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An RFID application in large job shop remanufacturing operations

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A B S T R A C T

In this study, we evaluate the use of radio-frequency identification (RFID) technology for improving remanufacturing efficiency. We report the results of discrete-event simulation model that analyzes how RFID creates value within the remanufacturing operation. We find that the simulated gains from using RFID are quite modest, and propose alternative justifications for the major benefits seen in practice. We then provide a framework for deciding on the adoption of active RFID technology such as real-time location system (RTLS) for easy identification of components in the remanufacturing process and the adoption of passive RFID for permanently tagging components of remanufacturable products.

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1. Introduction

In this paper, we study how radio-frequency identification (RFID) technology, including active RFID technology such as real-time location system (RTLS), may generate value in remanufacturing operations. The US Department of Defense (DoD) has capabilities in 19 depots across the US that are able to remanufacture aeronautical, automotive and naval equipment, in addition to a variety of electronic instruments (DoD, 2003). The timing for this study is opportune for two main reasons. First, the DoD's demand for remanufacturing operations continues to grow with the intensive, long-term operational demands placed on its equipment in Iraq and Afghanistan. This increased level of demand places a premium on the optimal use of remanufacturing facilities and personnel available in the DoD system. Second, RFID technology continues to evolve at a rapid pace, so understanding its benefits will help in decision-making regarding investments in this technology. With RFID technology becoming more widely integrated within the DoD infrastructure, it is the right time to analyze its effectiveness. Our study discusses the implementation of real-time location systems at the Tobyhanna Army Depot in Pennsylvania as a means to improve its remanufacturing performance. Our objective is to identify the impact of the technology on process control, and what process characteristics make the technology most valuable. Finally, we propose a qualitative framework that helps identifying the conditions under which RFID should be used in a remanufacturing job shop.

This study proceeds with a quick overview of some related work on remanufacturing in Section 2 and on the use of RFID in production environments in Section 3. Then we provide a concise appraisal of what has been learned in past studies of RTLS in a remanufacturing operation in the DoD in Section 4, which sets the scene for the rest of the paper. Section 5 reports the results of a discrete-event simulation model to analyze the narrower issue of how RTLS creates value in the remanufacturing shop through reductions in flow-times. Our results suggest that the direct gains are relatively modest, compared to the overall gains found in other studies. In Section 6 we discuss the process of selecting specific RFID technology in a remanufacturing environment and the alternative choice of directly tagging components with passive RFID at the beginning of their service life rather than at the remanufacturing facility. We argue that this choice is largely driven by the feasibility of passive tagging and the value of information gained through monitoring the tag during its entire service life. The article closes with a conclusion, implications for practitioners and suggestions for future research.

2. The remanufacturing shop

Remanufacturing provides the basis for product recovery and re-use in supply chains. It focuses on value added recovery, rather than just materials recovery (recycling). It differs from repair operations because the product is typically completely disassembled, and all parts are inspected and returned to like-new condition before re-assembly.

There is substantial literature on remanufacturing dealing with tactical, operational and strategic questions. Several authors have argued that current manufacturing technologies, practices and

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processes can and should be used in support of remanufacturing operations (Ferrer and Whybark, 2000; Giuntini and Gaudette, 2003). Thus, in many ways, remanufacturing has the same broad goals as manufacturing including quality, speed, flexibility and cost. Therefore, the transfer of relevant best practices from manufacturing to remanufacturing is an important concern of many managers.

Also, many authors see remanufacturing as a process of growing importance in the overall product lifecycle. There are several reasons for this, including product take-back laws that mandate that manufacturers bear the burden of disposal at the end of a product's useful life (Mangun and Thurston, 2002), and the profitability/cost-effectiveness of remanufacturing durable products. In short, remanufacturing may make good business sense, with producers extracting benefits that offset some of the costs of take-back policies instituted in various countries. The key point is that, in every organization, it is useful to conceptualize remanufacturing as a profit-enhancing or cost-reduction activity.

A third point is that remanufacturing may often include the incorporation of component upgrades to add new features to the product or to improve compatibility with newer systems (Ayres et al., 1997). This point is particularly important for the DoD, which is frequently engaged in refreshing its hardware stock with new technologies. Excellent examples are found in the US Army's Bradley and Abraham armored vehicles upgrade program, the US Marine Corps' Harrier upgrade program, periodic updates of the US Navy's aircraft carrier fleet, and numerous examples in the US Air Force (including those involving the B52 Stratofortress bomber and the KC135 Stratotanker tanker, which were originally designed and built in the 1950s). The authors know of no formal models justifying the upgrade decision – including time and extent of repair – and note that this topic clearly warrants further study in the military context.

In the context of job shop operations, the remanufacturing literature remains limited. The main difficulty in this research stream is to model the job shop in a meaningful, generalized way. Guide, Srivastava and Kraus studied regular and expedited schedule, inventory buffer and capacity planning in simulated remanufacturing scenarios based on Air Force aviation depots (Guide et al., 1997a, 1997b). These studies generally recommended best approaches to schedule the disassembly–repair–reassembly sequence considering the uncertainty of the process. Since then, although much has been studied about high volume remanufacturing operations, but very little work has been done to understand the remanufacturing job shop.

3. RFID technology in production processes

In its simplest classification, radio-frequency identification (RFID) tags can be separated in two types: passive (where the tags do not have its own source of energy) or active (where the tag has a battery). The absence of battery allows passive tags to be smaller, simpler, and less expensive, which makes it a natural upgrade from barcode, with the benefit of carrying more information about the tagged item. Active tags, however, are bulkier and more expensive. The active design is generally selected when other tag capabilities are desired, in addition to item identification (Landt, 2001; Lahiri, 2005; Ngai et al., 2008). One particular type of active RFID tag is the real-time location system (RTLS).

Real-Time Location System (RTLS) is a special-purpose active RFID technology that is used to locate an object or a person within a pre-defined area. In its basic structure, three or more RFID readers (strategically distributed in the area of interest) sense the tags in the area and, by triangulation, indicate their location on a computer screen. It has been used in a variety of contexts to locate individuals, such as in amusement parks and in prisons (Ferrer et al., 2010). RTLS has been used in ports to facilitate the location of a specific container among thousands, and at automobile distribution centers to help finding a specific vehicle in the lot (Armanino, 2005). Its use in manufacturing sites has helped locating individually tagged items that may be lost in a large job shop (Miertschin and Forrest, 2005; Phelps and Rottenborn, 2006).

There is a substantial literature on the implementation of RFID to manage manufacturing operations. Concerns include the management of machine-paced processes (Wang et al., 2008; Vlad et al., 2009), shop floor control (Hozak and Collier, 2008, Thiesse and Fleisch, 2008), reverse logistics (Kärkkäinen, 2003; Karaer and Lee, 2007; Kulkarni et al., 2007; Sameer et al., 2009), integration with ERP or similar legacy systems (Kohn et al., 2005; Günther et al., 2008) and inventory accuracy (Fleisch and Tellkamp, 2005; Doerr et al., 2006; De Kok et al., 2008; Rekik et al., 2008, 2009; Szmerekovsky and Zhang, 2008; Uçkun et al., 2008).

Hozak and Collier modeled the use of RFID as a tracking device and as an enabler of lot splitting in first-time manufacturing. For a benchmark of performance, they used the performance of the facility when lots were labeled with barcodes. They developed an experimental design varying four factors: the transfer lot tracking mechanism (where RFID was one of three possible levels), the number of transfer lots using lot splitting (five levels), the job dispatching rule (first-come first-served, shortest processing times, and earliest due date), and the setup to run time ratio (three levels). Two performance measures were considered: mean flow time and proportion of jobs tardy. Analysis of variance was used to evaluate the performance improvement that could be attributed to RFID in this simulation, and to indicate under what scenario this contribution was more significant. In the direct comparison between barcodes and RFID, the authors found that the performance improvement was negligible with large lots, but they observed a significant impact from RFID when each batch was split into very small lots (Hozak and Collier, 2008). In a follow-up, they modeled the impact of imperfect information collected from RFID in lot-splitting manufacturing environments (Hozak and Hill, 2010).

Thiesse and Fleisch (2008) examined the use of RTLS to provide information on the location of physical items in a semiconductor fabrication facility, and the use of that information to generate efficient job schedules. They developed a simulation model of the manufacturing process incorporating RTLS-enabled dispatching rules, and found substantial benefits in terms of process speed achieved through improved efficiency gained by the new level of process visibility.

In some circumstances, permanent tagging may generate valuable information for the pre-remanufacturing process of disassembling components. Two articles have recently discussed the value of component information prior to disassembly (Kulkarni et al., 2007; Zikopoulos and Tagaras, 2008). Their analyses suggest that, since there is a high level of uncertainty about the quality of components entering the remanufacturing process, RFID-derived information can help sort components wherever it provides an alternative to manual inspection. Information about the history of the component might help lower costs in the remanufacturing process. Based on our experience, and confirmed by the findings in both studies, we notice that:

- The value of information from tracking components increases with potential variability in component quality. If variability is high, then information on component history has more value, which favors tagging. This may be true for parts that are sensitive to maintenance quality or use/abuse/environmental factors. (For example, officers at North Island Naval Air Station told us that FA-18 aircraft entering the remanufacturing process vary greatly in how many hours of work they require, largely depending – in their opinion – on the maintenance practices of the sites where they operated.) Moreover, some components may be malfunctioning when they enter the remanufacturing process; at the extreme, some parts are completely missing. Early identification of defective components helps planning the remanufacturing process. Using RFID-enabled data, it may be possible to presort and prioritize components based on their history: some parts can be fast-tracked, some components may not need disassembly, and some may not be suitable for remanufacturing (and hence must be replaced).

- The value of presorting using RFID-enabled data is contingent on several other costs: if disassembly costs are high, component tagging is more valuable, as this may enable the assessment that the component does not need disassembling. If holding costs are high, passive RFID data may enable faster sorting and routing compared to manual inspection processes. The costs of manual sorting and testing also add to the value of RFID tagging. Finally, the accuracy of alternative sorting and testing procedures, and the cost of errors in sorting and testing has to be considered.

There is a growing literature on the use of RFID tags on aircraft components to support lifecycle maintenance (Ngai et al., 2007; Ramudhin et al., 2008; Apte and Ferrer, 2010). Tracking aircraft components under repair in a large remanufacturing shop presents hurdles that cannot be solved with the same approach adopted in manufacturing sites. The requirement to reassemble parts into the same product from which they came makes each component unique and requires that all components be tracked individually as they flow from workstation to workstation. This fact, in combination with the size of these types of facilities and the extremely large volume of components, makes RFID tagging extremely challenging, but also potentially very beneficial.

Our research analyses this type of situation. We first present a specific example of an RFID implementation in a US Army facility where very large and complex radar systems are regularly remanufactured. We then present a simulation model that we developed to explore the potential benefits of RFID usage in these types of facilities. In both the example facility and the simulation model, three main features are present: it must be ensured that components are reassembled into the same specific product from which they came; the products have many component parts; and the facilities are large, with many separate buildings. In addition, the component parts are not assumed to be previously tagged, (or existing tags are not useful for location tracking) and so must be tagged upon disassembly.

4. Operations at Tobyhanna Army Depot

The Tobyhanna Army Depot in Pennsylvania is the largest full-service electronics maintenance facility in the DoD, providing design, manufacturing and remanufacturing services for satellite terminals, radio and radar systems, electro-optics, night vision and anti-intrusion devices, airborne surveillance equipment, navigational instruments, electronic warfare, and guidance and control systems for tactical missiles. The Army designated Tobyhanna as its Center of Industrial and Technical Excellence for communications—electronics, radar, and missile guidance and control, while the Air Force has designated Tobyhanna as its Technical Source of Repair for command, control, communications and intelligence systems. The variety of jobs undertaken by Tobyhanna clearly classifies this facility as a job shop, with all the challenges that a typical job shop faces including requiring high operational flexibility. It differs from the typical job shop, though, in its exceptional size including several buildings adding to 4.1×10^6 sqft (almost 400,000 m^2).

In early 2004, Tobyhanna conducted a pilot program incorporating RTLS technology into its radar remanufacturing operations. The program resulted in a payback of less than one year and measurable improvements in average repair flow-time and direct labor-hour per job, enabling higher throughput and more reliable lead-time promises (Miertschin and Forrest, 2005). Table 1 shows the radar systems remanufactured at Tobyhanna including the AN/TPS-75 Ground Theater Air Control System Radar System and the AN/TRC-170 Tropospheric Scatter Microwave Radio Terminal. As shown in Table 1, AN/TPS-75 has very low annual demand. The disassembly process generates 100 parts of which 75 are tagged. These parts undergo approximately 350 traceable actions. Prior to the introduction of RTSL, flow-time ranged from approximately 8–15 months. Much of this time was wasted due to missing components. Supervisors had to walk the large distance between several buildings to locate where these 'lost' parts might be located.

Six performance measures were used to evaluate the benefits of RFID technology in Tobyhanna (Phelps and Rottenborn, 2006). Three of these measures relate directly to customer concerns:

- *Lead-time accuracy*: The ability to make good estimates about lead-times is a valuable service to customers that was improved by using RTLS.
- *Job visibility response time*: The ability to assess the status of a job in real-time, which was improved.
- *Flow-time*: Better scheduling process improved wait time between tasks, thus reducing flow-time.

The other three measurable impacts relate to remanufacturing efficiency:

- *Labor-hours per job*: Workers spent less time on jobs, as a consequence of reduced non-value-added time looking for parts lost in the shop floor. This greatly reduced the need for scheduling overtime work.
- *Resource utilization*: Greater visibility enabled better scheduling of resources and improved asset utilization.
- *Shrinkage and theft*: Better visibility eliminated permanent material loss.

Table 1
Radar systems remanufactured at Tobyhanna Army Depot.

	No. of Parts (No. of tags)	No. of Traceable actions	Annual demand	Time to input data+add tags (h/system)	Cycle time before (range) (days)	Cycle time after (range) (days)	Shop population
AN/TPS-75	100 (75)	350	4–5	4–6	245–445	147–324	15 systems (7 w/some RFID+8 w/o RFID)
AN/TRC-170	30 (30)	120	63–66	2	55–86	63–243	39 systems (27 w/some RFID+12 w/o RFID
AN/TPQ-36			49		262–947	First case: 367	
AN/TPQ-37			8		178–272	All cases: about 210	

In separate meetings, workcenter leaders for both radar types credited RTLS for the elimination of "menial, non-value tasks" such as searching for assets on the shop floor. The manager of the AN/TPS-75 indicated to following substantial benefits:

- Total repair flow-time generally reduced from 24 months to 9 months.
- Component shop flow-time reduced from 3–4 months to 30 days.
- Total personnel reduced from 35 to 25 workers on the shop floor.
- Disassembly and reassembly personnel reduced from 3 to 2 workers.

Similar benefits were not observed with the AN/TRC-170. The manager was not enthusiastic about the use of RTLS clarifying that, although it gives visibility to part location, it is important to physically visit the parts to understand exactly why they are in a certain location.

To further leverage the technology, managers at Tobyhanna extended the program for three more years, and two other radar types joined the program: AN/TPQ-36 Firefinder Radar System and AN/TPQ-37 Firefinder Artillery Locating Radar. Both are large, low-volume systems with long flow-times. At the time the data was collected, only one AN/TPQ-36 system with RTLS tracking had been completed, and three AN/TPQ-37 systems with RTLS tracking were in process. The adoption of RTLS has been smoother for both systems, and there is some indication that they are experiencing sizable flow-time reduction.

In what follows, we model a remanufacturing operation with many of the characteristics found at Tobyhanna, in an attempt to identify the performance drivers.

5. Simulation of RTLS in remanufacturing

In very large facilities where each part must be treated as unique, the use of RFID is expected to reduce the complexity of parts handling, facilitate the identification and location of components from the same original product for quick reassembly, and thereby reduce flow-times. In this section we describe the simulation model that we developed to test the effect of these differences in material handling, and how locating components affected overall product flow-time in this type of facility.

We chose to use discrete-event simulation to model a representative facility with and without RFID. Specifically, we modeled a remanufacturing facility that disassembles, repairs, and reassembles two different products. The model is not intended to be an exact representation of Tobyhanna. Rather, it introduces some general characteristics that are shared by Tobyhanna and other similar remanufacturing facilities. Beyond the basic disassembly, repair, and assembly flow, some general characteristics are represented, including component parts having differing flows, often flowing through different repair shops; long assembly, repair, and reassembly times; the requirement to reassemble components into the same original product; and occasional difficulties identifying to which original product a given part belongs. In our model, we adopted certain assumptions and simplifications to isolate the effects of certain changes to the facility's operations.

5.1. Simulation model

The general product flow through the facility, along with times, probability distributions, and resource information is modeled as follows: Products of type 1 (P1) arrive at the average rate of one every 4 working days, and products of type 2 (P2) arrive at the average rate of one every 52 days, with all inter-arrival times being exponentially distributed. Each product goes through the disassembly process; P1s take on average 6 days to be disassembled, and P2s take 13 days. There are two workers assigned to disassembly, which, due to the arrival and service rates, results in an expected utilization of these workers of roughly 90%. Each component part then flows through one of four repair shops before being available for reassembly; P1 component parts flow through one of the four repair shops, whereas P2 component parts flow through one of only three repair shops (shops 1 through 3). Additional model details differ by scenario, so the scenarios are discussed next, followed by the additional model details.

Initially, we ran the simulation model in four different configurations, Scenario 1 through Scenario 4, by varying two factors; in addition to varying whether or not RFID was used, we also chose to vary the number of components parts per product (few, many) in order to determine if the effect of using RFID would differ depending on the number of component parts. Accordingly, the first two scenarios modeled the simpler facility operations with only a few parts per product, where Scenario 1 modeled the facility operating without RFID and Scenario 2 with RFID. Scenarios 3 and 4 modeled the facility with many parts per product, without and with RFID, respectively. Table 2 shows this experimental design. Table 3 shows the average processing times for each of the four repair shops and the number of parts flowing through each shop in each scenario.

In Scenarios 1 and 2, P1s are disassembled into four parts, with each flowing through one of the four repair shops. As shown in Table 3, P1 parts spend, on average, 65, 60, 55, and 50 days in shops 1 through 4, respectively. P2s are disassembled into three parts, and each of these flows through one of the repair shops 1 through 3. On average the P2 parts spend 150, 170, and 190 days in these shops, respectively. The repair shop flow-times were modeled using a Beta distribution defined by parameters $\alpha_1 = 1.5$ and $\alpha_2 = 5$. The range of the flow time distribution was scaled such that the minimum time was two-thirds of the average time that the items spent on the shop. We intentionally chose distribution parameters that result in a long right tail, representing a small proportion of parts with much longer repair times than average, which can arise in a remanufacturing facility that is not able to track parts well. These times can be caused by inappropriate prioritization of work, misplaced parts, or simply because, on occasion, some parts require more work. In order to isolate the effects that RFID has on the disassembly and assembly operations and workers, the total flow-times of the parts through the shops were modeled, rather than modeling the complex within-shop

Table 2
Experimental design.

	Few parts	Many parts
No RFID	Scenario 1	Scenario 3
With RFID	Scenario 2	Scenario 4

Table 3
Number of parts in each shop for each scenario.

	Shop 1	Shop 2	Shop 3	Shop 4
Scenarios 1 and 2				
P1 (4 parts)	1 (65 d)	1 (60 d)	1 (55 d)	1 (50 d)
P2 (3 parts)	1 (150 d)	1 (170 d)	1 (190 d)	
Scenarios 3 and 4				
P1 (15 parts)	3 (65 d)	3 (60 d)	4 (55 d)	5 (50 d)
P2 (25 parts)	10 (150 d)	10 (170 d)	5 (190 d)	

processes, resources constraints, and resultant queues. Once a part finishes repair, it waits in the repair shop to be delivered to the assembly area. Deliveries occur at the end of each day so parts are available for the assembly workers at the beginning of the next day.

In Scenarios 3 and 4, where products with many more component parts were modeled, the shop flow-time distributions were kept the same. In these scenarios each P1 was modeled as having the following number of parts flowing through each of the repair shops 1 through 4, respectively: 3, 3, 4, and 5. Each P2 was modeled as having 10, 10 and 5 parts flow through each of the shops 1 through 3, respectively. Therefore, each P1 was modeled as comprising of 15 parts, and each P2 was modeled as comprising 25 parts, to test the effects of RFID on a facility that needed to keep track of many more parts per product.

The reassembly operation in each scenario was modeled with the same average processing time as the disassembly process, with the same processing time distribution. The assembly process was also modeled with two dedicated workers with an expected utilization of 90% on assembly work. However, these workers also have the task of receiving parts from the shops, determining which product each part belongs to, and sorting these parts in preparation for assembly. In the simulation model scenarios where the factory does not use RFID (Scenarios 1 and 3), this additional work is assumed to take an average of 7 minutes per part, and Beta distribution with parameters $\alpha_1=1.5$ and $\alpha_2=5$, scaled so the minimum assembly time is set as two-thirds of the average. This results in a maximum of about 15 minutes per part. In addition, when the assembly workers do not have any products ready to be assembled or parts to sort, one of them goes to the shops to look for parts. In the models where RFID is used (Scenarios 2 and 4), the worker only goes to a shop if parts are ready for assembly, whereas in the models without RFID, the worker will have to visit each of four shops onsite to see if parts are ready. If all shops have been checked and no parts are ready, the assembly workers wait a few hours before checking again to prevent continuous walking between shops. In addition, when RFID is used, the sorting time takes less than a minute, representing the time to look up the part in the computer system and sort it into the correct location next to the assembly area.

Table 4 summarizes the models across scenarios. Other than the differences shown in the table, the models have identical flows, time distributions, and resources.

5.2. Simulation results and analysis

The primary performance measure of interest is the total flow-time for each product. The primary contributor to differences in the flow-times is the time parts spend waiting for the start of the assembly process once they've completed repair in the shops, so this measure is also useful. Other measures of interest include the disassembly and assembly worker utilizations. Although the expected utilizations were calculated to be 90%, that calculation did not include time disassembly workers spend attaching RFID tags to parts (and recording them in the system) and the time assembly workers spend sorting parts or getting parts from shops; these work efforts will change across scenarios. We also tracked the percentage of time assembly workers spent going to or from shops to look for and bring back more parts. The four scenarios were modeled in Arena 12.0 (Rockwell Software) and run for 1000 replications each. Each replication was run for a lengthy warm-up period to bring the facility into near steady state before collecting statistics. The results for each of these four scenarios are given in Table 5.

Several of the results shown in Table 5 are interesting. First we compare Scenarios 1 and 2. The flow-times appear to be slightly different but this difference is not significant. The time parts spend waiting to be assembled is significantly different between Scenarios 1 and 2 but that difference is of a very small magnitude. Perhaps running the scenarios for more replications will give us a statistically significant difference in flow-times but the practical difference is likely to be immaterial. This result is interesting because we would anticipate that the time saved on sorting parts and assembly workers searching for parts would be large. However, even with RFID, the results in the last few columns of Table 5 show that the assembly workers still spend time gathering parts even when RFID is used, and the assembly worker utilizations are not different enough to change the queue times in front of the assembly process much. Looking at similar comparisons between Scenarios 3 and 4, they show that even these small benefits provided by RFID seem to go away when there are many more parts in each product, a more realistic situation.

In the four scenarios analyzed, we intentionally controlled many aspects of the facility so we could observe how the impact of RFID on the assembly and disassembly operations would affect the measures of interest. The experiment demonstrates that if nothing changes in the rest of the facility, and assembly workers are not involved in different activities such as expediting, any small differences from RFID may disappear as the operations become more complex. However, the assumption that other parts of the facility would not be affected by RFID is not realistic. RFID not only makes part location and identification easier, but having information about parts readily available in a computer screen can also have other benefits such as allowing sensible prioritization of parts through the repair processes (which is generally first-come, first-serve) and can

Table 4
Model differences between scenarios.

	P1 parts	P2 parts	A disassembly worker RFID tags parts	Assembly worker part sorting time	An assembly worker looks for parts
Scenario 1	4	3	No	Beta (1.5; 5.0), average 7 min	When idle
Scenario 2	4	3	Yes	0.5 min	When idle and parts are ready
Scenario 3	15	25	No	Beta (1.5; 5.0), average 7 min	When idle
Scenario 4	15	25	Yes	0.5 min	When idle and parts are ready

Table 5
Results for Scenarios 1 through 4.

	P1 cycle time (days)	P2 cycle time (days)	Part time from shop to starting assembly (days)	Disassembly worker utilization	Assembly worker utilization	Assembly worker getting parts utilization
Scenario 1	109.21	255.75	22.98	0.884	0.916	0.049
Scenario 2	108.46	255.96	21.87	0.884	0.893	0.017
Scenario 3	124.17	311.73	24.79	0.883	0.938	0.057
Scenario 4	124.60	312.06	24.68	0.892	0.949	0.070

reduce instances of parts being misplaced. These are generally two of the major contributors to the long right tail on repair shop flow-times, as discussed previously. With this in mind, we ran one additional scenario.

In Scenario 5 we repeated Scenario 4 but modified the repair shop flow-time probability distributions. To keep the comparison fair, we maintained the same average flow-times and the same minimum time used in the other four scenarios. However, we changed the Beta distribution parameters to $\alpha_1=5$ and $\alpha_2=5$ resulting in a symmetric distribution with equal weight below and above the average, therefore lowering the maximum value allowed by the distribution. This reduced the right tail significantly but did not drastically change the coefficient of variation (c.v.), keeping the distribution realistic. The c.v. on the Beta distribution used in Scenarios 1–4 was 0.89 and the c.v. in Scenario 5 is 0.77, which retains quite a bit of variability.

Table 6 shows the results for Scenario 5 in comparison to Scenario 4. Here we see that the flow-times for both products are reduced significantly in Scenario 5. As expected, the average per-part time waiting for assembly also goes down. Also, since the processing times and workloads on the disassembly and assembly workers did not change, there is no change in the utilizations. Recalling our assumption that the average flow-times through the shops did not change, we can see that these results are likely conservative when we consider the fact that reducing the number of parts that have excessively long repair shop flow-times will likely also reduce the average flow-times through these shops as well, which further reduces the product flow-times.

5.3. Simulation implications and limitations

Our simulation study leads to two direct implications. The results of the first four scenarios imply that efficiency gains for the assembly workers alone do not yield significant overall benefits in terms of product flow-times. In addition, this implication does not appear to depend on the number of parts in each product. When comparing the results of Scenarios 4 and 5, however, we do see that increased ability to track parts across the facility, as manifested by a decrease in the right-hand tail of the shop flow-times, does provide enough improvement to see significant benefits in overall product flow-times.

Looking at the Tobyhanna case with this additional information from our simulation results can also add insight. At Tobyhanna, the manager of the AN/TPS-75 repair process reported several very significant improvements that were attributed to the use of RTLS and to the adoption of "Lean" processes. On the other hand, the manager of the AN/TRC-170 process did not observe the same benefits. One reason given was that the manager felt that personal visits were still required to assess why a part was in an unexpected location, which presumably mitigated any efficiency gains in those areas. Our simulation model demonstrated how leveraging one part of the potential efficiency gains from RFID (reduced time looking for parts at assembly) without realizing other efficiency gains (the reduced right-hand tail on shop flow-times) could effectively eliminate any overall benefits.

Becker et al. (2010) have identified four main "effects" that RFID has on processes: process time reduction—resulting from the substitution of manual tasks of item identification into an automated activity; Error reduction—resulting from the automation of identification processes that, when executed manually, are prone to errors; Resource consumption reduction—resulting from the reduction of materials and equipment time due to process automation; and Enhanced process information—resulting from easier dissemination of valuable information that can result in greater efficiencies. Similar benefits were also identified by Ferrer et al. (2010). A considerable challenge identified in both works is the difficulty in modeling these benefits. This limitation is also felt in our simulation.

Through the presentation of the Tobyhanna case and the simulation study, we have lent insight to some of the potential benefits of using RFID in certain types of remanufacturing facilities. Overall, Tobyhanna's experiment with RFID was an operational success. The remanufacturing process for the AN/TPS-75 was the recipient of the Shingo Prize for Excellence in Manufacturing in 2006 and the AN/TPQ-36 remanufacturing process received the award in 2007. This success leads to the question: should RFID be adopted in other remanufacturing shops in the DoD? If so, what type of RFID should be used? Under what conditions should components be tagged at source (using passive RFID), and under what conditions should they be tagged only within the remanufacturing site (using RTLS)? Within remanufacturing operations, what characterizes a job shop that would benefit from using RFID to track the movement of parts and components on the shop floor? In the following section we explore important considerations in the decision of whether or not to adopt RFID, as well as in two additional significant decisions related to RFID tagging.

6. Tracking technology for remanufacturing

In this section, we propose a framework for decisions related to RFID adoption and tag selection in remanufacturing job shops. We consider the choice between tagging a component with a passive RFID tag, which may be used to track its whereabouts over its lifetime (as Boeing and Airbus are reportedly doing with certain aircraft parts) or using a temporary tag, usually an RTLS, just to track part movement within the remanufacturing facility. More specifically, in this section we are trying to distinguish – qualitatively – the remanufacturing operations that have the greatest potential to benefit from automated tagging technologies. We follow a hierarchical decision-tree approach starting with the facility characteristics, then the process characteristics and finally the part characteristics.

6.1. Should the remanufacturing facility adopt an automated tracking system?

Many remanufacturing operations have low economies of scale, and the DoD's depots fit this description. Considering the standard product-process matrix classification, the DoD depots are job shops because of their process-oriented layout, high product variety, high demand variability for each product and low volume associated with each job. Hence, they cannot benefit from some of the efficiencies found in a line flow (human-paced or machine-paced assembly lines), such as steady demand and considerable economies of scale. Parts being remanufactured in military depots

Table 6
Results for Scenarios 4 and 5.

	P1 cycle time (days)	P2 cycle time (days)	Part time from shop to starting assembly (days)	Disassembly worker utilization	Assembly worker utilization	Assembly worker getting parts utilization
Scenario 4	124.60	312.06	24.68	0.892	0.949	0.070
Scenario 5	110.72	264.30	16.94	0.892	0.949	0.070

face a jumbled flow, which makes it very difficult to schedule work orders and to keep track of jobs as they progress through the system. This difficulty leads to inefficient operations with unpredictable deadlines, low resource utilization, and high incidence of delays, defects and rework. To reduce uncertainty in the job shop, floor managers may try to track the jobs using simple paper-and-pencil methods, which have many associated risks. Clearly, the use of a reliable tracking technology would be more appropriate in this environment. Better job shops make a consistent effort to be lean, and the use of RTLS to track parts may be a useful tool to achieve this objective. Using manual systems to follow the movements of individual components in the job shop can be difficult, due to the high propensity for some parts to lag behind and delay final re-assembly. Moreover, if the shop is large enough, busy enough, or if the items are similar enough (where *enough* is introduced subjectively), tracking individual parts using some automated system may simplify decisions and allow the parts to move more quickly from station to station until all processes are complete. This suggests two situations in which automated tracking is useful in the remanufacturing shop:

- *Large population of unique parts*: Some shops repair a large number of similar products at the same time, where each product's parts must be treated as unique so as to be reassembled with the same specific parts that came from the same original product. The sheer number of unique items may overwhelm even the most experienced scheduler, or the most talented worker, making it difficult to enforce any kind of scheduling policy based on which product the part came from. This is exacerbated if the remanufacturing shop handles a large variety of similar parts.
- *Flow complexity*: Some repair processes are complex, requiring the parts to follow through various operations in multiple workstations. The typical process-oriented layout found in most shops would force the part to travel in a non-linear fashion through the shop floor, increasing the scheduling complexity. This complexity is a function of the site layout, the number of different workstations onsite that are processing the components, and the number of offsite subcontractors outsourced to execute specialized processes. These arrangements are typical and result in loss of visibility. The visibility is further reduced if the remanufacturing facility is very large, as it is common in repair shops owned by the Department of Defense. In addition, the resulting scheduling difficulties are magnified when there is high variability in component processing times.

If the remanufacturing shop exhibits the conditions described above, it would benefit from using automated technologies to track the progression of parts in the process. However, once the decision is made to use RTLS, more decisions must be made regarding which parts should be tracked using the technology, and whether parts need to be tagged individually or can be tagged as a set of parts traveling together to be reassembled into a given product. These questions are addressed in the next section.

6.2. *Should the tracking tag be attached to individual components?*

As seen in the Tobyhanna case (specifically in Table 1), even if RTLS is used in a facility, not all parts are necessarily tracked. For example, many nuts and bolts are too inexpensive or ordinary to warrant the costs of tagging, so we focus on the meaningful parts. For each meaningful part, the manager may choose to tag it individually, tag with other parts coming from the same core, or not tag it. With a little discipline to ensure that containers and parts are correctly associated in the system, and that the parts stay in the same containers until the process is completed, the same benefits can potentially be obtained using tagged containers (the system used at Tobyhanna Army depot) or tagging individual parts directly. The three options are likely to coexist in a given facility, and the choice of which treatment to adopt is a function of each part's characteristics. Here are descriptions of types of parts that warrant each of the three part-tagging choices:

- *Unique flow*: Specialized parts (e.g. hydraulic, pneumatic, optical or electronic components) usually follow a unique flow, separate from the majority of parts requiring mechanical repair. They may be sorted away, tagged individually, and sent to the respective shop where they are repaired.
- *Common flow*: The disassembly process generates several parts that require mechanical repair. If these parts need to be reassembled together, it may be convenient to adopt a common flow. To operationalize this, one can use a container or bin to transfer parts from workstation to workstation. The container can be tagged rather than tagging each individual part.
- *Part size*: Very large parts that define the whole product tend to be easily recognized. The fuselage of an aircraft being repaired is easily identified and moves very infrequently in the shop. These types of parts generally do not require tracking. Fig. 1 provides a simple flowchart that summarizes the decision discussed above. It is also possible, however, that some parts may already have permanent tags that were applied early in their lifecycle with the objective to support maintenance planning. These tags may be suitable for tracking the part's location in the remanufacturing shop, which leads to next section.

6.3. *Should the individual component carry a permanent tag?*

In some cases, permanent tags may be placed on a product or component early in its lifecycle. There are various reasons for attaching a permanent tag onto components including:

- *Regulation or policy*: Some products or weapons systems are subject to maintenance rules that require keeping all components together as a kit, never swapping parts from one product to speed the repair of another. In some cases passive RFID tagging may be used to help ensure this rule is followed. Tagging is particularly beneficial when errors are relatively expensive (i.e., cost of rework or cost of errors to users are high), when testing is relatively expensive (to check conformance of the reassembled original components), and if the error rates and costs of the alternatives to tagging are high. Regulatory policies may require tagging at the source for safety reasons, i.e., it may be necessary to record major events in the life of certain components and to follow their use, degradation, repair and re-use until they are discarded. To complete the system, each part's tag should be associated with the part's serial number, and the data should be recorded in a master database (Obellos et al., 2007).
- *Usefulness or value*: Permanent tagging may generate valuable information by recording the part's history. This information may facilitate the execution of timely maintenance of expensive items. In some systems, such as aircraft engines, components are required to follow a cycle of inspection and refurbishment after a pre-specified number of flight hours, or after exceptional operating conditions are recorded (such as temperatures outside normal operating ranges). There may also be value in information generated about a component during its operational life for its disassembly as it goes into remanufacture.

In these situations there is either a requirement or an anticipated benefit in tracking the part's history over its lifetime.

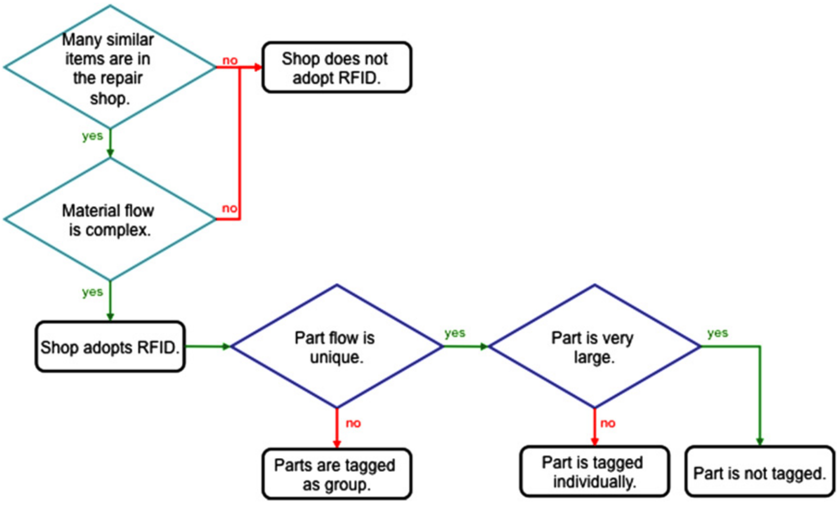

Fig. 1

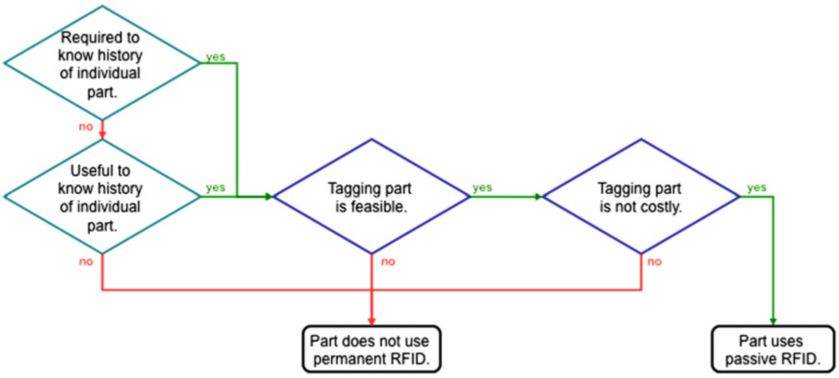

Fig. 2

Tagging the part with passive RFID may facilitate the collection of this data. In addition, some items go through several remanufacturing cycles during their lives, each time burdening the repair shop with the same scheduling and tracking challenges listed earlier, so one might consider permanent tagging in preparation for future remanufacturing operations as well. This decision would require evaluating the trade-off between the benefits and the complexity of execution. The important questions for this evaluation are summarized in Fig. 2 and detailed below:

1. Is it feasible to apply an RFID tag to the part? This assessment must consider:
   - The effect of the tag on the component's functionality during its normal operating cycle.
   - The ability to effectively read the tag under various operating environments.
   - The tag's resilience to the remanufacturing process (perhaps requiring replacement).
   - The impact of the tag on the efficiency of the remanufacturing process (value of information provided by the tag; potential requirement of tag removal or replacement).
2. Is the cost of tagging the individual part acceptable? The answer to this question requires assessing:
   - The cost of the tag itself.
   - The cumulative cost to replace the tag during the part's lifetime.
   - The cost of additional RFID hardware and software in the system.
   - The cost of managing the tracking process.
   - The costs of not having an automated tracking system (the cost of using a manual tracking method, or not tracking at all).

If the answer to these questions is positive, then the parts should be individually tagged with passive RFID, possibly associated with the part's serial number. If the answer to either set of questions is negative, the solution depends on the purpose of tagging. If the value lies in the knowledge of individual part's history (specifically, if it is a regulatory requirement) then a traditional recording method must be adopted, with all its inherent weaknesses. Whether or not the questions above lead to individually tagging the parts, it is possible that the permanent tag may be useless for tracking purposes, so the manager may choose a redundant system by which a component bearing a passive tag may still receive a specialized tag for tracking while in the remanufacturing shop.

7. Discussion and conclusions

In this study, we explored the potential benefits of using RFID in large remanufacturing job shops through a case study and a simulation study. In addition, we focused on two issues pertaining to how to implement RFID: which parts to tag in the remanufacturing facility, and when to use passive RFID tagging of components throughout their lifetime versus using RFID only within the remanufacturing facility.

Passive lifetime RFID tagging is beginning to happen for some components used in the commercial aircraft industry but is not yet embraced by the DoD. Given the contingencies we highlight in our proposed decision framework, at the moment we see a fairly limited scope for applying passive RFID to components in existing systems owned by the DoD. However, as manufacturers start to adopt permanent tagging of critical components, the opportunities may change, which leads to the framework proposed in Figs. 1 and 2: if tagging individual items is not technically or economically feasible, it may be desirable to tag the containers that carry the components as they travel through the repair processes with RTLS tags.

Active RFID systems (including RTLS) have proven their effectiveness in several applications. We simulated the use of such tags using a model inspired by the Army Depot in Tobyhanna, PA, where remanufacturing flow-times are often measured in months, and components travel long distances between workstations. It is quite clear that substantial savings were garnered by introducing an RTLS at Tobyhanna Army Depot (Miertschin and Forrest, 2005; Phelps and Rottenborn, 2006), though our simulation study showed only moderate benefits on our measure of interest (flow-times). In our simulations, we learned that, if better component tracking enables the elimination of components with process times far greater than the average, average waiting time prior to reassembly is greatly reduced, with substantial impact in total flow-time, as shown in Table 6. Yet these results do not seem to explain all the efficiency gains from using RTLS in remanufacturing operations.

7.1. Theoretical implications

One way to view the work presented here is as part of a larger program of detective work that researchers are engaging in to find out how, when and why RFID technology produces improvements in manufacturing productivity. In thinking about the implications of this detective work, it is particularly instructive to triangulate our findings with those of Thiesse and Fleisch (2008) and Hozak and Hill (2010). In both cases these researchers find that RFID can enhance efficiency, but that the efficiency gains only occur by making changes to complimentary aspects of the manufacturing process—not from RFID as a standalone technology. Our study confirms these results by showing that there is a significant gap between the savings predicted by our simulation model of material flows with only the addition of RFID (an 11–15% reduction in flow-times achieved in Scenario 5) and the actual savings experienced at Tobyhanna as reported by the AN/TPS-75 manager (a 62% reduction in flow-times). We cannot specifically identify what fills this gap, but we will speculate on this in a moment. These studies collectively present an important theoretical implication that RFID technology should be conceptualized and modeled as part of an "innovation bundle" rather than as a standalone technology adoption. In the case of Hozak and Hill, the innovation bundle is RFID and lot splitting implemented together; for Thiesse and Fleisch, the innovation bundle requires defining the appropriate dispatching rules that most benefit from the RFID technology. For our case-study, the innovation bundle is likely the RFID technology and a collection of low-visibility process improvements that were implemented at the same time. The theoretical lesson is therefore that researchers must build an understanding of RFID by analyzing how it can be combined and bundled with a collection of process improvements or redesign, rather than looking at the technology as a standalone entity. Hozak and Hill (2010, p. 2741) make a similar point by arguing that "Managers should therefore not think of RFID as an investment to be implemented in isolation…" Such an understanding of RFID also has significant practitioner implications.

Based on our observations at Tobyhanna we can speculate on some additional process changes that might enrich this theoretical implication. The first change involved worker scheduling. In the case of Tobyhanna worker overtime costs are particularly prominent. It may be that RTLS creates information that enables and prompts managers to address issues such as scheduling and overtime, thus adding production flexibility and creating cost savings. These factors are not captured in our simulation model. Another possibility is that the implementation of RTLS in remanufacturing processes requires substantial housekeeping and reorganization, which can only be obtained with *unrestrained commitment from top management*. This housekeeping benefit is the same as is often observed during the implementation of Just-In-Time or Lean Six Sigma programs. In order to be able to introduce RTLS in the shop and track the movements of components, it may have been necessary to remove excess inventory, tools, bins and other items from the working area to allow for a smooth material flow. In doing so, the job shop saw substantial process improvement as a spillover effect of implementing RTLS. These housekeeping gains and top management commitment may not be amenable to simulation modeling but could be investigated through case study research. Nevertheless, they represent another component in the innovation bundle that deserves further scrutiny.

One final point with regard to seeing RFID implementation as part of an innovation bundle: it might be argued that sometimes efficiencies could have been realized without the use of new technology. Innovation bundles vary in this regard. In some cases the spillover effect of introducing RFID is motivational, in the sense that its arrival focuses management attention on their processes and therefore encourages improvements. In other cases the use of RFID and another technology may have compounding effects. Ultimately however, the larger point is that RFID has a variety of (potentially positive) spillover effects that can only be captured by changing other aspects of the production process. Mapping this variety of spillover potentialities would be another fine issue to research empirically, with recent work by Brintrup et al. (2010) being an example of this kind of effort.

7.2. Practical implications

Generalized practitioner implications from our study are also evident. One of the major puzzles RFID has posed for practitioners is finding the return on investment (ROI) from its adoption. Many practitioners have lamented that they cannot justify RFID adoption based on the current economics of tags and readers. Our study highlights that a key reason for this may be that the payback from adopting an RFID system may come through its spillover effects which (a) are not part of the business case analysis for implementing the technology, and (b) involve other process or technology changes in order to be realized. In short, a main cause of the difficulty in finding the ROI for RFID adoption may be because the payoffs lie in areas outside the scope of traditional payback models and may not be obvious without actually implementing the technology. Or – to paraphrase economist Paul Romer – "An RFID implementation is a terrible thing to waste."

Looked at this way, this puzzle also suggests its own solution, which is that adopters must be willing to adopt a "creative destruction" approach to find the benefits that RFID implementations can provide for their system. There are two crucial issues such experimentation must encompass. The first is that the changes RFID can be bundled with are not necessarily obvious from implementing RFID. What practitioners have to do is experiment with changes to *associated* parts of the production system in order to find out what new things RFID enables them to do. Second, the costs of experimentation can be reduced if firms share and diffuse information on their findings. This points to a continuing role for industry consortia, conferences and industry media (such as trade journals) that share lessons-learned from a wide variety of adoptions. Considered more broadly, these institutional factors are machinery for a kind of collective experimentation for RFID adopters.

7.3. *Future research directions*

Further studies are necessary to evaluate how RFID may be used to generate production efficiencies. We have already mentioned some of these above, such as worker scheduling and housekeeping improvements. One type of empirical study that might benefit research on this topic would be a large survey that examines the impact of RFID implementation by looking at a range of other factors and testing for interaction effects. This would be one way researchers could empirically examine what the spillover effects of RFID implementations are, and when they tend to occur. For example, which manufacturing plants realize the most benefit from implementing RFID systems, those with low or high capacity utilization, and/or those with varied or homogeneous product lines? This would help improve understanding of how RFID technology would help an organization enhance its flexibility without jeopardizing its productivity.

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