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THE EFFECTS OF RFID AND EDI TECHNOLOGIES ON SUPPLY CHAIN DYNAMICS

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Abstract

Process automation and information sharing are becoming increasingly important to the successful operation of supply chains. While previous works have investigated the effects of radio frequency identification (RFID), electronic data interchange (EDI), and other transparency technologies on model production/distribution systems, the studies completed to date have not fully examined the implications of these technologies on the supply chains' dynamic behaviour. This is especially true for supply chains which feature heterogeneously implemented transparency technologies. The present work seeks to fill this apparent technical void, by characterizing the impact of both heterogeneously and homogeneously implemented EDI and RFID technologies on the system dynamics of a prototypical multi-stage supply chain model: the beer distribution game. To this end, the effort utilizes high-throughput numerical simulation to characterize the influence of transparency technologies on transient performance metrics (*e.g.* settling time, cost, and stock outages), and to form a series of succinct conclusions on the technologies' relative utility.

Key Words

Radio-frequency identification, supply chain management, beer distribution game, high-throughput computing, simulation

1. Introduction

Recent advancements in information processing and manufacturing have rendered inexpensive technologies that are revolutionizing the way supply chains operate [1]–[4]. These transparency technologies (TT), named for the supply chain visibility they provide, include, but are not limited to, wireless communication systems, radio-frequency identification (RFID) systems, global positioning systems (GPS), and their accompanying softwares, which allow for collaborative use. Amongst these entities, electronic data interchange (EDI) and RFID have received the most attention as of late, due to the positive influence they can have on supply chain performance. Previous efforts have demonstrated that EDI can be used to streamline the management of multi-stage supply chains [5], even when implemented independently, and many believe that information technology (IT) infrastructure founded upon both EDI and RFID will yield further benefits, including improved inventory replenishment rates, reduced processing delays, streamlined collaboration, and reduced inventory shrinkage [1]–[3], [6]–[8].

Despite the positive reception that TT have received in some circles [1]–[4], it is important to note that there are a number of controversies hindering the widespread, homogeneous implementation of TT, especially RFID. A recent federal lawsuit opposing the use of RFID in livestock [9], for example, illustrates just one of the deeply rooted societal concerns associated with the technology. Likewise, recent efforts examining easily cloned, border-crossing cards [10], upcoming pharmaceutical RFID mandates [11], and human/radio-frequency signal interactions have revealed potential security, privacy, and medical concerns, which are not unfounded [12]–[16]. These concerns, coupled with early product failures and high implementation costs, have stymied the broad implementation of RFID systems [4], [17]–[19]. As the technology is refined and successful implementations continue to be reported, the technology can be expected to proliferate, but only in a heterogeneous fashion [1]–[4].

Given the high likelihood for a heterogeneous expansion of TT in many production/distribution chains, it is critical to understand the consequences of technological non-uniformity on supply chain performance. To this end, the present effort seeks to examine the nonlinear dynamics of a prototypical multi-stage supply chain model, the beer distribution game (BDG), operating in the presence of both homogeneously and heterogeneously implemented TT. It is important to note this effort is not without precedent. A number of prior efforts, for example, have considered the impact of various subgroups of TT, as well as other lead time reduction mechanisms, on the nonlinear system's performance [5], [7], [8], [20]–[26]. These efforts, however, primarily emphasized information sharing, and focused solely

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on homogeneous technology implementations, which are unlikely to emerge given the societal complications noted above.

To ensure broad applicability, the current work utilizes a classic anchoring and adjustment ordering policy, known to mimic human decision-making behaviour [27], [28]. This approach, used in conjunction with high-throughput numerical simulation, was successfully utilized by the authors in prior work to provide some of the most extensive characterizations of the BDG reported to date [29]. Here, structural changes to the BDG, used to capture the effects of EDI and RFID implementations, are also considered. These structural permutations are simulated across the entirety of the BDG's feasible parameter space to acquire pertinent system characteristics. These metrics, which include the length of the system's transient period (hereafter referred to as "settling time" – a metric loosely based on the linear settling time employed in control systems analysis), the number of time periods with stock outages, average and cumulative operating costs, average backlog (BL), and average supply chain inventory, are analyzed to determine the relative benefits of heterogeneous and homogeneous TT implementations, and, ultimately, to determine where these technologies can be implemented for greatest effect.

2. Modelling and Simulation

The system map of the BDG can be used to illustrate the structural effects of EDI and RFID implementation on a prototypical supply chain. The original system map, shown in Fig. 1, is a modified version of that originally presented by Mosekilde [30]. This map contains 27 distinct dynamic variables, governed by a high-dimensional, nonlinear iterative map, and an exogenous customer demand (COR). A brief review of the historical development of the BDG helps to clarify the structural modifications that are made to the system in the presence of EDI and RFID technologies. The BDG began as a multi-stage supply chain model [31]–[34], which systematically captured various processing delays in product ordering and delivery. The delays involved at each level included: clerical order processing, order mailing and filling, product transportation, and handling. Traditionally, these delays have been combined into a 2-week delay for ordering and a 2-week delay for transportation [35].

Electronic commerce, realized through the use of EDI, reduces the number of system variables in the BDG, in a manner that depends on the scale of implementation. Physically, EDI can replace bills of lading, product/service orders, and checks, while simultaneously facilitating extensive collaboration across the supply chain [5]. In the context of the BDG, EDI implementations can be seen as minimizing the delays associated with clerical processing [36]. As these delays are factored into the BDG as part of the 2-week mailing delay, 1 week of delays can be removed if EDI is implemented. This means that if two consecutive supply chain partners, for example the wholesaler and distributor, are both capable of EDI transmissions, then 1 week of ordering delays between the entities in the information upstream can be removed (see Fig. 2). It is important to note that this reduction in ordering delays is consistent with the treatment of delays in prior literature [21].

As with EDI, the integration of RFID technologies into a given supply chain allows for a significant increase in productivity and a decrease in processing and handling delays. When correctly implemented, RFID systems enhance inventory accuracy, increase replenishment rates, decrease processing time for outgoing and incoming shipments (ISs), and increase sales effectiveness [1]–[4], [8]. The real-world impact of RFID on common business practices, such as quarterly inventory verification and shipment processing, directly applies to the BDG's original 2-week delay associated with order processing and product handling. As such, the relationship between RFID and transportation

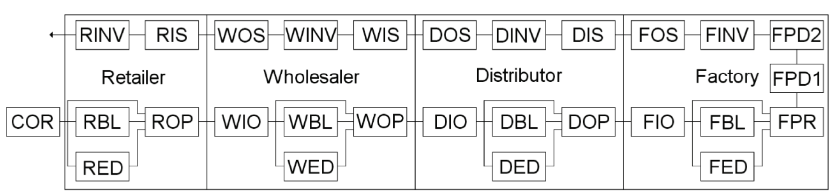

Figure 1. The classic BDG system map. The system variables include orders placed (OP), incoming orders (IO), outgoing shipments (OS), incoming shipments (IS), inventories (INV), backlogs (BL), expected demands (ED), factory production request (FPR), factory production delays (FPD1, FPD2), and customer order rate (COR). Each variable is preceded by the respective supply chain member; *R* for retailer, *W* for wholesaler, *D* for distributor, and *F* for factory.

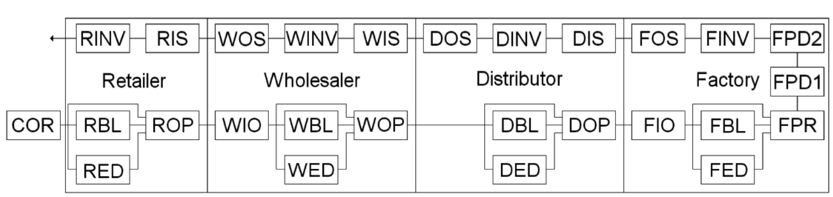

Figure 2. A BDG system map with an EDI link between the wholesaler and distributor. Notice that the incoming order delay for the distributor has been removed, effectively reducing the number of system variables by one.

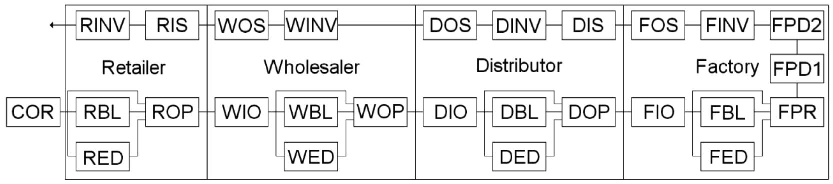

Figure 3. BDG system map with a RFID link between the wholesaler and distributor. Notice that the incoming shipment for the wholesaler has been removed, effectively reducing the number of system variables by one.

delays is truly analogous to the relationship between EDI and mailing delays. Accordingly, by utilizing RFID in the BDG between two consecutive supply chain partners, 1 week of delays in the product downstream can be removed. Figure 3 illustrates the effect of introducing RFID between a wholesaler and distributor in the BDG.

The current work utilizes a FORTRAN 90 simulation of the BDG, which was previously exploited by the authors in [29] and is based on the system model described in [27]–[29]. As noted above, this simulation captures the dynamic behaviour of 27 distinct dynamic variables, which are governed by a set of 27 coupled equations of motion. For illustrative purposes, the equations of motion which govern the actions of one of the supply chain's constituents (the distributor) in the absence of EDI and RFID technologies are included here, along with a brief description of corresponding business actions, which were originally described by Sterman [28]. The actions of the remaining supply chain constituents are governed by analogous equations of motion. Note that the subscripts t and $t-1$ in the following steps refer to the current week and previous week of the simulation, respectively. Also note that each of the following equations can be modified a particular supply chain member by replacing the first letter of the respective location, *i.e.* R for the retailer, W for the wholesaler, D for the distributor, and F for the factory. The remaining portion of each variable is described in the following steps.

1. The distributor receives ISs and moves recent outgoing shipments (OSs) from the upstream supply chain constituent to the second transportation delay position, ISs:

$$DIS_t = FOS_{t-1} \tag{1}$$

2. The distributor fills the orders and places them in the first transportation delay, OSs:

$$\begin{aligned} DOS_t = \max\{&DINV_{t-1} + DIS_{t-1}, \\ &DBL_{t-1} + DIO_{t-1}\} \end{aligned} \tag{2}$$

3. The distributor updates inventories (INV) and BLs. Each of these values is based upon the previous weeks' inventory, ISs, BL, and incoming orders (IOs):

$$\begin{aligned} DINV_t = \max\{0, &DINV_{t-1} + DIS_{t-1} \\ &-DBL_{t-1} - DIO_{t-1}\} \end{aligned} \tag{3}$$

$$\begin{aligned} DBL_t = \max\{0, &DBL_{t-1} + DIO_{t-1} \\ &-DINV_{t-1} - DIS_{t-1}\} \end{aligned} \tag{4}$$

4. The distributor moves the orders placed (OP) to the second ordering delay, the IOs, and updates expected demand (ED). Note that the ED is based on the previous ED and previous IOs:

$$DIO_t = WOP_{t-1} \tag{5}$$

$$DED_t = \theta DIO_{t-1} + (1-\theta)\, DED_{t-1} \tag{6}$$

5. The distributor places orders based on the ED, BL, previously placed and unfilled orders, and target inventory and supply line levels:

$$\begin{aligned} DOP_t = DED_t + \alpha\,[&Q - DINV_t + DBL_t \\ &-\beta\,(DIS_t + FIO_t + FBL_t + FOS_t)] \end{aligned} \tag{7}$$

The anchoring and adjustment ordering heuristic used to represent human decision-making is captured here (for the distributor) by (6) and (7), and, more specifically, four key variables (α, β, θ, Q) contained therein. These four variables are defined as the stock adjustment parameter (α), supply line adjustment parameter (β), rate at which the ED (anchor) is updated (θ), and combined target stock/target supply line levels (Q) [27]–[29], [37]. The stock adjustment parameter, $\alpha \in [0,1]$, is the weight put on the stock discrepancy, where $\alpha = 0$ means the stock discrepancy is ignored, and $\alpha = 1$ means the full stock discrepancy is taken into account. The supply line adjustment parameter, $\beta \in [0,1]$, is the weight put on the supply line discrepancy, where $\beta = 0$ means the supply line discrepancy is ignored, and $\beta = 1$ means the supply line discrepancy is taken into account as much as the stock discrepancy. The rate at which the ED is updated, θ, is also on the interval of [0,1], where $\theta = 0$ means the ED is static, and $\theta = 1$ means the ED is set equal to the demand from the previous week. While the BDG can exhibit a wide range of solution types (periodic, quasiperiodic, chaotic, *etc.*) across the entirety of the (α, β, θ, Q) parameter space, the current work specifically focuses on parameter regions which render constant-valued steady-state solutions. These solutions are of particular interest here, as they capture the vast majority of reported behaviours exhibited by real-world ordering and distribution systems, as well as human-based BDG simulations [27].

For this work, the aforementioned FORTRAN program was initiated at over 8,120,000 evenly distributed points in the (α, β, θ) unit cube for 151 distinct Q values, ranging from 5 to 20 in increments of 0.1. This breadth in operating conditions was introduced to ensure that the work accounted for the vast majority of observed player behaviours [27]. Each simulation was allowed to run for 10,000 weeks, or, using a literal interpretation of the simulations' time periods, approximately 200 years. If, at any time, the Euclidean distance between two consecutive state vectors (each incorporating 27 distinct state variables (SV)) was determined to be less than $<10^{-8}$, the simulation was stopped and previous weeks were compared to the constant-valued state using the following numerical criteria:

$$0.02 \geq \max_{i} \frac{SV_i^{\text{Const. Val.}} - SV_i^{n}}{SV_i^{\text{Const. Val.}}} \tag{8}$$

This criteria, based loosely on control systems' theory, allowed the program to identify the first state to have all dynamic variables within 98% of the final constant-valued state. It is worth noting that few, if any, of the solution trajectories utilized for analysis herein reached the 10,000th week of simulation. In fact, more than 90% of constant-valued solution trajectories reached steady-state in less than 1,000 time periods, and the highest average settling time for a single Q value was less than 350 weeks.

Once a constant-valued steady-state solution had been identified, costs were calculated using a holding cost of \$0.50 per unit and a BL cost of \$2.00 per unit, in a manner consistent with prior literature [27], [29]. Note that average costs, BLs, and the total amount of beer in the supply chain were time averaged, and the cumulative costs were summed, over the length of the transient. The program also tallied the number of weeks wherein at least one supply chain member had a BL greater than zero, as a means of identifying the number of weeks in which stock outages occurred. All of these values were then averaged over the constant-valued solution space for each of the 151 Q values.

An in-depth description of the BDG model and a generic simulation procedure can be found in previous work by the authors [29]. The only modification to the simulation procedure introduced here, to accommodate the implementation of EDI and RFID, was a reduction in processing and transportation delays. Structurally, this modification resulted in system order reduction. For example, in the implementation scenario depicted in Fig. 2, the distributor's incoming order (DIO) variable, is removed due the presence of a TT, in this case EDI. With respect to the distributor's equation set, the IO (DIO) variable is replaced by the closest ordering delay (WOP) in (2), (3), (4), and (6), while (5) is removed from the simulation procedure. The wholesaler's ordering policy is also affected by removing the DIOs from the wholesaler's respective orders placed (WOP) equation.

3. Results and Discussion

The results presented in this work are divided into two distinct sections, delineated by how the RFID and EDI technologies were specifically implemented. The section on symmetric implementations considers situations in which EDI and RFID are used concurrently, while the section on asymmetric implementations considers the separate use of EDI and RFID technologies. Two asymmetric implementations are illustrated in Figs. 2 and 3, respectively. In both scenarios, symmetric and asymmetric, the pertinent performance metrics associated with each of the six possible permutations of TT implementation, were benchmarked against the original BDG. Possible technology implementations between two consecutive supply chain partners include retailer–wholesaler (RW), wholesaler–distributor (WD), and distributor–factory (DF) implementations. For three consecutive supply chain members there are two plausible combinations, retailer–wholesaler–distributor (RWD) implementation and wholesaler–distributor–factory (WDF) implementation. Likewise, there is one additional implementation permutation for four consecutive supply chain constituents, retailer–wholesaler–distributor–factory (RWDF) implementation, which corresponds to the homogeneous case.

3.1 Symmetric Implementations

Simulations of symmetric RFID and EDI implementations provide clear insight relevant to the development of managerial policy, due, in large part, to the clear hierarchy of performance gains associated with the various heterogeneous and homogeneous technology implementations noted above (see Figs. 4–6). As evident, the homogeneous implementation, RWDF, renders the best cost and performance metrics. However, this implementation can be expected to have the highest implementation costs and draws appreciable public scrutiny. As such, there may be practical value in scaling back the implementation of TT to three or even two supply chain constituents, though limited demand forecasting may render a distinct bullwhip effect [38].

Reductions in the total amount of product in the supply chain may improve many aspects of its operation, including environmental impact. While implementing TT at a larger number of supply chain constituents, or at those higher in the supply chain, renders larger decreases in the total amount of beer in the supply chain, as evident from the results included herein, all of the possible combinations of technology implementation allow for noticeable reductions in inventory. These reductions are vital in the presence of rising business costs, especially given that the costs associated with standing inventory often far outweigh the costs associated with transportation [39], [40]. Additionally, smaller inventory levels allow companies to increase adaptability, an important trait during hard economic times [40]. Note that the observed trends for large values of Q in Figs. [4]–[6] allude to a decreasing effect associated with RFID and EDI for supply chains with larger Q values.

Also evident from Figs. [4]–[6] is that EDI and RFID implementations which are higher in the supply chain (at the factory end) result in larger performance gains and lower costs. The WDF combination, for example, performs significantly better than the RWD combination. WDF has

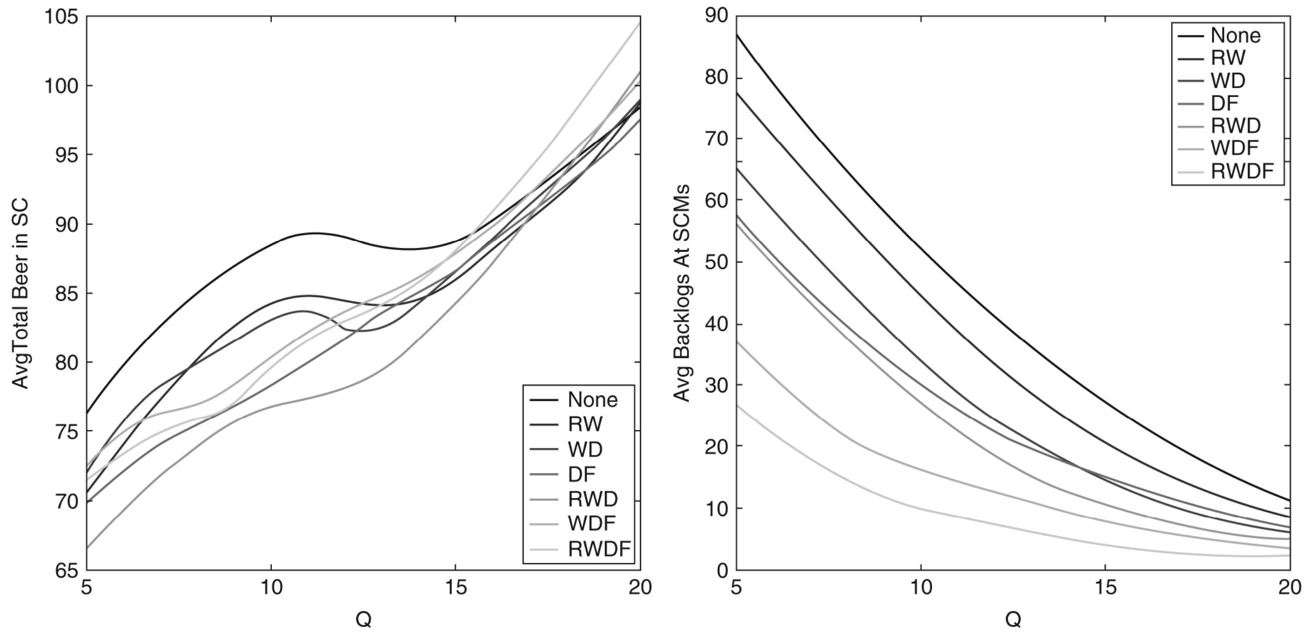

Figure 4. The average amount of beer in the supply chain (left) and average order BL at each supply chain member (right) for each of the possible permutations of EDI and RFID implementation. Note that there are significant decreases in the average BL as the number of supply chain members with TT increases. Additionally, note that technology implementation occurring higher in the supply chain (at the factory end) have a more linear relationship between Q and average total beer, than those lower in the supply chain. Finally, note that the plateaus in average amount of beer in the supply chain decrease in magnitude as additional supply chain members utilize RFID and EDI technologies.

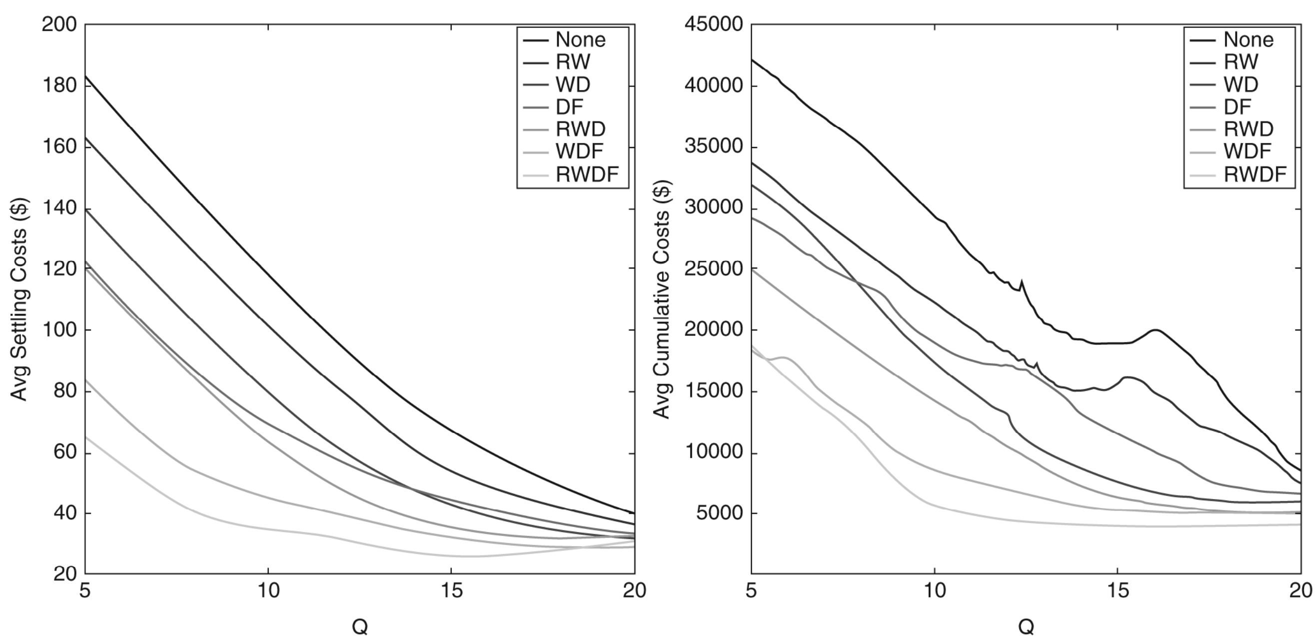

Figure 5. The average operating (left) and cumulative settling time (right) costs (in thousands of dollars) for each of the possible permutations of EDI and RFID implementation. Note that the displayed cost trends are the same as those shown above for average BL. Also note that technology implementations incorporating more supply chain members have lower average operating and cumulative costs. In general, technology implementations which are higher up in the supply chain (at the factory end) have lower costs than implementations lower in the supply chain.

lower average BL, cost, settling time, and stock outages for the majority of Q values when compared with RWD. The same trend can be observed in implementation permutations incorporating two supply chain members. The WD and DF combinations, for example, perform better than the RW combination in terms of average and cumulative costs and average BL. While WD also performs better than RW in terms of settling time, DF only outperforms RW for

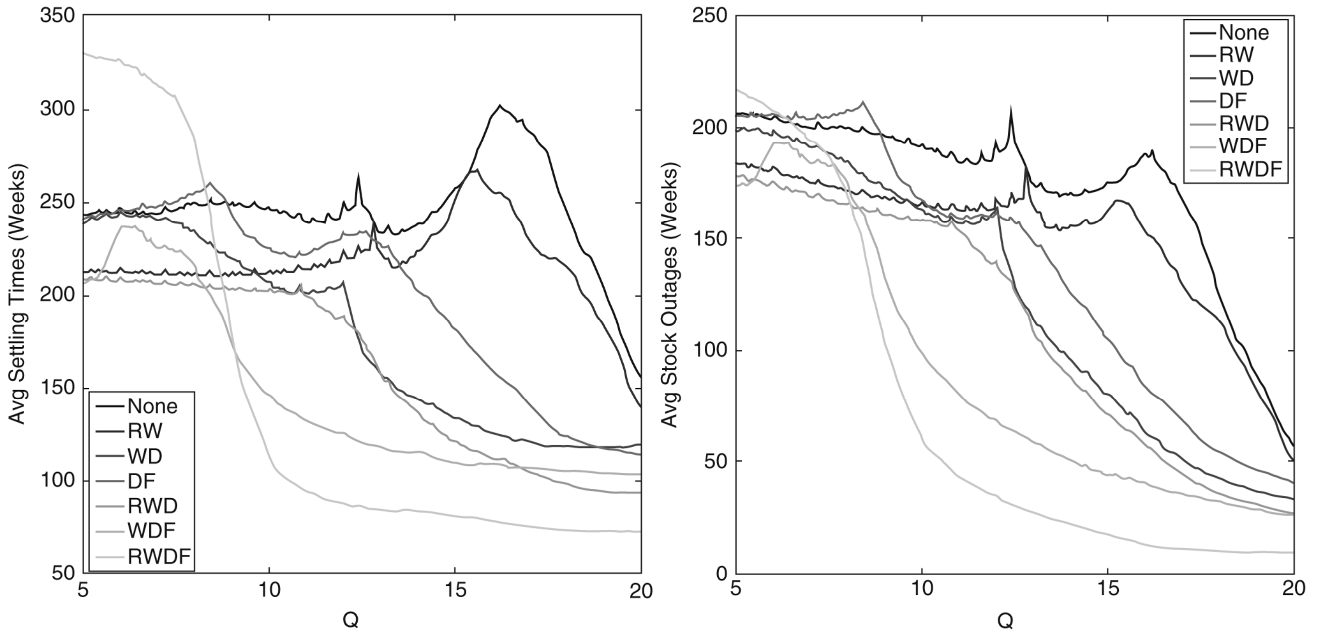

Figure 6. The average settling times (left) and stock outages (right) for each of the possible permutations of EDI and RFID implementation. As in Figs. 4 and 5, an increase in the number of supply chain members with implemented technologies leads to an increase in performance levels. Likewise, technology implementations higher in the supply chain (at the factory end) tend to perform better than those implemented lower in the chain, though this trend is nullified for smaller values of Q.

approximately half of the Q space investigated. Demand forecast updating is often worse higher up in the supply chain, so it is intuitive that damping this factor of the bullwhip effect, by removing delays, will have a larger impact at these higher positions. It is also interesting to note that these technology implementations which are higher in the supply chain are consistent with RFID deployment strategies adopted by Wal-Mart Stores Inc. and Best Buy [41]–[44]. While these retailers may have alternative motivation, it appears that they clearly chose the best place in the supply chain to implement TT to realize maximum gains in performance. Likewise, it is interesting to note that the implementation policy suggested by the included results contradicts the view of some supply chain professionals [45] who believe in a "retail first" policy. This may be attributable to the fact that the reported performance gains and cost reductions do not take into account the other uses of RFID technologies in a retail setting [46], [47].

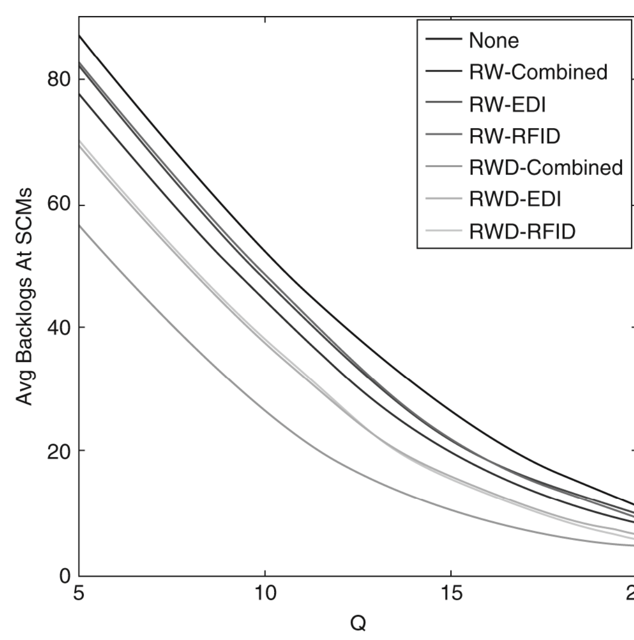

Figure 7. The average BLs for associated with RW and RWD technology implementations. Note that independent implementation of RFID and EDI yields similar, but not identical, performance levels. Combined RFID and EDI implementations perform better than the independent implementations.

3.2 Asymmetric Implementations

Given the societal concerns associated with some TT, such as RFID, it is feasible that EDI and RFID technologies could be implemented independently. For reference purposes, Fig. 7 contains the average BL for RW and RWD combinations for each set of technologies, EDI, RFID, and the two implemented concurrently. The similarities depicted here between the BLs of the two independently implemented technologies are representative of those seen for all of the characteristics presented in Section 3.1. Not surprisingly, there is an appreciable difference between implementing just one technology and implementing both. This trend was observed for all of the characteristics presented in Section 3.1.

4. Conclusions

The present work utilized validated performance metrics and a high-throughput computing transient analysis of the BDG to draw valuable insights on the impact of heterogeneously and homogeneously implemented RFID and EDI technologies. The analysis focuses on a small set of pertinent performance metrics, associated with the transient portion of the systems' constant-valued system response, which have practical relevance. Not surprisingly, the work's results revealed that increasing the use of TT improves overall system performance and decreases cost. Additionally, RFID and EDI technologies implemented higher up in the supply chain (near factory end) were found to have a greater impact on system performance. Overall, significant decreases in stock levels were recovered with RFID and EDI, while desired performance levels were sustained. Collectively, these results verify that TT implemented at the factory end of the supply chain can be expected to yield higher returns on investment, than those implemented at a retail level. Interestingly, the results also illustrate that supply chains which maintain high Q values, combined target stock and target supply line levels, after implementing RFID and EDI technologies will not realize the full benefits of these systems.

Current research efforts are aimed at investigating the technical implication of removing a given supply chain constituent, such as the wholesaler or distributor, and characterizing the impact of EDI and RFID technologies in these scenarios. The technical differences between continuous and discrete versions of the BDG are also being considered.

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Biographies

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Jeffrey F. Rhoads is an assistant professor in the School of Mechanical Engineering at Purdue University. He received his B.S., M.S., and Ph.D. degrees, each in mechanical engineering, from Michigan State University in 2002, 2004, and 2007, respectively. His current research interests include the predictive design, analysis, and implementation of resonant micro/nanoelectromechanical systems (MEMS/NEMS) for use in chemical and biological sensing, signal filtering, and inertial sensing systems, the behaviour of nonlinear, parametrically excited systems and coupled oscillators, and the behaviour of mechanical and/or electromechanical parametric amplifiers. He is a member of the American Society for Engineering Education (ASEE) and the American Society of Mechanical Engineers (ASME), where he serves on both the Student Design Committee and the Design Engineering Division's Technical Committee on Micro/Nanosystems. In 2009, he received the National Science Foundation's Faculty Early Career Development (CAREER) Award and the Purdue School Mechanical Engineering's Harry L. Solberg Best Teacher Award.

Sangtae Kim is the executive director of the new, private not-for-profit Morgridge Institute for Research located in Madison, WI. Prior to his appointment at the Morgridge Institute, he was the Donald W. Feddersen Distinguished Professor of Mechanical Engineering and Distinguished Professor of Chemical Engineering at Purdue University. His past work experience includes serving the National Science Foundation as director of the division of shared cyberinfrastructure, as well as 6 years of executive industry experience gained at Lilly Research Laboratories, Pfizer Global Research and Development, and Parke-Davis Pharmaceutical Research. He earned a Ph.D. in chemical and biological engineering from Princeton University in 1983, following concurrent bachelor's and master's of science degrees from the California Institute of Technology in 1979. In 2001, he was elected a member of the prestigious National Academy of Engineering for his contributions to microhydrodynamics, protein dynamics, and drug discovery through the application of high-performance computing.