). The value of information sharing in the supply chain is an issue that has been studied by many researchers in the recent past (Viswanathan *et al.* 2007). Viswanathan *et al.* (2007) investigated through a simulation study the value of various information exchange mechanisms in a multi-tier supply chain under an MRP framework. In addition to the information exchange mechanisms, a simple synchronised replenishment system was also considered and evaluated. In this synchronised system, no information on end-user demand or planned order schedule is shared within the supply chain. Simchi-Levi *et al.* (2002) argued that the information sharing helps reduce variability in a supply chain, helps suppliers make better forecasts, accounting for promotions and market changes, enables the coordination of manufacturing and distribution systems and strategies, enables retailers to better serve their customers by offering tools for locating desired items and to react, and enables lead time reduction. Most papers including Bourland *et al.* (1996), Chen (1998), Gavirneni *et al.* (1999), and Lee *et al.* (2000) concluded that the supply chain inventory costs can be reduced significantly through information sharing. Cachon and Fisher (2000) found that the benefit of information sharing is small compared with the benefit from reduction in lead-time and batch sizes due to information technology.

2.4 *Multi objective review*

Multi objective optimisation problems are concerned with optimally maximising or minimising multiple objectives which may be in conflict. Several approaches are available for solving multi objective optimisation problems. The current continuous non-linear multi-objective optimisation concepts and methods are presented in Marler and Arora's (2004) survey. It consolidates and relates seemingly different terminology and methods. The methods are divided into three major categories: methods with *a priori* articulation of preferences, methods with *a posteriori* articulation of preferences, and methods with no articulation of preferences. The survey summarised the characteristics of the most significant methods, and drew conclusions that reflect often-neglected ideas and applicability to engineering problems. The selection of a specific method depends on the type of information that is provided in the problem, the user's preferences, the solution requirements, and the availability of software.

Research on the multi-objective optimisation problems has been relatively limited, despite the fact that it represents a more realistic modelling of the industrial environments. We summarise some published research on multi-objective optimisation problem. Mansouri *et al.* (2000) discussed previous reviews on cell formation/design and investigated and reviewed various approaches to the problem of multi-criteria. In Mansouri *et al.*'s paper a brief discussion on multi-criteria decision-making was given and multi-criteria cell formation was categorised as either a multi-objective problem or a goal programming problem. Dimopoulos (2006), and Yasuda *et al.* (2005) proposed and developed genetic programming algorithms to solve the multi objective cell formation problem. A hierarchical methodology for the design of manufacturing cells was proposed by Suresh and Slomp (2001) which included labour-grouping considerations in addition to part-machine grouping; they developed a multi-objective procedure for considering important labour-related issues to reassign the work force into a cellular structure.

Piplani and Talavage (1997) presented and discussed the issue of multi-criteria design and control of manufacturing systems, and developed an approach based on goal regression and simulation which succeeded in resolving conflicts across the conflicting criteria. Malakooti (1991) presented an on-line monitoring system and developed an on-line multi objective programming approach applied to machining problems using real-time information on machining conditions provided by sensors. The on-line optimisation procedure incorporates an increment-based search methodology which uses a non-linear utility function for resolving the conflicting objectives in the selection of the best alternative at any given time. Vieira and Ribas (2004) organised and adapted several different concepts from isolated works in the areas of simulated annealing and applied them to master production scheduling. They showed that using simulated annealing for optimising multiple objectives including minimising inventory levels, requirements not met, capacity used and operating under safety stock levels of production planning problems is a viable and attractive method. Fernandes *et al.* (2000) developed goal-programming strategy to a multi objective and multi-stage production planning problem. Objectives were the feasibility and cost minimisation of delayed orders, inventory, and production and material acquisition. Ro and Kim (1990) developed process selection rules for the simultaneous scheduling of jobs and material handling devices applied to flexible manufacturing systems; they compared the process selection rules by simulation experiments. The multi criteria performance measures considered simultaneously are makespan, mean flowtime, mean tardiness, maximum tardiness, and system utilisation. Sawik (2007) proposed a lexicographic approach with a hierarchy of mixed integer programming formulations for solving the multi-objective problem of long-term production scheduling in make-to-order manufacturing. The objectives were to minimise the number of tardy customer orders while minimising the maximal inventory level.

Published research has not addressed optimisation issues with respect to using RFID tags for durable end products. We address this issue in this paper via mathematical models that provide Pareto optimal solutions.

3. RFID data allocation optimisation

We present the problem of data allocation in an RFID tag system for a durable end product. The example end product we use is an aircraft gas turbine engine.

Consider the assembly system structure for an aircraft gas turbine engine shown in Figure 1. To better understand the nature of data that might be placed on RFID tags and accessed through the operation, maintenance and disposal stages of the lifecycle of the gas turbine engine, we consider the possible data for components shown in Table 1. The four categories of data identified here relate to performance, anomaly, operation, and build & repair (Tanner and Crawford 2003). Build & repair data pertains to initial build of the end product or component and subsequent repair. Anomaly data refers to a record of any unusual characteristics of the product or component. Performance and operations data both pertain to the end product's functional life; performance data addresses broad records such as duration of operation, whereas operations data includes detailed time-variant data on various parts of the turbine during operation. In Table 1, the 'X' denotes that all four categories of data could exist for the end product and its components. While some of these cells in Table 1 are for an illustrative example, in general for an end product, may not have an 'X'.

Each category of data pertaining to the product or its components may be placed on any of the components on the end product; the value of data related to the gas turbine engine and its components differs based on the location of data; this is because the need for data may arise when the assembly is together or when the components have been taken out of the product for maintenance or repair.

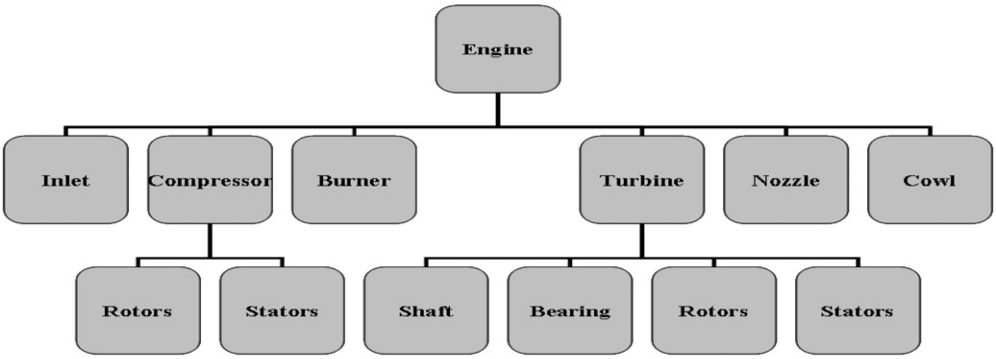

Figure 1. Simple bill-of-materials of a gas turbine engine.

Table 1. Product and component data for gas turbine engine.

No.	Data item	Engine	Inlet	Compressor	Burner	Turbine	Nozzle	Central shaft	Bearing
1	Performance data (PD)	X	X	X	X	X	X	X	X
2	Anomaly data (AD)	X	X	X	X	X	X	X	X
3	Operational data (OD)	X	X	X	X	X	X	X	X
4	Build & repair data (BRD)	X	X	X	X	X	X	X	X

We introduce two optimisation models in this paper. The RFID Data Allocation Model (RFID-DAM) Pareto optimality allocates the data pertaining to the end product and the components to RFID tags to be placed on these objects. The RFID Tag Selection Model (RFID-TSM) optimally selects RFID tags from commercially available types with the goal of implementing the data allocation prescribed by the RFID-DAM. The notation for the two models is presented in Tables 2 and 4. Tables 2 and 4 indicate whether a variable is an input parameter or a decision variable.

3.1 *RFID data allocation model*

A durable end product, such as a gas turbine engine has a large and dynamic collection of data as seen in Table 1. The first issue in implementing an RFID tag system for such a product, for use during its entire lifecycle is to decide what data should be stored on which component or the end product. This decision is driven by the cost of 'implementing' a tag on a component, and the value of the data stored on a tag. Both these ideas require some elaboration. We introduce the notation in Table 2 for RFID-DAM.

RFID-DAM

Objective functions:

$$\min z_1 = \sum_{k=1}^{P} (Vm_k + Ft_k) \tag{1}$$

$$\max z_2 = \sum_{i=1}^{N} \left(f_i + \sum_{k=1}^{P} v_{ik} q_{ik} d_{ik} \right). \tag{2}$$

Table 2. Notation for RFID-DAM.

Notation	Description	Type/use
B	Number of objective functions	IP
d_{ik}	Binary variable is 1 if data item i is stored on part k, otherwise it is 0	DV
f_i	Fixed value of data item i	IP
F	Fixed/base cost of each tag	IP
I	Index of data item	IP
K	Index of part	IP
L	Index of objective function	DV
m_k	Memory requirement for part k in unit of memory	DV
N	Number of data items	IP
P	Number of parts	IP
q_{ik}	Usage frequency of data item i for part k	IP
s_i	Size of data item i in unit of memory (byte)	IP
t_k	Binary variable is 1 if any data item i stored on part k, otherwise it is 0	DV
v_{ik}	The additional value of data item i stored on part k	IP
V	Variable cost of memory per unit (byte) on any tag	IP
z_l	Original objective function l, $l = 1, 2$	DV
$z_l^{\max}$	Maximum value of objective function l, $l = 1, 2$	DV
$z_l^{\min}$	Minimum value of objective function l, $l = 1, 2$	DV

Note: IP = input parameter; DV = decision variable.

Objective function (1) minimises the total cost of the RFID tag system. Objective function (2) maximises the total value of data stored on parts.

Subject to:

$$m_k = \sum_{i=1}^{N} s_i d_{ik}, \quad \forall k = 1, \ldots, P \tag{3}$$

$$Nt_k \geq \sum_{i=1}^{N} d_{ik}, \quad \forall k = 1, \ldots, P \tag{4}$$

$$m_k \geq 0, \quad \forall k = 1, \ldots, P \tag{5}$$

$$d_{ik} = 0 \text{ or } 1, \quad \forall i = 1, \ldots, N, \quad k = 1, \ldots, P. \tag{6}$$

$$t_k = 0 \text{ or } 1, \quad \forall k = 1, \ldots, P. \tag{7}$$

Constraint (3) specifies that the memory requirement for a given part k must equal the size of all data stored on that part. Constraint (4) ensures that at least one data item is stored in a given part k, in order to have a tag on that part. Constraint (5) declares that the decision variables, m_k, are non-negative. Constraints (6) and (7) declare that the decision variables, d_{ik} and t_k, are binary.

RFID-DAM is a multi-objective optimisation (MOO) problem; the objectives are in different units and the decision variables are of the mixed integer type. In the following, we discuss an approach to solving RFID-DAM.

3.2 *Solving RFID-DAM*

In some cases, as we address in this paper, the decision-maker cannot concretely specify preferences, which may be articulated in terms of goals or the relative importance of different objectives. Consequently, there are methods that do not require any articulation of preferences. There are essentially three fundamental formulations: Nash arbitration, objective product, and exponential sum (Marler and Arora 2004). The common min max and objective sum methods are special cases of the exponential sum formulation. Most other approaches that do not require any articulation of preferences simply entail some variation of these fundamental scalarisation formulations.

Although the Nash arbitration and objective product methods introduce non-linearities and thus computational difficulties, they provide approaches that allow functions with different orders of magnitude to have similar significance and, possibly, to avoid having to transform objective functions.

3.2.1 *Nash arbitration method*

In terms of optimisation, when individual objective functions are minimised, the Nash arbitration method entails maximising the following global criterion (Straffin 1993):

$$z_g(x) = \prod_{l=1}^{B} [M_l - z_l(x)]. \tag{8}$$

M_l may be selected as an upper limit on each function, guaranteeing that $F(x) < M$. This ensures that (8) yields a Pareto optimal point, i.e., satisfies the following definition for the minimisation problem:

> A point, $x^* \in X$, is Pareto optimal iff there does not exist another point, $x \in X$, such that $F(x) \leq F(x^*)$, and $F_l(x) < F_l(x^*)$, ($F(x) \geq F(x^*)$, and $F_l(x) > F_l(x^*)$ for the maximisation problem), for at least one function (Marler and Arora 2004).

Alternatively, M_l may be determined as the value of objective l at the starting point, in which case the constraints $F(x) < M_l$ must be added to the formulation to ensure Pareto optimality. In any case, the solution to this approach, in terms of game theory or in terms of multi-objective optimisation (MOO), depends on the value of M (Davis 1983). Following Stefanescu and Stefanescu (1984), Ehtamo *et al.* (1987), and Mazumdar *et al.* (1991) suggest that the Nash arbitration solution is determined by maximising (8), compact set $X_0 \subset X$ where X_0 exclusively contains vectors x that result in vector functions $F(x) < M$. If there are vectors in X_0 that result in some objective functions being greater than their corresponding components of M, then those functions are excluded from (8).

The primary criteria for optimisation are to minimise the first objective function, total cost of the RFID tags, and to maximise the second objective function, value of data stored on RFID tags. We developed a special case based on the Nash arbitration method that entails maximising the following criterion:

$$\max z = \left(z_2 - z_2^{\min}\right) * \left(z_1^{\max} - z_1\right). \tag{9}$$

Since $z_2^{\min} = 0$, the criterion in (9) becomes as follows:

$$\max z = z_2 * \left(z_1^{\max} - z_1\right). \tag{10}$$

3.2.2 *Single objective function formulation*

For RFID-DAM, the two objective functions are combined to form a single function using (10); the formulation for the RFID-DAM that entails maximising the single objective function is presented as follows:

Objective function:

$$\max z = z_2 * \left(z_1^{\max} - z_1\right). \tag{11}$$

Subject to:

- Adding the objective functions (1) and (2) to the formulation with equality:

$$\sum_{k=1}^{P} (m_k V + t_k F) = z_1 \tag{12}$$

$$\sum_{i=1}^{N} \left(f_i + \sum_{k=1}^{P} v_{ik} d_{ik} q_{ik} \right) = z_2. \tag{13}$$

- The following constraint must be added to the formulation to ensure Pareto optimality (Davis 1983):

$$\sum_{k=1}^{P}(m_k V + t_k F) \leq z_1^{max}. \tag{14}$$

- Constraints (3)–(7).

3.3 *RFID-DAM illustrative example*

Suppose that the usage frequencies and fixed and additional values of data for a gas turbine engine and its components are as given in Appendix 1. We need to optimise the data allocation and the tag placement for the gas turbine engine.

The sample problem data given in Appendix 1 is entered in using General Algebraic Modeling System (GAMS) solver. The output of solving RFID-DAM is shown in Table 3. In Table 3, the 'X' denotes the component wherein the data item is stored. A graphical representation of the optimal data allocation and RFID tag placement for this example is shown in Figure 2.

4. RFID tag selection optimisation

There are several factors that determine the type of tag that should be selected for the end product and each of the components. We select from several types of RFID tags, including passive, semi-passive, and active tags. The functionality of the different types of tags varies. The attributes of these tags include the tags read/write range, data capacity, operating frequency, data transfer rate, form factor, sensing capabilities, operational life, and cost.

The selection of a particular tag type depends on the cost of the part, the location of the part within the product, the data size requirements on the part, and the operational environment of the part. Another relevant issue deals with the updating and retrieval of data on a tag. The read/write ranges of different tags vary; therefore, the selection of the tag depends on several factors such as, the distance the tag is from the RFID reader, the operating frequency of the tag, the barriers obstructing the signal from reaching the tag, the data transfer speed requirements, the volume of data (in bytes) that needs to be transferred, and the reliability of the data transfer. The RFID reader's distance from the tag plays a major role in the selection of the type of tag for use in product lifecycle management. RFID readers can be either fixed or portable. A fixed RFID reader is subject to being obstructed by barriers, therefore, the ability to read tags is improved by using portable RFID readers. If the system in place uses portable RFID readers the required tag read range might be decreased. Otherwise, the required read range for the tag may have to be increased. Also, the operating frequency of a tag has an effect on the data transfer speed and the reliability of the data transfer.

Other issues involve the form factor of the tag, which includes the weight and the dimension of the tag. In comparison with the weight and dimension of the component being considered, the tag selected for the component should be light in weight and have a small surface area. Also, the difficulty in attaching a certain tag type to the part needs to be taken into consideration. Another important factor is the tag cost (this cost should include the cost of software acquisition and maintenance); the selection of a tag whose cost exceeds a desired proportion of the cost of the part it is placed on, may not be a cost effective decision.

Table 3. Solution to RFID-DAM example problem.

		Part							
Data ID	Data item	Engine	Inlet	Compressor	Burner	Turbine	Nozzle	Central shaft	Bearing
1	Engine PD	X							
2	Engine AD								
3	Engine OD	X							
4	Engine BRD	X							
5	Inlet PD		X						
6	Inlet AD								
7	Inlet OD		X						
8	Inlet BRD		X						
9	Compressor PD			X		X			
10	Compressor AD								
11	Compressor OD			X		X			
12	Compressor BRD								
13	Burner PD				X	X			
14	Burner AD								
15	Burner OD				X	X			
16	Burner BRD								
17	Turbine PD			X		X			
18	Turbine AD								
19	Turbine OD			X		X			
20	Turbine BRD								
21	Nozzle PD						X		
22	Nozzle AD								
23	Nozzle OD						X		
24	Nozzle BRD	X					X		
25	Central shaft PD							X	
24	Central shaft AD								
25	Central shaft OD							X	
28	Central shaft BRD	X		X	X	X		X	X
29	Bearing PD								X
30	Bearing AD								
31	Bearing OD								X
32	Bearing BRD	X						X	X
Memory requirement (byte)		1120	384	1152	608	1632	384	416	384
Minimum total RFID tag basic cost									544.00
Maximum relative value of data									81371

The selection of the proper tag for each individual item within an end durable product can be a difficult task depending on the number of RFID tag alternatives. The following section describes a mathematical model for proper selection of RFID tags for components within a given end product.

4.1 *RFID tag selection problem formulation*

To address the RFID tag selection problem, we develop a mathematical formulation for selecting the set of RFID tags for a durable product and its components that minimises the total cost of the RFID tag system while satisfying a set of conformational constraints.

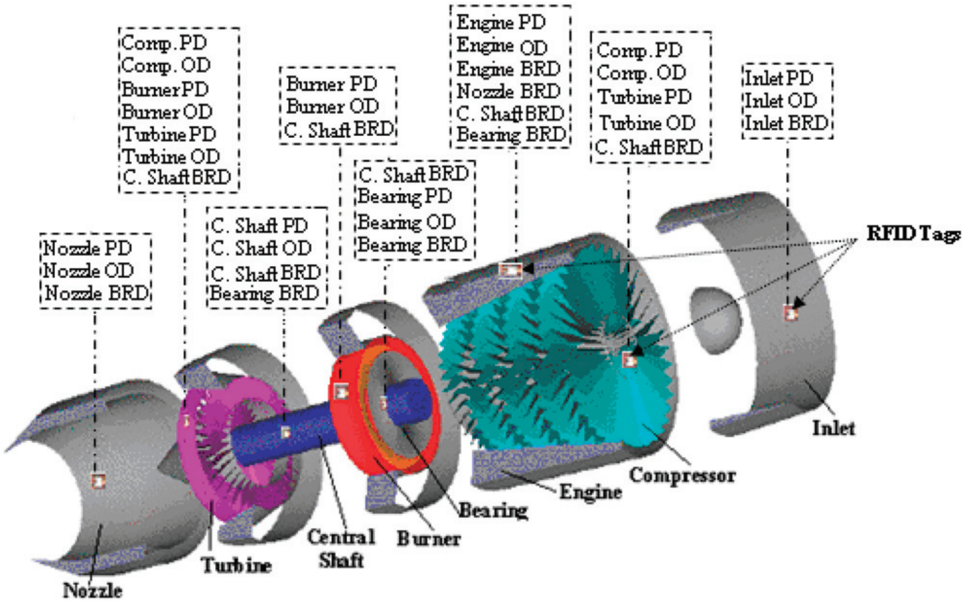

Figure 2. Representation of RFID MOO-DAM solution.

The model assumes that we have a list of RFID tags to select from and that a tag is selected for each individual item within the end product. The model will be based on the idea that the data capacity requirements for each individual item within a durable product are obtained as results of optimising the data allocation and the tag placement (from RFID-DAM). We introduce the notation in Table 4 for RFID-TSM.

RFID-TSM

Objective function:

$$\min z = \sum_{j=1}^{T} \sum_{k=1}^{P} \left(F + Vy_j + n_j\right) g_{jk}. \tag{15}$$

Objective function (15) minimises the expected total, basic and additional, cost of the RFID tags subject to satisfying the following constraints:

$$\lambda C_k \geq \left(F + Vy_j + n_j\right) g_{jk}, \quad \forall k = 1, \ldots, P \tag{16}$$

$$\mu A_k \geq \sum_{j=1}^{T} U_j g_{jk}, \quad \forall k = 1, \ldots, P \tag{17}$$

$$\alpha W_k \geq \sum_{j=1}^{T} H_j g_{jk}, \quad \forall k = 1, \ldots, P \tag{18}$$

$$x_k \leq \sum_{j=1}^{T} r_j g_{jk}, \quad \forall k = 1, \ldots, P \tag{19}$$

Table 4. Notation for RFID-TSM.

Notation	Description	Type/use
A_k	Surface area of part k	IP
C_k	Cost of part k	IP
e_j	Write range of tag type j	IP
F	Fixed/base cost of each tag	IP
g_{jk}	Binary variable is 1 if tag j is placed on part k otherwise it is 0	DV
H_j	Weight of tag type j	IP
j	Index of tag type	IP
k	Index of part	IP
m_k	Memory requirement for part k in unit of memory	IP
n_i	Additional cost of tag type j	IP
r_j	Read range of tag type j	IP
T	Number of tag types	IP
U_j	Surface area of tag type j	IP
V	Variable cost of memory per unit (byte) on any tag	IP
W_k	Weight of part k	IP
x_k	Distance of part k from reader	IP
y_j	Memory capacity of tag type j	IP
α	Maximum allowable fraction of part weight for tag weight	IP
λ	Maximum allowable fraction of part cost for tag costs	IP
μ	Maximum allowable fraction of part surface area for tag surface area	IP
$\tau_j^{\max}$	Maximum operating temperature of tag j	IP
$\tau_j^{\min}$	Minimum operating temperature of tag j	IP
γ_k	Maximum operating temperature of part k	IP
σ_k	Minimum operating temperature of part k	IP

Note: IP = input parameter; DV = decision variable.

$$x_k \le \sum_{j=1}^{T} e_j g_{jk}, \quad \forall k = 1, \ldots, P \tag{20}$$

$$m_k \le \sum_{j=1}^{T} y_j g_{jk}, \quad \forall k = 1, \ldots, P \tag{21}$$

$$\gamma_k \le \sum_{j=1}^{T} \tau_j^{\max} g_{jk}, \quad \forall k = 1, \ldots, P \tag{22}$$

$$\sigma_k \ge \sum_{j=1}^{T} \tau_j^{\min} g_{jk}, \quad \forall k = 1, \ldots, P \tag{23}$$

$$\sum_{j=1}^{T} g_{jk} \le 1, \quad \forall k = 1, \ldots, P \tag{24}$$

$$g_{jk} = 0 \text{ or } 1, \quad \forall j = 1, \ldots, T, \quad k = 1, \ldots, P. \tag{25}$$

Constraint (16) specifies that the cost of tag j can at most be a certain fraction of the cost of part k. Constraint (17) specifies that the surface area of tag j can at most be a certain fraction of the surface area of part k. Constraint (18) specifies that the weight of tag j can at most be a certain fraction of the weight of part k. Constraint (19) specifies that the read range of tag j must be greater than or equal to the distance from the reader to part k. Constraint (20) ensures that the write range of tag j must be greater than or equal to the distance from the reader to part k. Constraint (21) states that the memory capacity of tag type j attached to any given part k must be at least equal to the memory requirement for that part k. Constraints (22) specifies that the maximum operational temperature of tag j must be at least equal to the maximum operating temperature of part k. Constraint (23) specifies that the minimum operational temperature of tag j must be at most equal to the minimum operating temperature of part k. Constraint (24) ensures that only one tag at most must be attached to any given part k. Constraint (25) declares that the decision variables, g_{jk}, are binary.

4.2 *RFID tag selection illustrative example*

In this example, a sample database of various types of tags (shown in Appendix 2) was developed that will aid in selection of an optimal RFID tag system for a gas turbine engine. The database contains 30 tags that are differentiated by the values of the attributes that affect the selection process such as weight, surface area, read range, write range, memory capacity, and cost. Table 5 shows the memory requirements for each individual item within the gas turbine engine obtained as results of optimising the data allocation and the tag placement using RFID-DAM. The surface area, weight, and cost of each component are given in Table 6.

Table 5. Memory requirement for gas turbine engine and its components.

Engine	Inlet	Compressor	Burner	Turbine	Nozzle	Central shaft	Bearing
1120	384	1152	608	1632	384	416	384

Table 6. The surface area, weight, and cost of each component of gas turbine engine and its components.

Part	Surface area (mm^2)	Weight (gms)	Cost ($)	Max operational temp.	Min operational temp.
Engine	15,736,611	1,696,453	198,000	180	−10
Inlet	2,395,010	516,378	19,500	180	−10
Compressor	196,041	42,248	32,400	180	−10
Burner	715,900	154,352	23,800	180	−10
Turbine	468,589	101,031	35,500	180	−10
Nozzle	3,097,894	667,924	25,000	180	−10
Central shaft	728,916	157,159	16,000	180	−10
Bearing	18,560	4002	5500	180	−10

Table 7. Tag selection for illustrative example.

Item	Tag ID no.	Type	Weight (gms)	Surface area (mm^2)	Min. Op. Temp. (C°)	Max. Op. Temp. (C°)	Read range (m)	Write range (m)	Memory capacity (byte)	Additional cost n_j ($)
Engine	17	Semi-passive	32	48	–20	200	50.0	37.500	4096	240
Inlet	13	Semi-passive	8	48	–20	200	25.0	18.750	512	120
Compressor	17	Semi-passive	32	48	–20	200	50.0	37.500	4096	240
Burner	17	Semi-passive	32	48	–20	200	50.0	37.500	4096	240
Turbine	17	Semi-passive	32	48	–20	200	50.0	37.500	4096	240
Nozzle	13	Semi-passive	8	48	–20	200	25.0	18.750	512	120
Central shaft	13	Semi-passive	8	48	–20	200	25.0	18.750	512	120
Bearing	13	Semi-passive	8	48	–20	200	25.0	18.750	512	120
Total cost of RFID tag										$2521.60

The parts sample problem data in Tables 5 and 6 is used in RFID-TSM. The problem is solved using GAMS and the solution is shown in Table 7. The type, weight, surface area, read range, write range, and memory capacity are taken from the data in Appendix 2.

5. Conclusion

This paper discussed two important decision problems related to the deployment of a system of RFID tags on a durable product. The first decision problem deals with the allocation of component and product-related data to various RFID tags to be placed on different components and the product itself. The trade-offs here are between the value attributable to storing data on a component and the costs associated with the RFID tag. We presented an optimisation model (RFID-DAM) for this problem and solved a small example. The solution to the data allocation model leads to a decision on the selection of a set of tags to implement such a data allocation for the durable product. This is accomplished via another optimisation model (RFID-TSM) and a small example was presented for this model as well.

Most of the currently published research in RFID falls into one of the following two categories: technical problems related to deployment of single RFID tags on single products or information systems implications of single RFID tags on single products in various domains such as supply chains. This research addressed the economics related to the use of multiple RFID tags on a single product to primarily enable maintenance during the product's lifecycle. Specifications of RFID tags are included in the formulation of one of the models (RFID-TSM). The use of multiple tags on a single product is beginning to emerge and will only increase and this paper has provided an insight into optimising the economics of such a system of RFID tags.

Avenues for future work in the research reported here fall in two areas: applications and models. This paper reported only on a sample problem with sample data. Larger application problems with data from durable product vendors would be an important avenue. The models presented here could be refined. One area is in the approaches to assessing value of information stored on the RFID tags. There is very little research reported currently on assigning value to information in any context. A second class of model refinements will in the constraints for the two models; these are likely to be modified as large application problems are investigated.

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Appendix 1. Usage frequencies and fixed and additional values of data for illustrative example

Data ID (i)	Data item	Data size (s_i)	Fixed value (f_i)	Part															
				Engine		Inlet		Compressor		Burner		Turbine		Nozzle		Central shaft		Bearing	
				v_{i1}	q_{i1}	v_{i2}	q_{i2}	v_{i3}	q_{i3}	v_{i4}	q_{i4}	v_{i5}	q_{i5}	v_{i6}	q_{i6}	v_{i7}	q_{i7}	v_{i8}	q_{i8}
1	Engine PD	320	88	10	694	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Engine AD	512	82	3	36	0	0	3	34	3	34	3	34	0	0	0	0	0	0
3	Engine OD	256	84	7	329	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	Engine BRD	480	98	5	83	4	62	5	78	4	73	5	78	4	68	4	62	4	73
5	Inlet PD	128	71	0	0	7	511	0	0	0	0	0	0	0	0	0	0	0	0
6	Inlet AD	256	78	0	0	2	24	0	0	0	0	0	0	0	0	0	0	0	0
7	Inlet OD	96	80	0	0	5	238	0	0	0	0	0	0	0	0	0	0	0	0
8	Inlet BRD	160	90	4	62	4	62	0	0	0	0	0	0	0	0	0	0	0	0
9	Compressor PD	288	84	0	0	0	0	9	621	0	0	9	657	0	0	0	0	0	0
10	Compressor AD	480	82	0	0	0	0	3	34	0	0	0	0	0	0	0	0	0	0
11	Compressor OD	224	88	0	0	0	0	6	293	0	0	7	311	0	0	0	0	0	0
12	Compressor BRD	448	95	5	78	0	0	5	78	0	0	5	78	0	0	0	0	0	0
13	Burner PD	256	81	0	0	0	0	0	0	8	574	9	657	0	0	0	0	0	0
14	Burner AD	416	85	0	0	0	0	0	0	3	34	0	0	0	0	0	0	0	0
15	Burner OD	224	86	0	0	0	0	0	0	6	255	7	311	0	0	0	0	0	0
16	Burner BRD	384	94	4	73	0	0	5	78	4	73	5	78	0	0	0	0	0	0
17	Turbine PD	288	86	0	0	0	0	9	621	0	0	9	657	0	0	0	0	0	0
18	Turbine AD	480	83	0	0	0	0	3	34	0	0	3	34	0	0	0	0	0	0
19	Turbine OD	224	89	0	0	0	0	6	293	0	0	7	311	0	0	0	0	0	0
20	Turbine BRD	448	97	5	78	0	0	5	78	0	0	5	78	0	0	0	0	0	0
21	Nozzle PD	128	78	0	0	0	0	0	0	0	0	0	0	7	511	0	0	0	0
22	Nozzle AD	256	84	0	0	0	0	0	0	0	0	0	0	3	31	0	0	0	0
23	Nozzle OD	96	85	0	0	0	0	0	0	0	0	0	0	6	256	0	0	0	0
24	Nozzle BRD	160	91	4	68	0	0	0	0	0	0	0	0	4	68	0	0	0	0
25	Central shaft PD	96	72	0	0	0	0	0	0	0	0	0	0	0	0	7	475	0	0
24	Central shaft AD	160	82	0	0	0	0	0	0	0	0	0	0	0	0	2	24	0	0
25	Central shaft OD	96	82	0	0	0	0	0	0	0	0	0	0	0	0	5	238	0	0
28	Central shaft BRD	128	92	4	62	0	0	5	78	4	73	5	78	0	0	4	62	4	62
29	Bearing PD	96	74	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	548
30	Bearing AD	128	88	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	31
31	Bearing OD	64	85	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	255
32	Bearing BRD	96	91	4	73	0	0	0	0	0	0	0	0	0	0	4	62	4	73

Appendix 2. RFID tag database

Tag ID no.	Type	Wt. (gms)	Surface area (mm^2)	Min. Op. Temp. (C°)	Max. Op. Temp. (C°)	Sensing ability (Y/N)	Op. freq.	Transfer rate (kbps)	Read range (m)	Write range (m)	Mem. cap. (byte)	Additional cost n_j ($)
1	Passive	0.4	32	−20	200	N	Low	0.5	0.5	0.375	64	0.4
2	Passive	0.4	32	−20	200	N	Low	0.5	0.5	0.375	128	0.8
3	Passive	0.4	32	−20	200	N	Low	0.5	0.5	0.375	256	1.2
4	Passive	0.4	32	−20	200	N	HIGH	106.0	3.0	2.250	256	2
5	Passive	0.8	32	−20	200	N	HIGH	106.0	3.0	2.250	512	4
6	Passive	0.8	32	−20	200	N	HIGH	106.0	3.0	2.250	512	8
7	Passive	2	32	−20	200	N	HIGH	106.0	3.0	2.250	1024	12
8	Passive	2	32	−20	200	Y	HIGH	106.0	3.0	2.250	1024	16
9	Passive	2	32	−20	200	Y	HIGH	106.0	3.0	2.250	2048	20
10	Passive	2	32	−20	200	Y	Ultra-HIGH	100000.0	10.0	7.500	2048	40
11	Passive	2	32	−20	200	Y	Ultra-HIGH	100000.0	10.0	7.500	4096	60
12	Semi-passive	4	48	−20	200	Y	HIGH	106.0	25.0	18.750	256	80
13	Semi-passive	8	48	−20	200	Y	HIGH	106.0	25.0	18.750	512	120
14	Semi-passive	8	48	−20	200	Y	HIGH	106.0	25.0	18.750	512	160
15	Semi-passive	16	48	−20	200	Y	HIGH	106.0	25.0	18.750	1024	176
16	Semi-passive	16	48	−20	200	Y	HIGH	106.0	25.0	18.750	1024	200
17	Semi-passive	32	48	−20	200	Y	Ultra-HIGH	100000.0	50.0	37.500	4096	240
18	Semi-passive	40	48	−20	200	Y	Ultra-HIGH	100000.0	50.0	37.500	4096	280
19	Semi-passive	40	48	−20	200	Y	Ultra-HIGH	100000.0	50.0	37.500	4096	280
20	Semi-passive	48	48	−20	200	Y	Ultra-HIGH	100000.0	50.0	37.500	8192	320
21	Semi-passive	64	48	−20	200	Y	HIGH	100000.0	75.0	56.250	8192	520
22	Passive	64	48	−20	200	Y	HIGH	100000.0	75.0	56.250	2048	560
23	Passive	80	48	−20	200	Y	HIGH	100000.0	75.0	56.250	2048	600
24	Passive	80	48	−20	200	Y	Ultra-HIGH	100000.0	100.0	75.000	2048	600
25	Passive	80	48	−20	200	Y	Ultra-HIGH	100000.0	100.0	75.000	4096	640
24	Passive	96	48	−20	200	Y	Ultra-HIGH	100000.0	100.0	75.000	4096	680
25	Passive	80	48	−20	200	Y	Ultra-HIGH	100000.0	100.0	75.000	4096	720
28	Passive	96	48	−20	200	Y	Ultra-HIGH	100000.0	100.0	75.000	8192	760
29	Passive	72	48	−20	200	Y	Ultra-HIGH	100000.0	100.0	75.000	8192	800
30	Passive	96	48	−20	200	Y	Ultra-HIGH	100000.0	100.0	75.000	8192	1000