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Mixed Methodological Approach to Advance the Analytical Examination of Performance Based Acquisition and Sustainment Strategies

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Abstract

This research, under the direction of the principal investigators and with support from the Naval Postgraduate School, the Systems Development & Maturity Laboratory at Stevens Institute of Technology, and the Complex Logistics Cluster and the Logistics Systems and Behavioral Science Laboratory at the University of North Texas, achieved its overarching goal of using a mixed methodological approach to advance the analytical examination of performance-based acquisition and sustainment strategies (PBASS). Qualitative research studies (using methods such as grounded theory and case studies) were completed that uncovered key characteristics, metrics, and their relationships that are important for a successful performance-based contract (PBC) between a customer and a post-production service provider. Quantitative research studies (using econometrics models, operations research techniques, and diffusion models) were completed that developed analytical models, incorporating these key characteristics and metrics, to assist the acquisition, design, and support communities in making informed business decisions.

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1. Introduction

Performance-based acquisition and sustainment strategies (PBASS) remain a potentially rewarding acquisition approach for procuring large-scale, complex repairable systems. The Department of Defense (DoD), faced with continued fiscal pressure, has been a leader in these types of strategies. As we uncovered in our previous research (NPS Acquisition Research Program Grant No N00244-10-1-0074) and continue to validate, successful PBASS strategies are characterized by incentive structures, multi-year contracts, and shared cost avoidance.

We extended our previous research by conducting interviews and administrating surveys in the defense and non-defense market place to uncover the discrete mechanisms that improve PBASS life-cycle affordability. The identified non-defense markets include the rail industry, fence-to-fence highway construction, social services, MRO, and manufacturing operations. We explored the use of a new market exchange paradigm, Service-Dominant Logic, for relevance to PBASS, both in theory and in practice. SDL focuses on knowledge, skills, and abilities and a shift from delivering product to delivering outcomes as a means to predict competitive success. We used the formal qualitative method of grounded theory to inductively argue for testable hypotheses. These testable hypotheses will now be used to collect data that we hope to use to create a series of multiple regression models to predict the likely success of a PBASS.

As part of previous research, we developed analytical models that determine the optimal contract price and investment strategy for a specific PBASS contract. The goal of these models is to understand the trade space between upfront system design costs and out year system sustainment costs. We improved the robustness of the underlying life-cycle affordability model by evolving its somewhat limited acquisition cost model. Additionally, we further explored the relationships between investment and incremental improvements in the "ilities"—reliability, maintainability, and supportability. This information, when validated, will enhance previously developed decision-theoretic, price optimization models. We created a multi-objective optimization model to simultaneously optimize profit, affordability, reliability, maintainability, supportability, and logistics footprint. To further assist the DoD acquisition and logistics community, our novel, multi-optimization model also generates Pareto fronts (i.e., decision-maker's trade-off space) for relevant competing and often conflicting PBASS metrics.

We addressed three issues that are often present in designing and sustaining large-scale, complex systems of systems (SoS):

1) *Stakeholder Requirements Abruptly Change*. Our interviews and surveys reveal that reliability and availability requirements may change abruptly or "urgently" from mission to mission. This was highlighted during Dr. Jacques S. Gansler's keynote presentation at the Eighth Annual Acquisition Research Symposium where he specifically addressed "*achieving rapid response to urgent requirements*" as one of the five major acquisition issues (Gansler, 2011).
2) *Budget Reductions*. Our interviews and surveys identified budget cuts as a major impediment in designing and sustaining SoS. This was also emphasized in Dr. Jacques Gansler's (2011) keynote presentation—"Acquiring all of the right things with fewer dollars, by focusing on costs (along with performance) throughout"—and supported by follow-on interviews with industry professionals.
3) *Disconnect Between Customer and Provider Investment Decision Schema*. Our online survey and experiment suggested that there is a fundamental disconnect between government customers' financial investment decisions, risk, and contract structure, and those of their industry providers. This suggests a foundation for flawed contract structure, pricing, and performance, and an asymmetry of reasonable expectations with regard to profit and investment.

This research—under the direction of the principal investigators and with support from the Naval Postgraduate School, the Systems Development & Maturity Laboratory at Stevens Institute of Technology, and the Complex Logistics Cluster and the Logistics Systems and Behavioral Science Laboratory at the University of North Texas—achieved its overarching goal of using a mixed methodological approach to advance the analytical examination of PBASS by

- uncovering key characteristics and metrics that define successful performance-based contracts (PBCs; Randall, Nowicki, & Hawkins, 2011);
- identifying key inter-firm, team-level psychological factors that may help to explain successful performance-based logistics (PBLs) by deriving an inter-firm, team-level model comprised of 11 constructs related through six testable propositions (Randall, Nowicki, Hawkins, Haynie, Armenakis, & Geary, 2012);
- developing an analytical model to determine the optimal price, length, and investment of a PBC (Nowicki, Ramirez-Marquez, Randall, & Murynets, 2012);

- developing an algorithm to improve the computational efficiency of the Multi-Echelon Technique for Recoverable Item Control (METRIC) class of inventory optimization problems (Nowicki, Randall, & Ramirez-Marquez, 2012b);
- developing a model that analyzes the trade-off between system design and supply chain performance (Nowicki, Randall, & Ramirez-Marquez, 2011, 2012a);
- developing the theoretical foundation for PBL by using a focused group of applicable business theories to improve a leader's ability to explain the business, economic, production, engineering, and supply chain science behind a successful PBL strategy (Randall, in press);
- using structured interviewing, qualitative data analysis, and archival research methods to develop a framework to guide decision-making and research in support of PBL (Randall, 2012b);
- showing that eight of the 10 fundamental premises of Service-Dominant Logic are supported by PBL in practice (Randall, Wittman, Nowicki, & Pohlen, in press); and
- developing a guide to create a business case analysis (BCA) to include performance-based options and offer analytical guidance to support direct economic comparison between the performance-based and the more traditional transactional-based post-production support options (Randall, Brady, & Nowicki, 2012).

This technical report includes our work, supported by NPS, that has either resulted in a published manuscript or is part of a working paper. Our approach for funded research is to ensure that each research question and deliverable (or some combination of those questions and deliverables) is explored using an academic publication framework. That means that our findings emerge by

1. identifying research questions, summarizing the state of the literature, and then describing the specific gap, and methological approach;
2. describing the extant literature that supports the investigation;
3. determining and applying the appropriate methodology;
4. describing the analysis; and
5. tying the findings associated with that research question in a discussion that addresses practical and theoretical impications.

We use this academic publication framework to validate our work through the rigorous double-blind review of refereed academic publications. Some of our research questions identified in this report have already been accepted for print, others are still in the review process, and others are part of a working paper. For the work that is accepted into print, every effort has been made to cite that work specifically. Other material is part of working papers that is in the review cycle. We also have also cited these. Lastly, some of our work is part of working papers that have yet to be submitted for publication. The references provide a listing of our published work and work in progress that is the source for NPS-supported research. These references are also listed in the Accomplishments Section of this technical report.

This technical report is organized as follows. First, we discuss performance-based acquisition strategies with an emphasis on how PBL strategies differ from traditional logistics support strategies. We then discuss PBL successes that span across industry sectors from government (e.g., defense) to for-profit (e.g., rail, airline, housing, and utilities).   Next, we present additional qualitative and quantitative research studies of our research. Finally, we list our project accomplishments.

2. Discussion of Performance-Based Acquisition Strategies

2.1. Overview

Performance-based acquisition strategies continue to receive increased attention in systems engineering, operations management, economic, supply chain, and logistics research (Kim, Cohen, Netessine, & Veeraraghavan, 2010; Kim, Cohen, & Netessine, 2007; Kratz & Diaz, 2012; Ng, Maull, & Yip, 2009; Nowicki, Kumar, Steudel, & Verma, 2008; Nowicki, Randall, & Ramirez-Marquez, 2012b; Randall, 2012a; Randall, 2012b; Randall, in press; Randall, Brady, et al., 2012; Randall, Nowicki, & Hawkins, 2011; Randall, Nowicki, Hawkins, et al, 2012; Randall, Pohlen, & Hanna, 2010; Randall, Wittman, et al., in press; Sols, Nowicki, & Verma, 2007; Ssengooba, McPake, & Palmer, 2012). We developed systemigrams, a validated soft systems method (Boardman & Sauser, 2008), to discuss performance-based acquisition strategies and how they differ from the more traditional, transactional-based strategies.

2.2. Systemigram Representation of Performance-Based Strategies

The research in the section is documented in Randall, Nowicki, and Hawkins (2011).

The systemigram representation of performance-based strategies and the corresponding discussions in this section are largely extracted from Randall, Nowicki, and Hawkins (2011).

Quite often, the logistics ecosystem associated with performance-based acquisition strategies, specifically a PBL strategy, is a three-tier system composed of suppliers, system integrators, and customers. We refer to this three-tier system, with its resources, technologies, policies, procedures, and flows, as the PBL ecosystem. PBL is a post-production service strategy that is highly dependent on the supply chain supporting its logistics ecosystem. Complex systems being supported through a PBL strategy rely on activities and decisions that span a broad array of functional areas, including research and development, engineering, operations, maintenance, support, logistics, purchasing, and supply chain. An example in the defense industry is the Joint Strike Fighter (JSF) with Pratt & Whitney (supplier) supplying the engines to Lockheed Martin (system integrator and original equipment manufacturer [OEM]) who will then integrate all of the components to provide mission-capable JSFs for the U. S. Department of Defense (customer) and its allied partners (F-35 Program Office, 2011). Similar relationships and structures exist in commercial industry, such as the high-speed rail industry where the operator, the end customer, and the OEM are different agencies (Siemens, 2011). Other examples can be found in the transportation sector (Transportation Research Board, 2009) and the health services sector (Administration for Children & Families, 2011; The World Bank, 2008).

PBL strategies have been credited with reducing life-cycle costs and improving system performance when compared to more traditional, transactional approaches to post-production logistics and support. Programs that have adopted PBL have experienced system up-time increases of 40% and logistics response-time cuts of 70%, all while generating billions of dollars in savings over traditional approaches (Fowler, 2008, 2009). For instance, the U. S. Navy saved $688 million on the F/A-18 program by using PBL, and the United Kingdom's Defense Ministry saved $250 million by converting its CH-47 post-production logistics and support contract to PBL (Fowler, 2008). There are similar PBL success stories dealing with projects in the for-profit sector. For instance, one recent study of a major Dutch housing project showed that life-cycle cost was reduced by 20% using a PBL approach (Straub, 2009).

In order to compare and contrast PBL with traditional approaches to logistics and post-production support, we provide a series of systemigrams. Systemigrams provide researchers with the ability to convey, in a conceptual manner, the inter-relationships of a complex system (Boardman & Sauser, 2008). Randall, Nowicki, and Hawkins (2011) developed Figure 1, which provides a systemigram of traditional post-production logistics and support. In traditional post-production logistics and support, the major business entities are suppliers; OEMs; maintenance, repair, and overhaul (MRO) providers; system operators; and customers. Here we use the airline and rail industries as examples of the traditional post-production support structure. The overarching concern of the system operator (e.g., airline or rail company) is to meet customer requirements while profitably operating the system. For the airline and rail industries, this means profitably operating routes and schedules at a particular price and comfort level (Flint, 2007; Siemens, 2011).

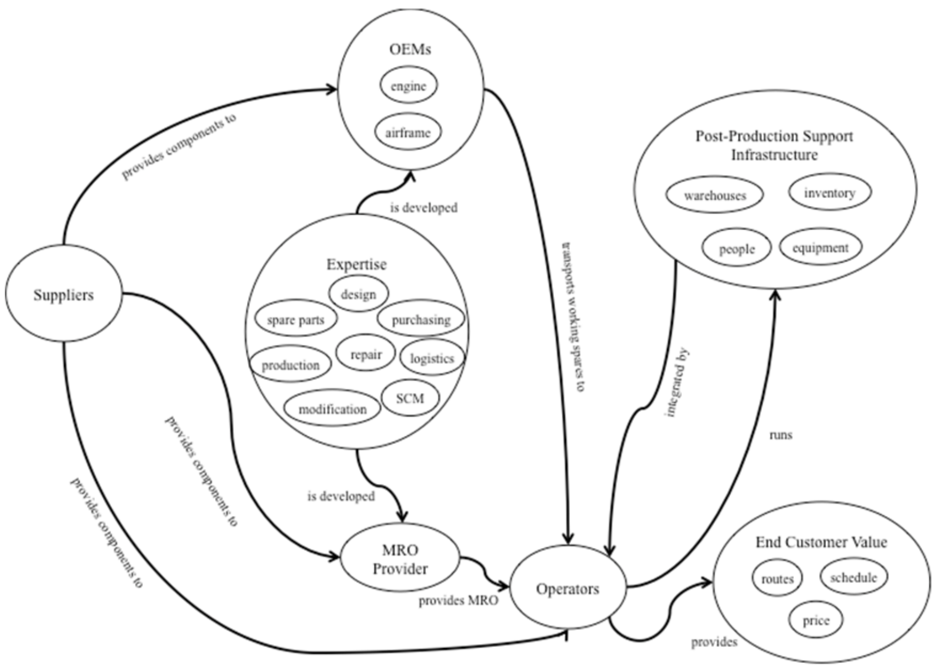

Figure 1. Representation of a Traditional Post-Production Logistics and Support Systemigram (Randall, Nowicki, & Hawkins, 2011)

As shown in Figure 1, the system operator's primary core competency revolves around determining profitable routes and schedules, and operating a system that meets these schedule requirements while dealing with disruptions (e.g., weather, change in customer desire, system failure) as they occur. Within a traditional post-production logistics and support system, the operators (e.g., the airline or the rail company) manage a network of warehouses, inventory, equipment, and people that keep the system in service or return the system to service when it breaks (Hypko, Tilebein, & Gleich, 2010). Considering the complexity of determining routes and price, it can be argued that running, maintaining, and integrating the post-production logistics and support infrastructure is a secondary competency of the rail and airline operator. As depicted in Figure 1, a great deal of the expertise needed to run the post-production infrastructure actually resides with the OEMs and MRO providers. Further, the operator seldom has the technical capability to control, much less reduce, cost as systems age and fatigue, manufacturing sources diminish, and corrosion takes a toll (MaClean, Richman, Larsson, & Richman, 2005).

This traditional strategy puts the end customer and the system operator at a disadvantage. They are saddled with such issues as corrosion, diminishing manufacturing sources (e.g., parts that are no longer being produced), and fatigue (MaClean et al., 2005) yet their core competency is typically not consistent with dealing with such issues (Prahalad & Hamel, 1990). As issues emerge, the system operators typically do not have the expertise, time, or funding needed to control and reduce the life-cycle costs of the system. Further, the operator, who is not the OEM, typically has little in-house capability to improve the reliability and design of the fielded system. In this traditional approach, the organization most capable of reducing life-cycle cost, the OEM, typically moves on to the next research design and production effort, leaving post-production support in the hands of a hodgepodge of suppliers and operators (Randall, 2009).

This structure devolves into competing objectives (e.g., OEM and supplier desires to sell more spares and repairs, customer desires to reduce spending) with little incentive to invest in life-cycle cost reduction beyond production (Geary & Vitasek, 2008). Without innovation and involvement from the OEM and suppliers, the efficiency of the post-production support infrastructure—characterized here as the operator's ability to integrate its warehouse, inventory, transportation, procurement, and labor functions—is limited (Randall, Pohlen, et al., 2010).

As depicted in Figure 2, from Randall, Nowicki, and Hawkins (2011), PBL corrects incentive misalignment in the post-production logistics and support network, and transfers roles and responsibilities to the entities most capable of performing these tasks efficiently and effectively. As a result, PBL manifests itself as a solution that effectively leverages the existing expertise that resides with the OEMs, suppliers, and MRO providers. PBL drives a governance structure that codifies the role of a systems integrator as the entity that establishes and performs critical supply chain integration functions across the life cycle of the system (Randall, Pohlen, et al., 2010). Because the system integrator is now responsible for integrating and orchestrating the post-production logistics and support infrastructure (e.g., warehouses, inventory, and transportation), the operators are now free to focus on their expertise—the actual operations of the system (e.g., route scheduling and pricing).

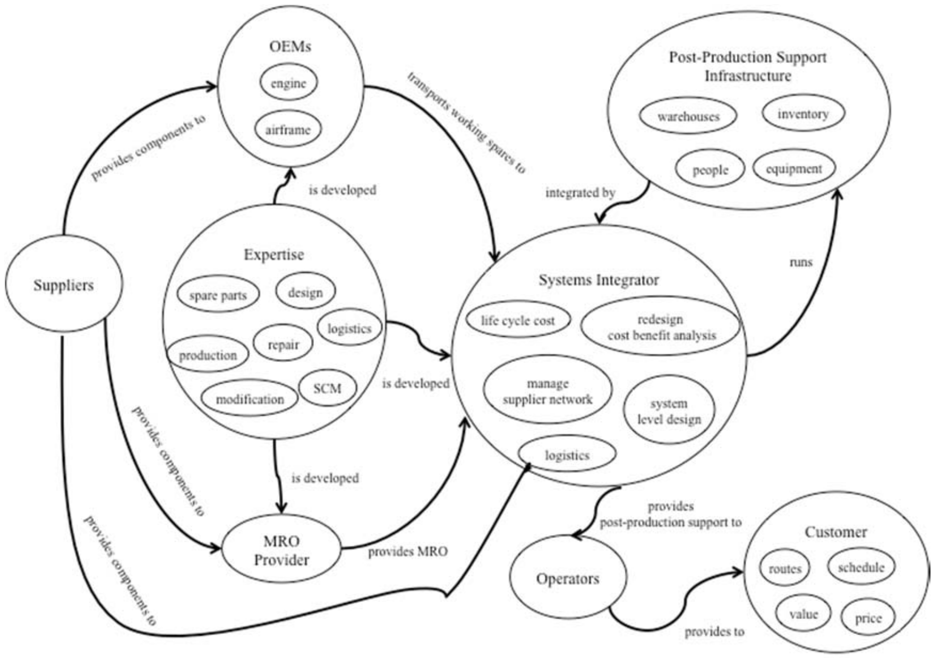

Figure 2. Representation of a PBL Post-Production Logistics and Support Systemigram (Randall, Nowicki, & Hawkins, 2011)

PBL integration is, therefore, particularly effective when the integrator (e.g., the OEM) keeps elements of the research, design, and production supplier network in place to manage and logistically support the system during post-production. This means that the integrator and suppliers are now capable of balancing and optimizing the cost of inventory, transportation, warehousing, on-equipment maintenance, and MRO against the potential to reduce those costs through redesign. This makes sense for a number of reasons. The OEM and the suppliers are in the best position to make initial forecasts of the reliability and subsequent demand for parts, and then to update those forecast models as the system evolves during use (Kim, Cohen, Netessine, & Veeraraghavan, 2010; Nowicki, Kumar, et al., 2008; Randall, Pohlen, et al., 2010). Further, the OEM and suppliers are typically most capable of affordably redesigning components to drive out costs or bad actors. As new technology, materials, and logistics processes become mature, these suppliers, who are further back in the supply chain, are most capable of affordably improving the design of both consumable and repairable products. In coordination with the integration expertise of the OEM, these products can then be infused into the system as the system fails—thus, reducing future logistics costs.

There are two keys differences between a PBL contract and traditional post-production support. The first involves contracting for performance, or an outcome, rather than repeatedly contracting for discrete products and services (Geary & Vitasek, 2008). Under a PBL contract, the buyer contracts for system performance, typically characterized as system "up time," as opposed to contracting for spare parts and repair services. System up time is defined as the amount of time the system either is ready to perform (e.g., aircraft fleets) or does perform (e.g., power generation networks) divided by the amount of time possible for that system to be up. The supplier is then free to ensure this contractual up time is achieved as efficiently and effectively as possible. The second key to PBL involves its reliance on a multi-year relationship. The multi-year relationship gives the supplier network time to determine whether certain reliability issues might be better served through redesign, as opposed to continued procurement of support resources and services, such as spares and repairs. These contract dynamics of PBL result in a structure where the integration, accountability, and risk for achieving performance objectives are left with those organizations that have the greatest set of relevant knowledge, skills, and abilities.

2.3. Breadth of Performance-Based Acquisition Strategies

PBL's success in defense has led to strategies that are now being employed in other industry sectors such as aerospace, transportation, telecommunications, power generation, health care, child and family services, and manufacturing support (Kim, Cohen, & Netessine, 2007; Flint, 2007). The use of performance-based contracting spans a rather diverse array of public and private industry sectors that include roads and bridges (Ozbek & de la Garza, 2011), high-speed rail (Siemens, 2011), transportation (Transportation Research Board, 2009), child welfare (Collins-Camargo, McBeath, & Ensign, 2011) and public healthcare (Ssengooba et al., 2012) Administration for Children & Families, 2011; The World Bank, 2008). In fact, many of these PBCs are private-public partnerships.

2.4. PBL as a Science of Discovery With Supporting Business and Economic Theories

The research in the section is documented in Randall, (2012a).

The content in this section on PBL as a science of discovery with supporting business and economic theories is largely extracted from Randall (2012a). Our PBL research to date hasessentially been a science of discovery (Randall, 2012a), looking at what works and what doesn't work to answer key questions and establish tenets. In general this research has led to the common consensus that PBL works, if done correctly. PBL is not a magic bullet but a strategy, one that needs to be correctly applied. We have uncovered insights into how to execute a PBL. Those insights suggest that execution depends on the system, the level of repair, and a strategy of sub-system or system-level PBL. There are insights into PBL contract length. Shorter term contracts appear to generate quick wins in classis logistics (warehousing, transportation, and inventory), medium length contracts can improve purchasing and item management, but real reliability-driven affordability requires a longer term contract. The primary system integrator(PSI) debate has been largely exposed as an argument in semantics. On one side, the government is the PSI when it comes to integrating war fighter requirements, determining and funding budgets, and defining operational and strategic objectives. When it comes to integrating the supply chain, the PSI of choice is the OEM. However, practice also shows that there are times when a government-industry PSI team might work, or even an industry non-OEM PSI.

The discoveries in the how, when, and why of PBL have been legion. These discoveries now provide us the necessary empirical data to propose a theoretical foundation for PBL. This is a key contribution, one that has potential to rationally close the PBL debate for all those interested in rationality. Ultimately, the goal of science is to explain and predict phenomena. Therefore, the next step is to understand PBL at an elemental level so that we can explain, predict, and extend PBL success.

Theory allows us the ability to explain and predict, and that gives us untold efficiency. Theory gives us the power to predict a future, explain why that future will occur, and then take action to improve that future. The current state of PBL research and practice provides the opportunity for us to synthesize business theory to describe a theory foundation for PBL that will improve our ability to explain and predict PBL success and overcome perceptual barriers to implementation and execution of PBL. Foundational business and economic theories for PBL include the following:

- Coase's (1937) Theory of the Firm,
- Transaction Cost Economics,
- Make vs. Buy,
- Core Competency, and
- Service-Dominant Logic.

As part of our research, we first discuss Coase's Nobel Prize–winning work (Coase, 1937) with regard to how the theory of the firm is used as a foundation to understand the role of a PSI as a network entrepreneur who links actions with outcomes, and improves the efficiency of transactions. Transaction cost economics (TCE) is used to affirm the role of integration, but adds to how PBL addresses human behavioral characteristics of bounded rationality and opportunism. Using bounded rationality helps defend the logic behind PBLs' use of networks of firms to deal with complex transactions that cannot be effectively managed in a single organization. The TCE concept of opportunism explains the underlying logic of multi-year contracts, metrics, and investment in the cost avoidance governance structures of PBL.   Make or buy decisions, another extension of TCE, explain how effective PBL governance structures determine when value should be created inside the firm or purchased from a supply chain. Make or buy is also extended to the idea of PBL incentive shift of the efficient frontier of repair to redesign. Together make or buy and repair or redesign provide a theory foundation to explain and predict who should repair and redesign, and when the efficient frontier shifts from repair to redesign. The discussion of efficient frontiers also reaffirms the predictive implication of contract length.

When it comes to who should be doing what, when, and why, Prahalad and Hamel's (1990) core competency theories provides an ability to predict PBL success by understanding, utilizing, and reinvesting in the core competency of the collaborative supply chain. Our empirical research demonstrates how PBL concepts of integration and integrated supply chains are consistent with the "buzz" associated with the rise of supply chain management as put into PBL (Koh, Saad, & Arunachalam, 2006; Randall, Nowicki, & Hawkins, 2011).   Somewhat dramatically, PBL is shown to be a practical implementation of Service-Dominant Logic, considered to be an evolutionary economic theory framework. This means the massive expansion into SDL research provides a readymade framework to explain and predict the role of knowledge, relationships, focus on value and metrics and not products, non-competitive learning, investment, and reward and reinvestment metric-based feedback loop of PBL. In PBL and SDL, it is not about parts, but about what matters most to customers: value.

Thus PBL resides on a theory foundation established by a governance mechanism that seeks to optimize supply chain management cost, while being cognizant of the link between supply chain management cost and the cost-effective introduction of material, process, and technology that improves the reliability of a system to reduce cost across the program life cycle. The theories reviewed clarify the underlying econometric model of a PBL strategy in a manner that should influence development of new sustainable and affordable design strategies that rest upon a goal to build systems and governance structures that accelerate the insertion of new materials, processes, and technologies that reduce life-cycle cost. For new start programs this means strategies such as modularity and redundancy that reduce the cost of sustainment engineering innovation. For fielded systems, this means focusing the development of materials, processes, and technologies that accelerate the shift from repair to redesign, or reduce supply chain costs. In both cases, these approaches are built against the backdrop of a theoretically sound PBL strategy.

3. Qualitative Research Studies

3.1. Successful Performance-Based Contracts—Key Characteristics and Metrics

PBL strategies are providing governments and for-profit organizations with a contractual mechanism that reduces the life-cycle costs of their systems. PBL accomplishes this by establishing contracts that focus on the delivery of performance, not parts. PBL establishes a metrics-based governance structure where suppliers make more profit when they invest in logistics process improvements, or system redesign, that reduce total cost of ownership. While work has been done to outline an overall PBL theoretical framework (Randall, Pohlen, et al., 2010), testing is required on the underlying theory that explains the enablers that lead to organizational and team-level, team-goal alignment associated with the PBL governance structure. The purpose of this research, therefore, was to quantitatively test previously posited relationships between enablers of PBL and PBL effectiveness. An additional objective was to explore any differences in PBL effectiveness between different business sectors (This aspect of the study has been encapsulated in working papers that are currently under review at *International Journal of Physical Distribution and Logistics Management).*

A multiple regression model was developed, tested, and validated to explain the effectiveness of PBL (Randall, Nowicki, & Hawkins, 2011). The model was externally validated with exploratory cross-sectional survey data of 61 practitioners. For a detailed discussion of the theoretical development of the multiple regression models see Nowicki, Ramirez-Marquez, and Randall (2011) and Randall, Nowicki, and Hawkins (2011).

This study strongly supported the recent PBL theory explaining PBL effectiveness (Randall, Pohlen, et al., 2010). Key antecedents included investment climate, relational exchange, PBL leadership, and business sector. This investigation also found that government organizations lag behind their commercial counterparts in PBL effectiveness and PBL leadership. Model results suggested that this lag had a negative moderating effect on PBL outcomes.

PBL business arrangements are more effective in more favorable investment climates. Thus, leaders should welcome new ideas, empower employees, and encourage entrepreneurship. Because PBL effectiveness increases with relational exchange, building trust and communicating with suppliers is key. Leadership is also important to PBL effectiveness. Leaders should accept risk, focus on long-term affordability and performance, and align activities to achieve end user goals.

3.2. A Framework for Understanding and Investigating Performance-Based Logistics Strategies

The research in the section is documented in Randall (2012b).

In this research study, we used structured interviewing, qualitative data analysis, and archival research methods to develop a framework to guide decision-making and research in support of PBL. The PBL Research Framework is shown in Table 1. Most of the content in this section is extracted from Randall (2012b).

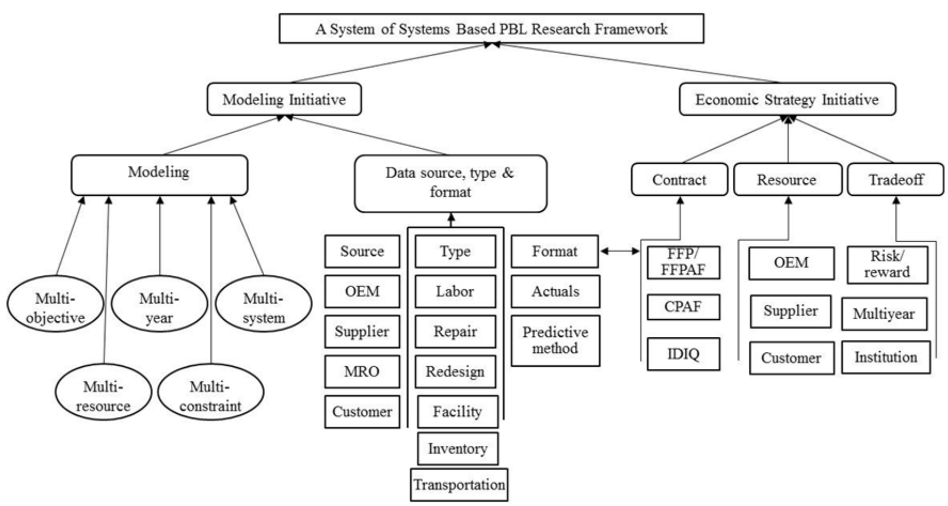

Table 1. PBL Research Framework (Randall, 2012b)

PBL managers satisfy demand for parts in two ways. First, they seek to fill demand while minimizing the cost of logistics (e.g., warehousing, transportation, and/or inventory). Next, these managers seek new materials, processes, and technologies that might allow them to drive out demand through cost-effective redesign in order to improve system reliability.

The interviews conducted with managers provided insight into how systems engineering and supply chain management interact to reduce life-cycle cost (LCC) in PBL. The economic model of PBL relies on the suppliers' ability to perform quantitative analyses to determine the economic viability of potential cost avoidance alternatives. Central to this analysis is development of hierarchical models that determine the amount, location, and timing of the support resources that are needed to make a profitable cost avoidance decision (Kim, Cohen, & Netessine, 2007; Nowicki, Kumar, et al., 2008).

This requires an understanding of how these decisions are affected by the level within the supply chain to which they apply (e.g., sub-system, system, or SoS) and how improvements in materials, processes, and technology drive a reexamination of those decisions over time. Most of the existing analytical models today require significant adjustments or are rendered invalid in the presence of PBL (Government Accountability Office [GAO], 2008; Randall, Brady, et al., 2012). In order to initiate, track, and evaluate PBL contracts, it is important to create a useful collection of analytical models that can be applied to particular PBL situations and used to make sound cost avoidance decisions throughout the SoS life cycle.

Performance metrics stand at the core of the analytical modeling activity of PBL and are typically used as modeling objectives, decision variables, or constraints. The interviews with managers highlighted the criticality of getting metrics correct. Metrics must be clearly defined, and when multiple metrics are used, the interdependencies must be understood. Archival reviews suggested that PBL metrics that include profit (including the implementation of cost avoidance strategies), material availability, material reliability, logistical foot print, aircraft availability, and logistics that delay time are often used to measure sustainment performance.

PBL success requires a firm understanding of the business model that lies at the core of the strategy. This research developed a framework that integrates the modeling and economic strategy in a natural, adaptable, and flexible guide. The offered framework bridges a significant gap by providing a platform for both research and practice, allowing for the design, execution, and evaluation of successful PBL programs.

PBL works, as clearly evidenced by the respondents (both government and industry) who stated that PBL can improve performance and affordability for customers. Moreover, industry executives claimed that properly structured PBL provides an opportunity to earn superior profit. The framework, elucidated from the interviews and conferences, can be summarized into five key findings (as cited from working papers by Randall, 2012a, 2012b, which are under review at the *International Journal of Logistics Management*):

1. PBL strategies focus the supplier network on value desired by the customer.
2. PBL creates affordability by creating innovation in the repair process, the logistics process, and system reliability.

3. Investment leads to affordability and performance improvement, and investment is directly related to the PBL contract structure; therefore, affordability and performance are directly related to the contract structure.
4. PBL strategies foster innovation that reduces life-cycle cost for the customer.
5. PBL contracts, when properly structured, offer suppliers a greater profit opportunity.

PBL trades the cost of recurring repair for upfront investment that focuses on driving repair cost efficiently out of the system. The return-on-investment sustainment approach rewards decisions that create continuous *system* performance improvement. PBL does this by creating a "win-win" situation. The PSI and suppliers create more profit when they drive down cost by first reducing the frequency of part failure and then improving the processes when failures do occur. The customer wins because fewer failures and improved maintenance response means increased system up time and decreased labor requirements.

Notably, the PBL research framework offers broad implications for the process of involving seemingly diverse business sectors such as rail, airlines, military systems, healthcare, and child and family services. All of these sectors use some type of PBL or performance-based contracting type of approach (Administration for Children & Families, 2011; Boeing Company, 2011; Flint, 2007; Siemens, 2011; The World Bank, 2008).

In conclusion, the PBL research framework represents an important contribution to both the literature and practice as it provides a research structure that is based upon empirical evidence that can efficiently and effectively accelerate a PBL research agenda. PBL has been highly successful, and the framework provides greater generalizability of that success by articulating the mechanism by which PBL leverages relationships, establishes and quantifies cost avoidance strategies, evaluates the systems dynamics of the inherent trade-offs between design and sustainment across multiple systems, and lays the bedrock for the emergence of practically applicable analytical tools.

3.3. Performance-Based Contracting and Inter-Firm Team Processes

The research in this section is documented in Randall, Nowicki, Hawkins, et al. (2012).

This research study establishes a new research path by examining inter-firm, team-level factors, in the context of PBL, that lead to successful supply chain teams. The majority of this section is taken directly from Randall, Nowicki, Hawkins, et al. (2012). This research provides managers a mechanism for improving team performance and learning by making adjustments to strategic metrics over time.

PBL uses long-term contracts and metrics to align inter-firm teams to create innovations and reduce costs. Because PBL initiatives are implemented using teams, we examined emergent team-level factors and their associations found in successful PBL inter-firm teams comprised of both public and private members.

Using grounded theory, we interviewed 17 managers who are part of government-industry teams that use a PBL strategy to determine key team-level psychological factors found in successful PBL teams. This methodology led to identifying the proximal factors and processes leading to PBL team success.

This research explicates the team-level psychological factors associated with PBL success. The study is novel as it captures the impact that inter-firm, team-level factors have on PBL strategy implementation and outcomes. Additionally, this study integrates key literature from logistics, management, and psychology as the foundation for the findings. The success of PBL is explained using an inter-firm, team-level model comprised of 11 constructs related through six testable propositions. The performance-based strategy inter-firm team model we developed is shown in Figure 3.

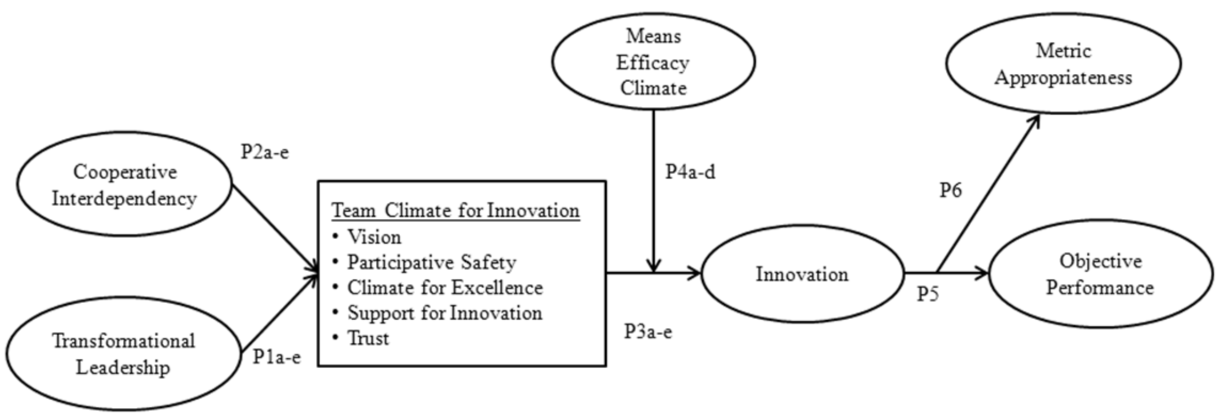

Figure 3. Performance-Based Strategy Inter-Firm Team Model (Randall, Nowicki, Hawkins, et al., 2012)

Based upon our research (Randall, Nowicki, Hawkins, et al., 2012), we derived six testable hypotheses:

1. Propositions 1a-e: Transformational leadership will be positively related to (a) team vision, (b) participative safety, (c) climate for excellence, (d) support for innovation, and (e) trust.

2. Propositions 2a-e: Cooperative interdependence will be positively related to (a) team vision, (b) participative safety, (c) climate for excellence, (d) support for innovation, and (e) trust.

3. Propositions 3a-e: (a) Team vision, (b) participative safety, (c) climate for excellence, (d) support for innovation, and (e) trust will be positively related to innovation.

4. Propositions 4a-e: Means efficacy climate will moderate the positive relationships of (a) team vision, (b) participative safety, (c) climate for excellence, (d) support for innovation, and (e) trust with innovation such that the relationships are stronger when means efficacy climate is high and weaker when it is low.

5. Proposition 5: Team innovation will be positively related with objective performance.

6. Proposition 6: The strength of the positive relationship between team innovation and performance will positively relate with metric appropriateness, such that when the slope is weak, metric appropriateness will be low and when the slope is strong, metric appropriateness will be high.

This research identified the behaviors and systems of behaviors that both support and are a result of a PBL initiative. This investigation develops two antecedents of Team Climate for Innovation (TCI)—cooperative interdependence and Transformational Leadership (TFL). Cooperative interdependence indicates the importance of having commonly shared goals in enhancing TCI. Consistent with Deutsch (1973), this climate engenders consideration for all team members to create and value cooperative goals. PBL creates goals that are cooperative and not competitive. Previous research has already established a positive relationship between TFL and support for innovation (Eisenbeiss, van Knippenberg, & Boerner, 2008), and we extend this by relating TFL to additional components of TCI including vision, participative safety, a climate for excellence, support for innovation, and trust.

Our findings have significant managerial implications. For example, organizations can benefit from these inter-firm, team-level psychology relationships by understanding the importance of cooperative team goals. Managerial tactics can be used to avoid creating a zero-sum game among team members. Our findings suggest that organizations need to appoint individuals into management positions who are transformational so that they can inspire individuals to challenge the status quo and promote an environment conducive for innovation.

Our research in the PBL setting supports recent meta-analytic results indicating a positive relationship between TCI and innovation (Hulsheger, Anderson, & Salgado, 2009). However, a large portion of studies in the meta-analysis examined research and development teams because they provided researchers with an objective means for tracking innovation through patents (Hulsheger et al., 2009). Thus, the main effects may in fact be limited. Research and development teams may have access to sufficient resources necessary for enhancing the likelihood of innovation. We found there may be environmental factors present that influence the strength of the positive relationship between a team climate for innovation and actual innovation.

We believe that another contribution is provided by examining means efficacy climate as a moderator of the positive relationship between TCI and team innovation. The managerial implication is that if organizations properly fund and assist in the success of PBL initiatives they should experience more innovations when teams have both the financial and policy support necessary for success. Thus, organizations that under-invest in PBL programs may not experience the same levels of innovation despite their focus on cooperative interdependency and transformational leadership to drive up a team climate for innovation.

Of considerable importance is our finding that metric appropriateness is a reaction to the relationship growth between team innovation and performance. When the relationship is weak, metric appropriateness is judged to be low. Conversely, when the relationship is strong, metric appropriateness is judged to be high. From a managerial perspective, it was important to take this information and incorporate it into future contracts. Therefore, PBL should not simply be thought of as a static process, but continual improvement is needed for long-term success. Teams that witness low metric appropriateness need to ensure this new knowledge is not lost and reevaluate the metrics to overcome the poor project performance. The reality of business suggests that there is not a single set of metrics that works with all projects so team members need to take action when these metric appropriateness evaluations are low. Metric appropriateness is, therefore, a factor to consider, and it may help teams to realize that adjustments to the metric should be made to improve metric appropriateness.

We indicate that the PBL strategy drives learning and innovations. Based on the knowledge gained, future adjustments to the metrics can be made. Although we do not model team learning directly, this is an important contribution to the supply chain literature, and metric appropriateness judgment is a critical component for learning to occur.

Collectively, our findings establish a new research path by examining inter-firm, team-level factors for judging success in PBL teams. We found that PBL is effective because there is a process of team learning and adjustments to the strategic metrics over time that leads to team success. Thus, the strategy itself requires a flexible mentality so that it never becomes static and remains always appropriate for the external context.

3.4. Service-Dominant Logic (SDL) and Supply Chain Management: Are We There Yet?

The research in this section is documented in Randall, Wittman, et al. (2012).

This research study investigated the positive (meaning "what is") question, To what degree are PBL practitioners implementing concepts that are consistent with SDL? The contents of this section are largely extracted from Randall, Wittman, et al. (2012).

We first determined the extent to which PBL is a practical application of SDL. Using those results and extant literature, we then answered the normative question, Should PBL practitioners implement concepts consistent with SDL?

The results generally support PBL as SDL in practice. Underlying SDL are 10 foundational premises (FPs), which provide a concise framework supportive of SDL research (Lusch, 2011). Vargo and Lusch (2010) summarize SDL in two tenets:

1. "Fundamentally, economic (and social) exchange can best be characterized as *service-for*-service exchange—that is, service is the basis of exchange," (p. 172) and
2. Value is created collaboratively and inputs (resources) must be integrated in order to realize value. Eight of the FPs are strongly supported as summarized in Table 2.

Service-Dominant Premise	Performance-Based Logistics
FP1: Service is the fundamental basis of exchange.	The fundamental basis for business exchange is not to buy goods but to gain performance-based value.
FP2: Indirect exchange masks the fundamental basis of exchange.	The complexities of production and extended supply chains have created a situation where individuals managing materials, supplies, and services (OEMs, suppliers, vendors, depots) seldom have direct contact with the end product or customer. The metrics of PBL provide tangible outcomes that bring production and supply functions back in contact with the customer and customer value.
FP3: Goods are a distribution mechanism of service provision.	Goods by themselves have no value and are simply a conduit to put performance from the supplier in the hands of the customer.
FP4: Operant resources are the fundamental source of competitive advantage.	Knowledge is the fundamental source of competitive advantage. PBL metrics measure value obtained through the application of knowledge and skills within the supply chain.
FP5: All economies are service economies.	All value chains are ultimately about providing performance. Knowledge- and skill-based competition overcomes the limitations of land, labor, capital, and manufactured output as a means for predicting success. Knowledge, and the ability to

	apply knowledge, predicts success.
FP6: The customer is always a co-creator of value.	The customer is always a co-creator of value. Value creation (i.e., performance) does not occur unless the customer can apply or benefit from the PBL outcomes.
FP7: The enterprise cannot deliver value, but only offer value propositions.	The extended supply chain network cannot deliver value, but only offer value propositions. Customers' view of performance is the final determination of value.
FP8: A service-centered view is inherently customer oriented and relational.	Viewing business as an exchange of performance-based value is inherently customer oriented and relational.
FP9: All social and economic actors are resource integrators.	Value creation occurs within a network of individuals, firms, or organizations. This ability to achieve performance-based outcomes by integrating resources and knowledge across the network is the most important core competency within a PBL strategy.
FP10: Value is always uniquely and phenomenologically determined by the beneficiary.	Performance value is ultimately determined by the end user or beneficiary.

Table 2. Service-Dominant Premises in a Performance-Based Logistics Context (Randall, Wittman, et al., 2012)

We now explore what this means for SDL, PBL, and SCM. The results also indicate two areas where PBL practitioners struggle to fully buy in to an SDL mindset. First is the idea of a service-dominant and modified goods-dominant view of goods. In the context of PBL, goods have value as both distribution mechanisms for performance and *potential performance* value as inventory. PBL practitioners understand that parts have little value unless they are in use. However, having parts in inventory to be ready when need is viewed as valuable. Additionally, the practitioners suggest that as transactions occur further upstream from the end customer, these transactions tend to be more goods oriented. Understanding and overcoming this extended supply chain alignment conundrum has tremendous implications for research and practice.

3.5. Business Case Analysis and the Confounds of Innovation Driven by Performance-Based Post-Production Support Strategies

The research in this section is documented in Randall, Brady, et al. (2012).

The post-production support cost of complex systems such as rail, power, and defense often exceed the cost of research, design, and production. As such systems age and degrade, the traditional maintenance, repair, and overhaul (MRO) approach does little to reduce their cost or improve performance. The failure of traditional MRO has given rise to a number of multi-year, performance-based, post-production support strategies. These strategies drive investment to reduce cost, infuse innovation, and increase system performance. The dynamism and innovation associated with these strategies make it difficult to conduct a business case analysis (BCA) that compares the return-on-sales model of traditional MRO to the return-on-investment model of performance-based strategies. To address this gap in practice and theory, we develop a framework for rationalizing performance-based and traditional strategies within the same BCA. In this study, we develop questions to guide the creation of BCAs that include performance-based options. Finally, we offer analytical guidance to support direct economic comparison between these two fundamentally different post-production support strategies. The content in this section is largely extracted from Randall, Brady, et al., (2012).

Attempting to understand how BCAs deal with PBL and traditional post-production support approaches combined leads to our research questions (Randall, Brady, et al., 2012):

1. What are the key characteristics of a PBL that should be included in the BCA process and its supporting analytical models?
2. How is time-based innovation addressed within a traditional post-production BCA?
3. How is system life-cycle affordability accounted for in the supporting cost models of BCAs that include a PBL alternative?

Our research led us to an understanding of the relationships and necessary conditions for successful PBL arrangements and subsequently successful PBL-traditional BCA. This relationship is reflected in Figure 4 (Randall, Brady, et al., 2012) and builds on the essential elements of a PBC (long-term and performance-oriented) and is what supports PBL as a transformational post-production support strategy that delivers long-run value.

Figure 4. Considerations for a Performance-Based Logistics Business Case Analysis
(Randall, Brady, et al., 2012)

We conclude that the current approach to performing BCAs lacks the following: a consistent and applicable method to model innovation; a true, multiple-year implication analysis process; and a sound econometric model for creating incentive, investment, cost avoidance, and risk trade-off studies. Our research has shown that converting from a traditional post-production approach to a PBL approach requires a totally new BCA strategy. Merely using existing BCA policy and templates will result in erroneous and costly recommendations. Failing to integrate the innovation and investment aspects of the underlying PBL econometric model when comparing a PBL with a non-PBL strategy will likely result in public funds being squandered or shareholder value not being maximized.

This investigation makes it clear that performance-based, outcome-focused arrangements are fundamentally different in the way they deliver post-production support services. Unlike transactional, cost-plus arrangements, PBL contracts often seek a blend of near-term and long-term cost reductions while simultaneously maintaining or improving performance. Achieving cost reductions in near- and long-term time horizons requires a mindset focused on driving out waste in the existing processes, while also focusing on innovation and product improvements that drive down life-cycle costs.

PBL differs from traditional sustainment in that PBL takes a multi-dimensional approach to demand fulfillment. The first dimension is to efficiently meet demand within the current supply chain structure. The second dimension is to design out demand. That reduction is achieved through improvements in material, process, and technology.

Traditional BCA generally fails to capture time, innovation, and the impact innovation can have on both lowering costs and improving performance. When making a choice between PBL service providers, one is faced not only with a decision regarding who can do the job as it is today, but also which organization is able to provide innovations that will either improve performance and/or drive costs down *in the future*.

We believe there is a strong case for developing a BCA structure that not only evaluates the performance among competing traditional sustainment support options, but also evaluates the unique aspects that define a PBL. Then, a reasonable and informed comparison can be made between the two. Such decision-making is central in this new approach to BCA.

We suggest creating a series of questions for the BCA built around an assessment of each of the building blocks leading to innovation. Questions critical to this approach are the following (Randall, Brady, et al., 2012):

1. Are the incentives designed to reward achievement of the outcome?
2. Does the provider have adequate knowledge across the identified domains to harvest potential cost avoidance?
3. Does the provider have informed experience?
4. What are the possibilities for innovation in the system being sustained?
5. What timelines are appropriate for making a comparison for cost savings?

Each of these questions is designed to incorporate the building blocks for a successful PBL BCA and set up follow-on questions that provide a multiple-year, apple-to-apple evaluation of the bottom line. A year-to-year contract may experience immediate short-term gains, while a PBL contract may experience a near-term increase in costs as suppliers invest in innovation and longer-term life-cycle affordability improvements.

4. Quantitative Research Studies

4.1. Determining the Optimal Price, Length, and Investment of a Performance-Based Contract

The research in this section is documented in Nowicki, Ramirez-Marquez, Randall, and Murynets (2012).

The content in this section is largely extracted from Nowicki, Ramirez-Marquez, Randall, and Murynets (2012). As shown in Nowicki, Ramirez-Marquez, Randall, and Murynets (2012), performance-based contracting has altered the fundamental relationship between buyers and suppliers engaged in the support of capital-intensive systems, such as high-speed rail, defense, and power generation. This shift is a movement away from a traditional transactional-based (return-on-sales) business approach and a movement toward a collaborative, performance-based (return-on-investment), multi-year contractual model. With PBCs, the supplier is compensated for system performance, rather than for each maintenance, repair, and overhaul (MRO) transaction. The success of the performance-based contracting approach lies in the incentive structure. Under performance-based contracting, the profits are highest, performance is improved, and operator costs are ultimately reduced when smart investment decisions are made that trade year-after-year MRO costs for upfront investments that reduce total cost of ownership. The amount of money to invest in improving the system performance is both an important design decision and a critical business decision that must be made prior to engaging in a PBC. This strategic investment decision is bound by five key variables: (1) PBC contract length, (2) initial system reliability, (3) willingness of a customer to engage in a PBC at a given offering price, (4) multi-year price break, and (5) average and variability of the cost to perform a maintenance task.

A decision-theoretic model was developed that determined the optimal contract length, optimal investment, and pricing strategies for performance-based, post-production service contracts that simultaneously maximize the profit to the supplier while satisfying the customer's needs. The model accounted for reliability as a function of investment and the average and variance of the cost to perform maintenance tasks, and for customers' willingness to pay for a contract depending on its length. For a detailed discussion on the decision theory and mathematical model used to determine the optimal price, contract length, and investment see Nowicki, Ramirez-Marquez, Randall, and Murynets (2012).

Optimal strategies depend on potential market size, expected cost per failure, and other parameters of the model. In summary, the following conclusions can be drawn:

- Optimal investment is an increasing function of the expected cost per failure, market size, and customers' willingness to pay, but is a decreasing function of the initial reliability.
- Optimal periodic contract fee is an increasing function of the contract's length, customers' willingness to pay, and an expected cost per failure, but is a decreasing function of the initial reliability and market size.
- Longer post-production service contracts require higher optimal investments, but provide higher system reliability.
- Optimal contract length is a decreasing function of the discount per period, expected cost per failure, and marginal investment parameter, and it is an increasing function of the market size and the maximal price that customers are willing to pay for a single-period contract.

4.2. Improving the Computational Efficiency of Multi-Echelon Technique for Recoverable Item Control (METRIC) Inventory Optimization Problems

The research in this section is documented in Nowicki, Randall, and Ramirez-Marquez (2012b).

We developed a new heuristic algorithm to improve the computational efficiency of the general class of Multi-Echelon Technique for Recoverable Item Control (METRIC) problems. The content of this section is largely extracted from Nowicki, Randall, and Ramirez-Marquez (2012b). The objective of a METRIC-based decision problem is to determine systematically the location and quantity of spares that either maximize the operational availability of a system subject to a budget constraint or minimize the system's cost subject to an operational availability target. This type of sparing analysis has proven essential when analyzing the sustainment policies of large-scale, complex repairable systems, such as those prevalent in the defense and aerospace industries. Additionally, the frequency of these sparing studies has recently increased as the adoption of PBL has increased.

We developed and validated a practical algorithm for improving the computational efficiency of a METRIC-based, inventory optimization approach. Details on the underlying theory and mathematical development of this novel, heuristic model are available from Nowicki, Randall, and Ramirez-Marquez (2012b). The accuracy and effectiveness of the proposed algorithm were analyzed through a numerical study. The algorithm showed a 94% improvement in computational efficiency while maintaining 99.9% accuracy.

PBL represents a class of business strategies that converts the recurring costs associated with maintenance, repair, and overhaul (MRO) into cost avoidance streams. Central to a PBL contract is a requirement to perform a business case analysis (BCA), and central to a BCA is the frequent need to use METRIC-based approaches to evaluate how a supplier and customer will engage in a PBL arrangement where spares decisions are critical. Due to the size and frequency of the problem, there exists a need to improve the efficiency of the computationally intensive METRIC-based solutions.

4.3. A System-of-Systems Design Decision under a Performance-Based Supplier-Customer Relationship

The research in this section is documented in Nowicki, Randall, and Ramirez-Marquez (2011).

The content of this section is largely extracted from our working paper Nowicki, Randall, and Ramirez-Marquez (2011). More often, the design community, often spearheaded by systems engineers, and the sustainment community are looking collaboratively for more cost- effective and profitable ways to provide simultaneously a better performing system and improved post-production support to their customers (Nowicki, Kumar, et al., 2008; Randall, Nowicki, & Hawkins, 2011; Randall, Pohlen, et al., 2010). In times of shrinking margins, reduced funding, and increased competition, it makes sense that managers would seek innovative strategies to facilitate such competitive challenges. Performance-based logistics (PBL), also known as performance-based contracting or power by the hour (PBH), is successfully providing new sources of customer value and supplier network profitability in the arena of complex system post-production support (also called sustainment).

A natural trade-off space exists between the system design and the makeup of the post-production support network necessary for its successful, on-going operation. Within this trade-off space reside competing investment opportunities. An example includes investing in improved system reliability (e.g., redundancy, higher quality components, etc.) with the consequence of avoiding out-year support costs (e.g., spares, transportation, etc.) On the other hand, investments in the support network (e.g., more spares, faster replenishment times, etc.) may provide the same desired system-level effect without the investment of more time and money in the research, design, and development cycles. Competing and complimentary desired system performance attributes often exist, such as reliability, maintainability, availability, life-cycle cost, and logistics footprint. Design and support decisions are often made in isolation of each other and are often made with the consideration of only one system-level performance measure. We have made progress on developing multi-objective, decision support models to assist decision-makers. These models simultaneously consider the effects on system design and the post-production support network needed to sustain system operation.

We developed a meta-heuristic model that enables optimal design decisions to be made when evaluating competing design alternatives using an analytical method capable of simultaneously considering multiple criteria such as reliability, availability, life-cycle cost, and logistics footprint. This novel meta-heuristic model is an evolutionary algorithm defined in an iterative, four-step process. These four steps are based on the generation of the system design configuration via Monte Carlo (MC) simulation, solution analysis, and estimation of the system-level, profit-based spares algorithm to provide the necessary support to the system. This is accomplished with a new meta-heuristic algorithm that drives the simultaneous selection of a primary system configuration (where and how much redundancy to design in) and design of the enabling support network (location and quantity of spares). For details on the theoretical development of this new, evolutionary algorithm see Nowicki, Ramirez-Marquez, et al. (2011) and Nowicki, Randall, & Ramirez-Marquez (2011).

In this research, we adopted the perspective of an original equipment manufacturer (OEM). The OEM desires to choose a design, from competing design alternatives, that simultaneously examines five fundamental systems engineering metrics—availability, reliability, maintainability, supportability, and total ownership cost. Existing design evaluation models only consider one metric, and possibly two, as an objective to make a design decision. With the continuing emphasis on PBL contracts, it is now even more imperative that design decisions are made in the presence of competing system-level performance metrics in order to judge both profitability and the ability to satisfy customer requirements.

4.4. Creating a Trade-Off Space Among Competing PBASS Evaluation Metrics

The research in this section is documented in Nowicki, Randall, and Ramirez-Marquez (2012a).

Nowicki, Randall, and Ramirez-Marquez (2012a) developed, in Python, a multi-objective optimization allocation model and corresponding Pareto front to create an investment trade-off space between the "ilities." Acquisition and sustainment communities make better decisions when an analysis produces more than just point estimates. Our research provides a response surface (i.e., tread-off space) that shows the impact competing "ilities" have on design and sustainment investment decisions.

In our previous research (supported by the NPS Acquisition Research Program under Grant No. N00244-10-1-0074), we developed a single objective optimization model. We have now developed a novel model that produces an optimal investment strategy that simultaneously considers system design improvements and increased capability of its sustainment network (Nowicki, Randall, & Ramirez-Marquez, 2011). We extended our single point model to improve both its theoretical foundation and its practical usefulness by (1) developing a multi-objective, optimization model; (2) creating response surfaces for decision-making; (3) developing a more comprehensive life-cycle affordability model; and (3) deriving two algorithmic approaches to solving the problem.

We took a SoS approach. The structure of the SoS under study is comprised of two highly interrelated systems, the primary systems (PS) and the corresponding support infrastructure (SI). The SI is responsible for sustaining the proper operation of the PS. A representative example of this type of SoS is shown in Figure 5. In Figure 5, the PSs are the F-22 and F-35 warfighters and their corresponding SI are dedicated sustainment resources as well as shared sustainment resources such as consumables provided from the Defense Logistics Agency (DLA).

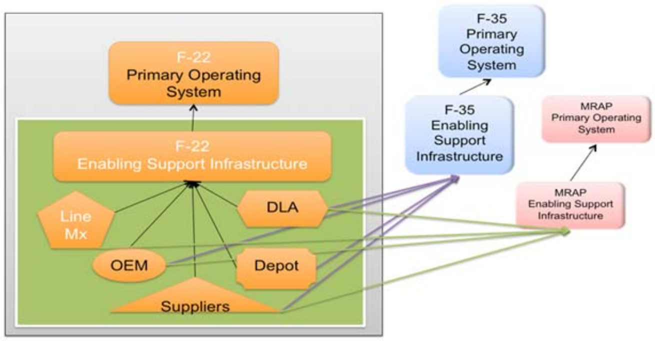

Figure 5. SoS Representation of the Primary System Configuration and Enabling Support Infrastructure

We are now able to identify a portfolio of SoS configurations—including PS and SI resources and effort—that describe the trade-offs among reliability, maintainability, supportability, logistics footprint, and life-cycle affordability. The SoS portfolio now reflects choices that consider maximizing reliability, minimizing repair time, maximizing affordability, minimizing logistic footprint, and maximizing operational availability, and also the impact these considerations have among each other. For SoS such as the one represented in Figure 5, it is now possible to have multiple competing requirements and multiple prospective solutions that may change as requirements change (Nowicki, Randall, & Ramirez-Marquez, 2011; 2012a).

We developed a novel multi-objective, optimization model that generates Pareto fronts to help the acquisition and logistics decision-makers visualize how changes in reliability, maintainability, supportability, availability, life-cycle costs, and logistics footprint affect the PS design and its SI.

The term multi-objective optimization is related to the problem of finding solutions for mathematical models that have multiple objective functions with multiple optimization criteria. Unlike optimization models with a single objective function, where a solution may satisfy the optimization criteria (i.e., become the optimal solution), the multi-objective case is concerned with obtaining solutions that best represent the conflicting nature of the different functions being optimized. Thus, the interest is on finding the set of solutions that describe how changes in the value of one of the objective functions (e.g., reliability) impact the value of the remaining objectives (e.g., life-cycle cost, supportability, etc.). It is important to stress that the interest is in understanding the effect over the whole range of possible values for each objective function (e.g., all values of reliability from 0 to 1).

A representative multi-objective optimization model is presented in the following equations where, vector $\mathbf{f}(\mathbf{x})$ describes those objective functions where the interest is in improving performance (reliability, availability, profit, etc.) while vector $g(\mathbf{x})$ includes those objective functions where the interest is on decreasing their value (logistic footprint, maintainability, life-cycle cost, etc.). Similarly, the first and second set of constraints describe possible constraints on system performance and resources. Finally, the last constraint dictates the decision variables behavior.

$$\text{Max } \mathbf{f}(\mathbf{x}) = \left(f_1(\mathbf{x}), \quad f_2(\mathbf{x}), \quad ..., \quad f_L(\mathbf{x}) \right)$$

$$\text{Min } g(\mathbf{x}) = \left(g_1(\mathbf{x}), \quad g_2(\mathbf{x}), \quad ..., \quad g_O(\mathbf{x}) \right)$$

s.t.

$f_l(\mathbf{x}) \geq F_l \ \forall \ l=1,\ldots,L'$

$g_o(\mathbf{x}) \leq G_o \ \forall \ o=1,\ldots,O$

x_{ij} is an element of $\mathbf{x}$.

For this multi-objective (MO) optimization problem, a solution $\mathbf{x}^*$ that satisfies the constraints, is called Pareto optimal if for any other feasible solutions $\mathbf{x}'$ and $\mathbf{x}''$

i) there is no $\mathbf{x}'$ such that $(f_l(\mathbf{x}') \geq f_l(\mathbf{x}^*) \ \forall \ l)$ and,

ii) $f_l(\mathbf{x}^*) > f_l(\mathbf{x}'')$ for some l .

The set containing all Pareto optimal solutions is usually referred to as the Pareto-optimal set. To identify such a set we plan to develop multiple-objective evolutionary algorithms (MOEA).

We used two analytical approaches: MO probabilistic solution discovery algorithm (MO-PSDA) and MO genetic algorithms (MO-GA). The first algorithm, MO-PSDA, offers a simple, efficient, and intuitive approach to solve model MO, with a minimum number of tuning parameters. We then developed an MO-PSDA model and compare its behavior with solutions obtained from an MO-GA. These algorithms provide similar Pareto fronts (i.e., trade-off space for competing criteria), as seen in Figure 6.

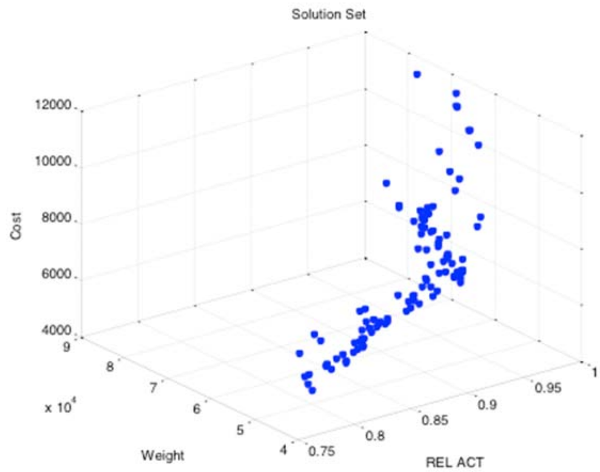

Figure 6. Pareto Set for a Multi-Objective Optimization Model: Max Reliability, Minimize Life-Cycle Cost, and Minimize Logistic Footprint

Figure 6 illustrates the values of reliability, life-cycle cost, and logistic footprint (in this case considered as weight) of a representative design system. These solutions have been obtained by solving the MO model: Max Reliability, Minimize Acquisition Cost, and Minimize Logistic Footprint. Note that each of these solutions represents a different SoS configuration. The solution to this MO model allows the acquisition manager to understand

1. The effects of abrupt changes in stakeholder requirements. For example, the acquisition and logistics managers can uncover general configurations for the SoS that can satisfy changes in reliability requirements at minimum life-cycle cost.
2. The impact of budget reductions. For example, the acquisition manager can better communicate the effects of budget costs on the system reliability or the resources defining its sustainment network.

5. Project Accomplishments

5.1. Publications

5.1.1. Journals

1. Randall, W. S., Wittman, C. M., Nowicki, D. R., & Pohlen, T. L. (in press). Service-dominant logic and upply chain management: Are we there yet? *International Journal of Physical Distribution and Logistics Management*.
2. Randall, W. S. (in press). Sustainable complex systems of systems: Architecting for life cycle affordability. *Systems Research Forum*.
3. Randall, W. S. (2012). Are the PBL prophets using science or alchemy to create life cycle affordability. Manuscript submitted for publication.

4. Randall, W. S. (2012). *A framework for understanding and investigating performance based logistics (PBL) strategies*. Manuscript submitted for publication.
5. Randall, W. S., Nowicki, D. R., Hawkins, T. G., Haynie, J. J., Armenakis, A. A., & Geary, S. R. (2012). *Performance-based logistics and inter-firm team processes: An empirical investigation.* Manuscript submitted for publication.
6. Nowicki, D. R., Ramirez-Marquez, J. E., Randall, W. S., & Murynets, I. (2012). *Optimal cost avoidance investment and pricing strategies for performance based post-production service contracts.* Unpublished manuscript.
7. Nowicki, D. R., Ramirez-Marquez, J. E., & Randall, W. S. (2012). *Creating a trade-off space among competing performance based acquisition and sustainment support evaluation metrics.* Unpublished manuscript.
8. Nowicki, D. R., Randall, W. S., & Ramirez-Marquez, J. E. (2012). Improving the computational efficiency of metric-based spares algorithms. *European Journal of Operational Research*, *219*(2), 324–334.
9. Randall, W. S., Brady, S., & Nowicki, D. R. (2012). Business case analysis and the confounds of innovation driven by performance-based post-production support strategies. *Transportation Journal*, *51*(1), 33–58.
10. Randall, W. S., Nowicki, D. R., & Hawkins, T. G. (2011). Explaining the effectiveness of performance based logistics: A quantitative examination. *International Journal of Logistics Management*, *22*(3).
11. Nowicki, D. R., Randall, W. S., & Ramirez-Marquez, J. E. (2011). *A system of systems design decision under a performance based supplier customer relationship.* Unpublished manuscript.

5.1.2. Conference Proceedings

1. Nowicki, D., Murynets, I., Ramirez-Marquez, J. E., & Randall, W. S. (2011). Optimal cost avoidance investment and pricing strategies for performance based post-production service contracts. In *Proceedings of the Eight Annual Acquisition Research Symposium*. Retrieved from http://www.acquisitionresearch.net

5.2. Presentations

1. Nowicki, D. R., & Randall, W. S. (2011). *Service and product design*. Invited talk at the Wharton Service Supply Chain Thought Leadership Forum, Wharton West, San Francisco, CA.
2. Randall, W. S. (2011). *A framework for a PBL system of systems approach*. Presentation at the Military Logistics Summit, Institute for Defense and Government Advancement (IDGA), Washington, DC.
3. Nowicki, D., & Randall, W. S. (2010). *Role of performance based logistics (PBL) and readiness*. Invited talk at the Military Air Assets Exhibition and Conference (MAASEC), Jacksonville, FL.

4. Johnson, J., Nowicki, D. R., & Randall, W. S. (2010). *Focus on business case analysis (BCA) structure*. Panelists at The Next Generation of PBL—Performance Based Lifecycle Product Support, Arlington, VA.
5. Johnson, J., Nowicki, D. R., & Randall, W. S. (2010). *Review of the product support assessment team (PSAT) report*. Panelists at The Next Generation of PBL—Performance Based Lifecycle Product Support, Arlington, VA.
6. Nowicki, D., & Randall, W. S. (2010). *Performance based logistics/contracting: How to measure performance and profit*. Workshop conducted at the Military Air Assets Exhibition and Conference (MAASEC), Jacksonville, FL.
7. Randall, W. S., & Nowicki, D. R. (2011). *Performance based logistics/contracting: How to measure performance and profit*. Presentation at the Military Logistics Summit, Washington, DC.
8. Nowicki, D., & Randall, W. S. (2010). *Proactive supply chain management in a PBL environment: People, performance, profit and culture*. Paper presented at the Military Air Assets Exhibition and Conference (MAASEC), Jacksonville, FL.
9. Randall, W. S., Geary, S. R., & *Nowicki, D. R.* (2010). *Profitability, competition, transaction costs, and PBL*. Presentation at the Defense Logistics Conferences: Resetting for the Future of Logistics, Arlington, VA.
10. Randall, W. S., & Nowicki, D. (2010). *The econometrics of performance based logistics*. Presentation at the Military Air Assets Exhibition and Conference (MAASEC), Jacksonville, FL.
11. Randall, W. S., & Nowicki, D. R. (2010). *PBL driven investment, innovation, and collaboration: Presentation of the comprehensive survey*. Presentation at The Next Generation of PBL—Performance Based Lifecycle Product Support, Arlington, VA.
12. Randall, W. S., Nowicki, D. R., & Geary, S. (2010). *Success factors for organic participation in performance based lifecycle product support strategies*. Presentation at The Next Generation of PBL—Performance Based Lifecycle Product Support, Arlington, VA.

5.3. Technical Reports

1. Nowicki, D. R., Ramirez-Marquez, J. E., & Randall, W. S. (2011). *Analytical examination of performance strategies*. Department of the Navy, Naval Postgraduate School, Acquisition Research Program, Program Grant No. N00244-10-1-0074.

5.4. Doctoral Student Research Supported/Supervised

1. Murynets, I. (2010). *Optimal investment and marketing strategies for technologically innovative services* (Doctoral dissertation). Available from ProQuest Dissertations and Theses database. (UMI No. 3428880)
2. Hernandez, I. *Emergency preparedness framework: A multi-objective approach.* Doctoral dissertation in progress.

5.5. Awards

<u>1. Best Dissertation in the School of Systems and Enterprises</u>

Awarded to Ilona Murynets for her doctoral dissertation, *Optimal Investment and Marketing Strategies for Technologically Innovative Services*.

2. Emerald Literati Awards for Excellence

"Explaining the Effectiveness of Performance-Based Logistics: A Quantitative Examination," published in *The International Journal of Logistics Management,* was chosen as a Highly Commended Award Winner at the Literati Network Awards for Excellence 2012.

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