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New Measures for Supply Chain Vulnerability: Characterizing the Issue of Friction in the Modelling and Practice of Procurement

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1. Introduction

Supply chains consist of readily recognizable linkages, often between commercially distinct organizations that must coordinate activities to ultimately meet customer demand. Such organizations are not necessarily bound by a central planner who can both determine and dictate what procurement policies are implemented across these inter-organizational links. In the absence of such coordination, each organization can be expected to resolve procurement and replenishment policies from a local perspective, passing the demands of such to its suppliers in a highly intuitive, pull-style fashion. While such policies may seem reasonable to all partners involved and may be the only solutions tolerable from a political perspective, there exists the possibility that the decentralized policies are operating at a combined cost substantially higher than that which could be achieved through global optimization. The purpose of this chapter is to define this vulnerability and to suggest methods for anticipating it, both in the simulation modelling of supply chains and in practice

Efforts to characterize the vulnerability of inter-organizational links arguably predates the phrase 'supply chain'. As much of the early work on multi-stage inventory planning was being accomplished, Bowersox (1969) protested the inherent assumption of vertical integration in the formulation of many distribution problems, warning of inefficiencies that could arise in practice if, in fact, various stages represented distinct organizations. Working with small multi-stage networks, Schwarz & Schrage (1975) coined the phrase *system myopic* to identify policies in which inventory replenishment is planned locally, the connation of which implies potential weakness (the condition of near-sightedness) when conducted in a complex system. Nonetheless, supply chain literature has traditionally maintained what Otto & Kaab (2003) would later call the *operations research perspective*, relying heavily on the assumption that policies will be set by central decision-makers to optimize the performance of complex systems.

The reality of inter-organizational dynamics in supply chain management has gained greater attention in recent years, highlighted in the taxonomy of Wang (1995) as a *nexus of contract perspective* on operations. The supply chain literature survey by Stadtler (2005) cited globally dispersed inter-organizational chains as a challenge central to this field. Disparities between centralized and decentralized procurement policies for specific instances are being

explored mathematically, such as for the relationship between a single retail outlet and its warehouse when demand for a particular product depends both on price and level of retail stock (Jørgensen & Kort, 2002), or for a single assembly operation supported by multiple suppliers each of which suffer uncertain component yields (Gurnani & Gerchak, 2007). To enable centralized solutions among independent organizations, *information sharing* emerges as an important issue in this context, such as the work summarized in the survey of Huang et al. (2003). Given that an inter-organizational supply chain is structured such that all relevant information required to achieve a centralized solution is not reliably available, development of decentralized, negotiation-based schemes to approximate the benefit of the operations research perspective has received attention, such as the coordination processes developed for two-tier systems by Dudek & Stadtler (2007).

Yet surprisingly, practitioner surveys such as that of Armistead & Mapes (1993) have suggested confounding inconsistencies in the reported usefulness of intuitively beneficial mechanisms such as information sharing in practice. Some simulation studies modelling these issue have echoed this theme, such as the counter-intuitive findings of Lau et al. (2004), in which all stages of a simulated supply chain did not always need to be engaged in information sharing to achieve satisfactory system performance. Furthermore, it is not uncommon for studies modelling system-wide cost performance under various assumptions of information sharing and inventory management (for example, the serial inventory systems in Chen (1998)) to suggest the average superiority of centralized solutions to be as little as 2%. This has sparked debate as to whether such a gap is of any practical significance at all, such as the commentary of Hofmann (1997) and Aderohumnu et al. (1997) concerning the degree of improvement apparent in more centralized algorithms for solving a dyadic buyer/supplier lot sizing problem.

Wang et al. (2004) discuss further drawbacks inherent in the operations research perspective on supply chain systems, such as ignoring the facts that the cost of information processing for centralized planning may be expensive, the system may be too complex to readily identify optimal solutions, and that competitive behaviour between independent stages may exclude the use of such solutions even if available. Nonetheless, the paradigm of the central planner and the optimal solution is the pursuit the most efficient operation of the entire supply chain system, and each of the concerns outlined by Wang et al. (2004) could be addressed with effort and investment. Simultaneously, there exists ample evidence that the potentially costly interventions required to operate a decentralized system in a centralized fashion would not always result in profoundly better results. Gavirneni (2001) observes that the benefits of information sharing and central coordination appear to depend heavily on environmental factors such as the supply chain structure and its existing modus operandi, but there remains little insight from the current literature on precisely what these factors are and how they influence these benefits. This leaves unanswered the question that, in the presence of independent supply chain partners, *when* would a substantial effort to restore the operations research perspective of the system make a substantial difference in the system's performance? Can it be anticipated which supply chains will prove most vulnerable to inefficiencies induced by decentralized pull-style planning, distinguishing them from those for whom elaborate contractual arrangements and information sharing do little to improve performance beyond what is achieved through their own intuitive local optimization? These are the issues examined in this chapter, beginning with proposed measures for the degree of disparity between the quality of centralized and decentralized

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supply chain solutions, discussed as various forms of *friction* in the next section. Friction is a direct measure of the degree of benefit of the centralized planning of procurement between two or more supply chain stages. After discussion of the concept of friction in its general form in Section 2, mathematical formulations of friction in two-stage and three-stage systems with level, deterministic demand are developed in Section 3, so that these models may then be utilized in the simulation of 127,680 experimental instances, representing a broad range of environmental factors described in Section 4. Section 5 details the results of the simulation study, employing descriptive statistics, polynomial and logistic regression, and graphical representations to explore the intricate interactions of various factors in determining the relative robustness or extreme inefficiency of decentralized, pull-style planning. Section 6 provides further discussion and interpretation, including intriguing results such as those supply chain partners most vulnerable to higher system costs through decentralized planning are those partners most similar to each other in general cost structures and independent order cycle preference.

2. Proposed measures of supply chain vulnerability

To focus on potential vulnerability inherent in any inter-organizational supply chain arrangement, we introduce these five concepts:

- **friction**- the disparity between the cost of a decentralized solution and that of an optimal solution when conducting procurement across a supply chain structure. Friction represents the loss, if any, suffered by local optimization among otherwise independent supply chain partners. Friction is stated as a ratio of a decentralized to an optimal solution's value. Thus, it is assumed that friction can be no less than 1.0 for any given instance.
- **link friction**- friction observed between two partners, a buyer and a supplier.
- **chain friction**- friction observed in generalized supply chain structures consisting of three or more partner stages.
- **implicit optimization**- an environmental instance in which a supply chain structure suffers no friction. These are conditions under which local optimization results in solutions identical to the policies dictated by global optimization. Thus, implicit optimization is the equivalent of a value of 1.0 for the ratio friction.
- **economic blind spot**- an environmental instance resulting in extreme friction, so named because the independently operated supply chain partners fail to "see" the substantial savings associated with another solution. This is an alarming vulnerability that could potentially be anticipated by identifying the environmental factors associated with its occurrence.

Link friction and economic blind spots are simple to demonstrate. Consider the two-stage, dyadic structure pictured in the upper left-hand corner of Fig. 1, representing the partnership between a single buyer and supplier.

Consider a case in which the buyer consumes or distributes 210 units of the supplier's product each period, incurring a fixed cost of 200 to procure any number of units and paying 1.0 to hold one such unit in inventory for one period. The supplier incurs a fixed cost of 600 to replenish the stock at the level below, and 0.95 per unit per period in inventory costs. In decentralized planning, the buyer will prefer to order lot-for-lot, as it costs more to carry one period's worth of demand in inventory than it does to place a new order with the

supplier. With heavier fixed costs and somewhat lesser inventory costs, the supplier will then minimize cost by replenishing once every three periods.

Using a 12-period planning horizon as an example, the buyer will incur a total cost of 12 * 200 = 2,400, while the buyer would pay 4 * 600 = 2,400 in fixed costs and 4 * 598.5 = 2,394 in inventory costs. This results in a total system cost of 7,194, which is not an optimal solution in this setting. Despite the fact that this solution is highly intuitive to the two independent partners, the lowest cost solution dictates that both the supplier and the buyer replenish once every three periods. In this scenario, the buyer would pay only 4 * 200 = 800 in fixed costs but 4 * 630 = 2,520 in inventory holding costs, while the supplier would pay the same 4 * 600 = 2,400 in fixed costs, but hold no inventory after serving the buyer. The total combined system cost is only 5,720. This discrepancy between the two scenarios is expressed as link friction of 7,194/5,720 = 1.258, or a cost increase of nearly 26% attributable to decentralized planning, and a distinct economic blind spot in this partnership.

Now consider the same two-stage scenario, but with the following revisions: the buyer consumes or distributes 190 units per period (as opposed to the original 210), and the supplier's per unit, per period inventory holding cost is 0.55 (as opposed to the original 0.95). Now the solution arrived at through decentralized planning is identical to the optimal solution to this scenario: the buyer will prefer to replenish every two planning periods and supplier, supporting the buyer's consumption pattern, will replenish every four periods. This scenario represents implicit optimization, in that centralized planning can not improve upon the decentralized activities of two independent partners.

3. Formulation

3.1 Two-stage formulation

To express friction mathematically in the context of discrete, deterministic and level demand, consider the following definitions concerning the two-stage dyadic system illustrated in Fig. 1:

d = the per period external demand requirement.

h_i = the per unit, per period inventory holding cost at stage i.

s_i = the fixed cost of replenishment (ordering cost) at stage i.

T = the length of the planning horizon.

λ_1 = the order cycle length of stage 1, stated in periods.

λ_2 = the order cycle length of stage 2, stated as a multiple of λ_1.
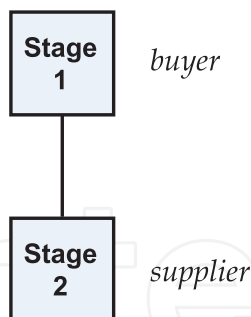
At stage 1 we expect T/λ_1 order cycles within a planning horizon of T periods, with an implicit assumption that T/λ_1 is an integer. Likewise, we expect $T/(\lambda_1\lambda_2)$ order cycles at stage 2, and thus total ordering costs of the two stage scenario can be stated:

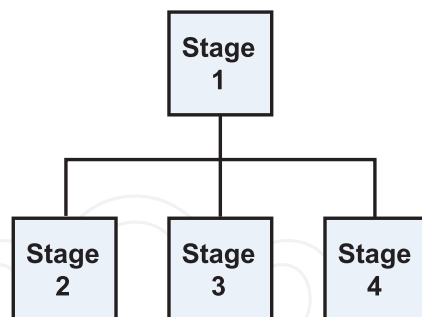$$\frac{T}{\lambda_1}s_1 + \frac{T}{\lambda_1\lambda_2}s_2 \tag{1}$$

For convenience, this expression can be consolidated into:
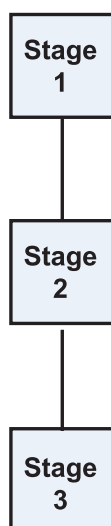
$$T\frac{s_1\lambda_2 + s_2}{\lambda_1\lambda_2} \tag{2}$$

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A two-stage dyadic system

Stage 1 — *buyer*

Stage 2 — *supplier*

A two-level, four-stage system

Stage 1

Stage 2 — Stage 3 — Stage 4

A three-stage serial system

Stage 1

Stage 2

Stage 3

A three-level, eight-stage system

Stage 1

Stage 2 — Stage 3 — Stage 4

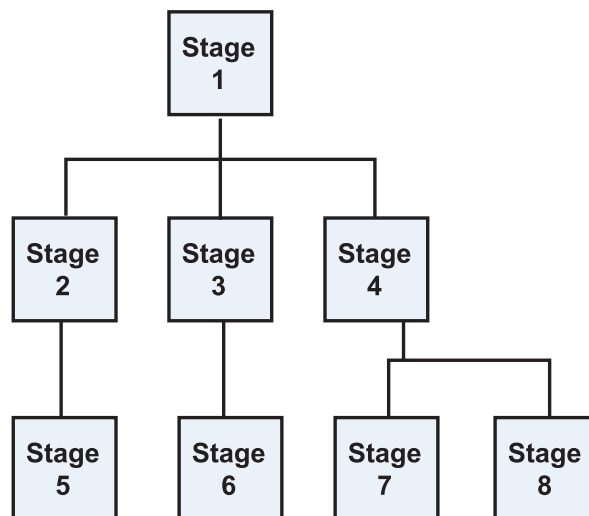Stage 5 — Stage 6 — Stage 7 — Stage 8

Figure 1. Four supply chain structures

To express the issue of inventory burden, consider the fact that each order cycle at stage 1 requires $d(\lambda_1^2 - \lambda_1)/2$ part periods of inventory, and thus each stage 2 order cycle incurs $\lambda_1^2 d(\lambda_2^2 - \lambda_2)/2$ part periods of inventory. Incorporating the respective holding costs and the number of order cycles yields an expression of the combined inventory holding costs for the two stages:

$$\frac{T}{\lambda_1} h_1 d\left(\frac{\lambda_1^2 - \lambda_1}{2}\right) + \frac{T}{\lambda_1 \lambda_2} h_2 \lambda_1^2 d\left(\frac{\lambda_2^2 - \lambda_2}{2}\right) \tag{3}$$

The latter half of expression (3) does assume a "one-to-one" demand relationship between the two stages; i.e. demand for d items from stage 1 results in the procurement of precisely d input items from stage 2. This highly convenient assumption can be made without loss of generality, in that any exception to this condition (i.e. two identical components are secured from stage 2 to support the provision of a single item for external consumption at stage 1) can be translated back into the former case by simply "kitting" the multiple components together and adjusting the associated holding cost.

$$\frac{Td}{2}(h_1(\lambda_1 - 1) + h_2\lambda_1(\lambda_2 - 1)) \qquad (4)$$

Thus, the combined relevant cost of any policy of λ_1 and λ_2 can be stated as:

$$T\left(\frac{s_1\lambda_2 + s_2}{\lambda_1\lambda_2} + \frac{d}{2}(h_1(\lambda_1 - 1) + h_2\lambda_1(\lambda_2 - 1))\right) \qquad (5)$$

To further simplify expression (5) and to highlight the roles of certain environmental cost factors that will later prove influential to the issue of friction, consider the following additional definitions:

p = the ratio s_2/s_1.

e = the ratio h_2/h_1.

$D = (dh_1)/2$.

Environmental cost factor p is an expression of the magnitude of the stage 2 fixed cost s_2 relative to the corresponding cost at the stage 1, or $s_2 = s_1p$. Similarly, environmental cost factor e allows the per unit per period holding cost at stage 2 to be stated in terms of the corresponding cost at stage 1, $h_2 = h_1e$. Introducing these relationships into expression (5) yields:

$$T\left(\frac{s_1(\lambda_2 + p)}{\lambda_1\lambda_2} + \frac{dh_1}{2}((\lambda_1 - 1) + e\lambda_1(\lambda_2 - 1))\right) \qquad (6)$$

At this point, the introduction of factor D yields:

$$T\left(\frac{s_1(\lambda_2 + p)}{\lambda_1\lambda_2} + D((\lambda_1 - 1) + e\lambda_1(\lambda_2 - 1))\right) \qquad (7)$$

To formulate the issue of link friction, it becomes necessary to discriminate between two policies, that which results specifically from decentralized planning versus an optimal policy with respect to minimizing expression (7). Therefore, we revise the definitions of order cycle lengths λ_1 and λ_2 to read:

λ_1 = the order cycle length of stage 1 which minimizes costs at stage 1, stated in periods.

λ_2 = the order cycle length of stage 2 which minimizes costs at stage 2 (given a value of λ_1), stated as a multiple of λ_1.

λ^*_1 = the order cycle length of stage 1 in a globally optimal solution, stated in periods.

λ^*_2 = the order cycle length of stage 2 in a globally optimal solution, stated as a multiple of λ^*_1.

Link friction, being the ratio of decentralized to optimal planning, can then be expressed as:

$$\frac{T\left(\dfrac{s_1(\lambda_2 + p)}{\lambda_1\lambda_2} + D((\lambda_1 - 1) + e\lambda_1(\lambda_2 - 1))\right)}{T\left(\dfrac{s_1(\lambda^*_2 + p)}{\lambda^*_1\lambda^*_2} + D((\lambda^*_1 - 1) + e\lambda^*_1(\lambda^*_2 - 1))\right)} \qquad (8)$$

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At this point we observe that link friction is essentially independent of planning horizon length T, and expression (8) can be simplified to:

$$\frac{\dfrac{s_1(\lambda_2+p)}{\lambda_1\lambda_2}+D((\lambda_1-1)+e\lambda_1(\lambda_2-1))}{\dfrac{s_1(\lambda^*_2+p)}{\lambda^*_1\lambda^*_2}+D((\lambda^*_1-1)+e\lambda^*_1(\lambda^*_2-1))} \tag{9}$$

The symbolic derivation of friction in a two-stage system now reaches an impasse, in that there exist no closed form expressions to further substitute for the order cycle factors λ_1, λ_2, λ^*_1 and λ^*_2, translating expression (9) into a statement of friction as a function solely of environmental parameters s_1, D, p and e.

3.2 Extensions of the two-stage formulation
3.2.1 Equivalent environmental instances.
Expression (9) demonstrates infinite environmental instances will share the same associated level of friction, due to the composite nature of the parameter D. Since D represents $dh_1/2$, a scenario in which $s_1=100$, $p=2$, $e=0.5$, $h_1=1.0$ and $d=50$ can be anticipated to have the same associated friction as a scenario in which $s_1=100$, $p=2$, $e=0.5$, $h_1=0.5$ and $d=100$, and so on.

3.2.2 General two-level supply chain structures.
Expression (9) not only represents an infinite number of environmental cases with equivalent link friction, this expression also calculates the *chain friction* associated with a special case of the generalized two-level structure, such as the two-level, four-stage system pictured in Fig. 1. In such a structure, the receiving level is populated only by stage 1, with the same parameters s_1, d and h_1 discussed early in Section 3.1. The supplying level, however, is populated by *n* stages numbered i = 2, … , *n*+1, each with an associated fixed cost of s_i and holding cost h_i, resulting in a potentially unique λ_i and λ^*_i for that stage. The combined fixed ordering costs of the system, the general two-level equivalent of expression (1), appears as:

$$\frac{T}{\lambda_1}s_1+\sum_{i=2}^{n+1}\frac{T}{\lambda_1\lambda_i}s_i \tag{10}$$

Likewise, the combined inventory holding cost of the two level system, the generalized form of expression (3), would be:

$$\frac{T}{\lambda_1}h_1d(\frac{\lambda_1^2-\lambda_1}{2})+\sum_{i=2}^{n+1}\frac{T}{\lambda_1\lambda_i}h_i\lambda_1^2d(\frac{\lambda_i^2-\lambda_i}{2}) \tag{11}$$

Similar to the arguments of Section 3.1, expressions (10) and (11) can be combined and simplified to yield the total relevant cost of the two-level system as:

$$T\left(\frac{s_1}{\lambda_1} + \sum_{i=2}^{n+1}\frac{s_i}{\lambda_1\lambda_i} + \frac{h_1 d}{2}(\lambda_1-1) + \lambda_1\sum_{i=2}^{n+1}\frac{h_i d}{2}(\lambda_i-1)\right) \tag{12}$$

Now consider a special case of the two-level system, in which the supplying stages are identical in cost structure. Thus, each second level stage incurs a particular fixed cost s'_2 and a particular per unit per period holding cost h'_2 associated with its replenishment cycles. Since each supplying stage likewise experiences the same level of demand from stage 1, all supplying stages would be observed to implement identical order cycles, in both decentralized (λ'_2) and globally optimal (λ'^*_2) planning of the system. Introduction of this condition into the general decentralized case represented by expression (12) yields:

$$T\left(\frac{s_1\lambda'_2 + ns'_2}{\lambda_1\lambda'_2} + \frac{h_1 d}{2}(\lambda_1-1) + \lambda_1 n\frac{h'_2 d}{2}(\lambda'_2-1)\right) \tag{13}$$

Following the definition of experimental factors p and e from the previous Section, let $p' = s'_2/s_1$ and $e' = h'_2/h_1$. Introducing the three factors p', e', and D into expression (13) yields:

$$T\left(\frac{s_1(\lambda'_2 + np')}{\lambda_1\lambda'_2} + D((\lambda_1-1) + \lambda_1 ne'(\lambda'_2-1))\right) \tag{14}$$

At this point, it is apparent that expression (14) is the equivalent to the two-stage expression (7), for any $p = np'$ and $e = ne'$. Thus, expression (9) calculates not only the link friction between a buyer and a supplier stage, but likewise the chain friction between a buyer and n supplier stages with homogenous cost factors such that $p' = p/n$ and $e' = e/n$.

3.3 Three-stage formulation

Extending the formulation to three stages in serial formation (such as pictured in Fig. 1) is simply a matter of appending the third stage to the model in Section 3.1 with the addition of these factors:

λ_3 = order cycle length of stage 3 which minimizes costs at stage 3 (given a value of $\lambda_1\lambda_2$), stated as a multiple of $\lambda_1\lambda_2$.
λ^*_3 = order cycle length of stage 3 in a globally optimal solution, stated as a multiple of $\lambda^*_1\lambda^*_2$.

The logic behind defining the order cycle length of stage 3 as a multiple of $\lambda_1\lambda_2$ is that any stage's order cycle length is measured relative to the order cycle length of its *parent*, or buyer stage above. Stage 1 has no parent item to supply, the equivalent to an order cycle being imposed on it in the form of external demand is one period in length. In the decentralized case, total ordering costs for the system can be stated as:

$$\frac{T}{\lambda_1}s_1 + \frac{T}{\lambda_1\lambda_2}s_2 + \frac{T}{\lambda_1\lambda_2\lambda_3}s_3 \tag{15}$$

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Each order cycle at stage 3 will require $\lambda_1{}^2 \lambda_2{}^2 d(\lambda_3{}^2 - \lambda_3)/2$ part periods of inventory. Thus, total inventory costs for T periods throughout the system is:

$$\frac{T}{\lambda_1} h_1 d\left(\frac{\lambda_1{}^2 - \lambda_1}{2}\right) + \frac{T}{\lambda_1 \lambda_2} h_2 \lambda_1{}^2 d\left(\frac{\lambda_2{}^2 - \lambda_2}{2}\right) \\ + \frac{T}{\lambda_1 \lambda_2 \lambda_3} h_3 \lambda_1{}^2 \lambda_2{}^2 d\left(\frac{\lambda_3{}^2 - \lambda_3}{2}\right) \tag{16}$$

Expressions (15) and (16) can then be combined and simplified to create a model of total system cost analogous to the two-stage case in expression (5):

$$T\left(\frac{s_1 \lambda_2 \lambda_3 + s_2 \lambda_3 + s_3}{\lambda_1 \lambda_2 \lambda_3} + \frac{d}{2}(h_1(\lambda_1 - 1) + h_2 \lambda_1(\lambda_2 - 1) \\ + h_3 \lambda_1 \lambda_2(\lambda_3 - 1))\right) \tag{17}$$

The earlier definitions of cost ratio factors p and e featured in the two-stage formulation in Section 3.1 must now be expanded to indicate which pair of stages the factors refer to. Now let:

p_1 = the ratio s_2/s_1.
p_2 = the ratio s_3/s_2.
e_1 = the ratio h_2/h_1.
e_2 = the ratio h_3/h_2.

Now the total three-stage system cost can be stated as:

$$T\left(\frac{s_1(\lambda_2 \lambda_3 + p_1 \lambda_3 + p_1 p_2)}{\lambda_1 \lambda_2 \lambda_3} + D((\lambda_1 - 1) \\ + e_1 \lambda_1(\lambda_2 - 1) + e_1 e_2 \lambda_1 \lambda_2(\lambda_3 - 1))\right) \tag{18}$$

As with any other structure linking more than two stages, chain friction is understood to be the ratio of a decentralized versus an optimal three-stage policy:

$$\frac{\left(\dfrac{s_1(\lambda_2 \lambda_3 + p_1 \lambda_3 + p_1 p_2)}{\lambda_1 \lambda_2 \lambda_3} + D((\lambda_1 - 1) \\ + e_1 \lambda_1(\lambda_2 - 1) + e_1 e_2 \lambda_1 \lambda_2(\lambda_3 - 1))\right)}{\left(\dfrac{s_1(\lambda^*{}_2 \lambda^*{}_3 + p_1 \lambda^*{}_3 + p_1 p_2)}{\lambda^*{}_1 \lambda^*{}_2 \lambda^*{}_3} + D((\lambda^*{}_1 - 1) \\ + e_1 \lambda^*{}_1(\lambda^*{}_2 - 1) + e_1 e_2 \lambda^*{}_1 \lambda^*{}_2(\lambda^*{}_3 - 1))\right)} \tag{19}$$

3.4 Three-level extension of three-stage formulation

Analogous to the relationship between the two-stage and two-level system, the three-stage serial formulation can be shown to represent special cases of more general three-level models, such as the three-level, eight-stage system pictured in Fig. 1. Consider such a system, consisting of top-level stage 1, n second level stages numbered 2 through $n+1$, and m third level stages numbered $n+2$ through $n+m+1$. Let i* represent the *parent* of stage i, also known as its immediate successor or its buyer. As with the two-level formulation, all

second level stages have stage 1 as their parent stage, thus i* = 1 for i = 2 through $n+1$. Expression (12), the total relevant cost of ordering policies in the context of a two-level system, can now be expanded to model three-level structures:

$$T\left(\begin{array}{c} \dfrac{s_1}{\lambda_1} + \displaystyle\sum_{i=2}^{n+1} \dfrac{s_i}{\lambda_1 \lambda_i} + \displaystyle\sum_{i=n+2}^{n+m+1} \dfrac{s_i}{\lambda_1 \lambda_{i*} \lambda_i} + \dfrac{h_1 d}{2}(\lambda_1 - 1) \\ + \lambda_1 \displaystyle\sum_{i=2}^{n+1} \dfrac{h_i d}{2}(\lambda_i - 1) + \lambda_1 \displaystyle\sum_{i=n+2}^{n+m+1} \dfrac{\lambda_{i*} h_i d}{2}(\lambda_i - 1) \end{array}\right) \qquad (20)$$

Now assume a specialized structure such that stages 2 through $n+1$ on the second level have identical cost parameters h'_2 and s'_2, and thus identical associated parameters e'_1, p'_1, and λ'_2. Likewise, stages $n+2$ through $m+1$ on the third level are assumed to have identical cost parameters h'_3 and s'_3, and thus identical associated parameters e'_2, p'_2, and λ'_3. Following an algebraic progression analogous to expressions (13) and (14) in Section 3.2, the total relevant cost of this particular three-level assembly structure can be restated:

$$T\left(\begin{array}{c} \dfrac{s_1\left(\lambda'_2\,\lambda'_3 + p'_1\,n\lambda'_3 + p'_1\,p'_2\,m\right)}{\lambda_1 \lambda'_2\,\lambda'_3} + D\big((\lambda_1 - 1) \\ + e'_1\,n\lambda_1(\lambda'_2 - 1) + e'_1\,e'_2\,m\lambda_1\lambda'_2\,(\lambda'_3 - 1)\big) \end{array}\right) \qquad (21)$$

Expression (21) is the equivalent to the three-stage expression (18), for any $p_1 = np'_1$, $p_2 = mp'_2/n$, $e_1 = ne'_1$, and $e_2 = me'_2/n$. Thus, expression (19) calculates not only chain friction for a three-stage serial system, but likewise the chain friction associated with a general three-level assembly structure with n second-level supplier stages with homogenous cost factors such that $p'_1 = p_1/n$ and $e'_1 = e_1/n$, and m third-level supplier stages with homogenous cost factors such that $p'_2 = p_2n/m$ and $e'_2 = e_2n/m$.

4. Computational experiments

4.1 Two-stage link friction test bed

The two-stage link friction test bed consists of 63,840 numerical experiments exploring the level of link friction concerning procurement between two simulated supply chain actors over a broad range of environmental factors. The policies associated with local versus central planning, (λ_1, λ_2) versus $(\lambda_1{}^*, \lambda_2{}^*)$, are identified through line searches employing segments versus all of expression (7). Link friction, the outcome of interest, is then calculated with expression (9).

The size of the test bed is driven by the objective of testing each of the environmental factors required in the formulation of expression (7) over a broad range of values. Factor s_1, the fixed cost of replenishment associated with the receiving stage, is varied from 25 to 200 at intervals of 25, while the fixed cost ratio p ranges from 0.25 to 3.0 at intervals of 0.25. Holding cost factor e is tested at values selected from 0.05 to 0.95, at intervals of 0.05, and the factor D is tested from 25 to 220, at intervals of 5. Thus, 7 S_1 levels * 12 p levels * 19 e levels * 40 D levels = 63,840 experimental instances of link friction.

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While the size of the 63,840 experiment test bed is intended to test friction levels over a broad range of environmental parameters, these 63,840 actually model an infinite number of scenarios of both link friction (as discussed in Section 3.2.1), and the chain friction associated with more general two-level structures with homogenous costs at the second level (as discussed in Section 3.2.2).

4.2 Three-stage chain friction test bed

The three-stage chain friction test bed consists of 63,840 numerical experiments exploring the level of chain friction between three simulated supply chain actors arranged in a serial configuration such as pictured in Fig. 1. In these experiments, factors p_1 and p_2, defined in Section 3.3, are assumed to be equal in value, and thus can be represented as environmental factor $p = p_1 = p_2$. Likewise, inventory holding cost factors e_1 and e_2 are set equal to each other, thus a single numerical factor $e = e_1 = e_2$ can be tested. The purpose of this assumption is to create a test bed design in which each of the 63,840 three-stage instances are directly analogous to a two-stage link friction instance. Thus, experimental factors p, e, D, and s_1 were all tested at the same levels described for the two-stage test bed in Section 4.1. In these experiments, the policies (λ_1, λ_2, λ_3) versus (λ_1^*, λ_2^*, λ_3^*), are identified through simple line searches employing expression (18). Chain friction is then calculated with expression (19). As with the two-stage test bed, these 63,840 experiments arguably model an infinite number of scenarios, including more general three-stage structures with the homogenous cost assumptions discussed in Section 3.4.

5. Numerical results

Simulation of the experiments described in Section 4 results in a total of 127,680 experimental instances of friction. Section 5.1 begins by outlining the summary statistics associated with friction levels observed within the two-stage and three-stage test beds. Section 5.2 follows with discussion of the results in terms of implicit optimization, or instances in which no loss is observed through decentralized planning. Section 5.3 explores the influence of the various environmental parameters on friction levels in general, and Section 5.3 focuses on typifying those observed instances of extreme friction, or economic blind spots, in particular.

5.1 Summary statistics
5.1.1 Two-stage link friction.

The 63,840 experimental instances in the two-stage link friction test bed exhibited an average friction of 1.03, as presented in Table 1. 42,277 of these instances, or 66% of the testbed, are examples of implicit optimization, in that an optimal solution to the experimenatal instance proved no better than a decentralized solution, resulting in a link friction of 1.0. However, embedded in the averages displayed in Table 1 are also 1,308 instances of link friction of at least 1.2. The maximum friction value observed was 1.317, indicating a 31.7% penalty in total cost incurred when the buyer stage plans first in that instance. Fig. 2 shows how friction, on average, responds to the ratio s_1/D, an environmental factor first shown to be significant in the earlier study by Simpson (2007). As parameter $D=dh_1/2$, the ratio s_1/D is the equivalent of $(2s_1)/(dh_1)$. Further interpretation of s_1/D will be discussed in later sections.

	s_1=50	s_1=75	s_1=100	s_1=125	s_1=150	s_1=175	s_1=200	Average
p=0.25	1.003	1.002	1.004	1.004	1.007	1.006	1.008	1.005
p =0.50	1.006	1.006	1.010	1.012	1.018	1.018	1.022	1.013
p =0.75	1.009	1.011	1.017	1.020	1.029	1.030	1.037	1.022
p =1.00	1.011	1.014	1.022	1.027	1.037	1.040	1.048	1.029
p =1.25	1.013	1.017	1.026	1.032	1.042	1.047	1.056	1.033
p =1.50	1.014	1.018	1.028	1.035	1.046	1.051	1.059	1.036
p =1.75	1.014	1.020	1.030	1.037	1.048	1.053	1.059	1.037
p =2.00	1.014	1.020	1.030	1.038	1.049	1.053	1.057	1.037
p =2.25	1.014	1.021	1.031	1.038	1.049	1.051	1.055	1.037
p =2.50	1.014	1.021	1.031	1.039	1.048	1.049	1.053	1.036
p =2.75	1.014	1.021	1.031	1.038	1.046	1.048	1.051	1.036
p =3.00	1.014	1.021	1.031	1.038	1.044	1.046	1.049	1.035
Average	1.012	1.016	1.024	1.030	1.038	1.041	1.046	1.030

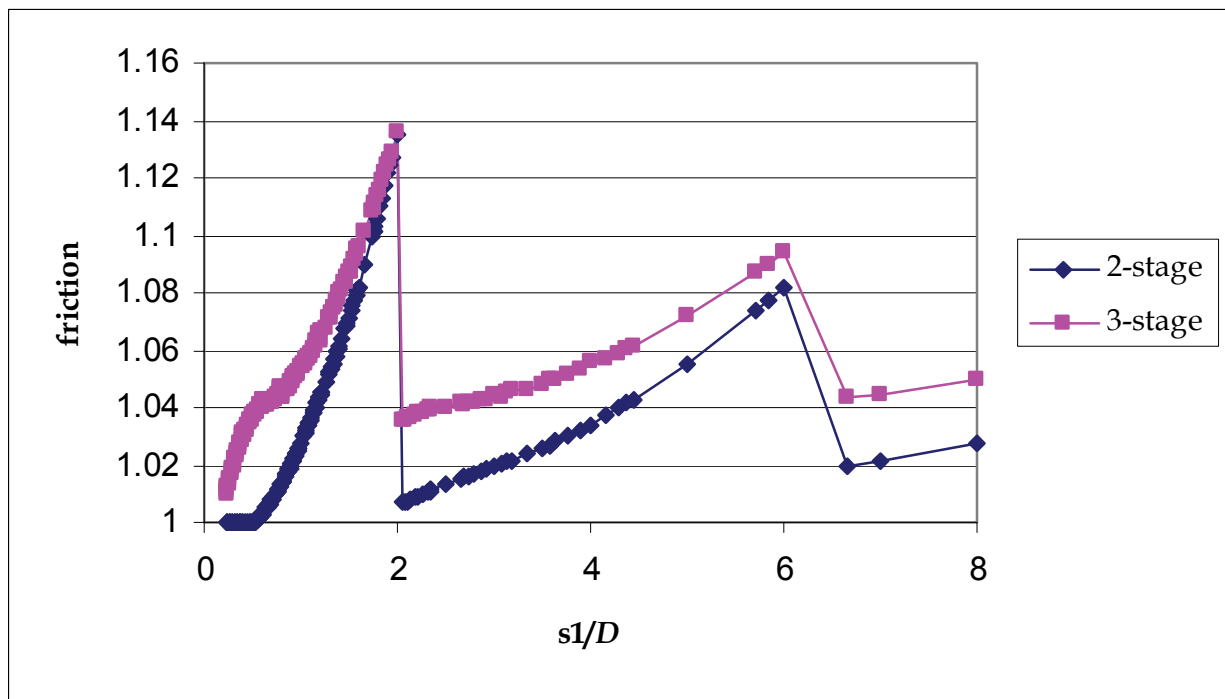Table 1. Link friction associated with two-stage test bed, n= 63,840 experiments

Figure 2. Interaction of link friction and the ratio s_1/D for two- and three-stage test beds.

5.1.2 Three-stage chain friction

The 63,840 experimental instances in the three-stage chain friction test bed exhibited generally higher friction than their two-stage counterparts, as is apparent in Fig. 2. Table 2 provides the summary of friction analogous to that provided for the two-stage cases in Table 1.

	s_1=50	s_1=75	s_1=100	s_1=125	s_1=150	s_1=175	s_1=200	Average
p=0.25	1.004	1.003	1.006	1.006	1.010	1.009	1.012	1.007
p =0.50	1.011	1.012	1.019	1.023	1.032	1.034	1.041	1.025
p =0.75	1.018	1.024	1.037	1.045	1.059	1.065	1.075	1.046
p =1.00	1.024	1.037	1.052	1.065	1.080	1.086	1.091	1.062
p =1.25	1.031	1.046	1.066	1.077	1.087	1.087	1.088	1.069
p =1.50	1.037	1.055	1.074	1.079	1.082	1.080	1.080	1.070
p =1.75	1.042	1.063	1.074	1.074	1.075	1.073	1.074	1.068
p =2.00	1.048	1.065	1.069	1.069	1.070	1.069	1.071	1.066
p =2.25	1.052	1.063	1.065	1.063	1.065	1.066	1.070	1.064
p =2.50	1.055	1.060	1.061	1.060	1.062	1.064	1.068	1.061
p =2.75	1.054	1.056	1.057	1.056	1.059	1.061	1.064	1.058
p =3.00	1.053	1.053	1.054	1.053	1.057	1.059	1.061	1.056
Average	1.036	1.045	1.053	1.056	1.062	1.063	1.066	1.054

Table 2. Chain friction associated with the three-stage test bed, n= 63,840 experiments

Only 26,627 experimental instances resulted in implicit optimization, or 37% less than associated with the two-stage test bed. Friction ranged as high as 1.466 in some instances, with 4,896 instances of at least 1.20, representing 7.7% of all experiments.

5.2 Anticipating implicit optimization
5.2.1 Two-stage test bed
To explore the factors associated specifically with implicit optimization, or the lack of friction, multivariate logistic regression analysis was employed to model that binary condition.   Models associating the presense of implicit optimization with the various environmental factors as independent variables were run in SPSS with binary logistic regression (against the dependent variable of implicit optimization), using the Wald Forward selection method. This method selects only significant variables with the strongest correlation to the dependent variable.   Pseudo r^2 values were then calculated to test the amount of variability explained and concordance and discordance measures were undertaken. As the full model displayed in step 5 of Table 3 indicates, every environmental parameter tested in this study is implicated in the issue of implicit optimization, although the majority of the explanatory power of this sorting scheme is captured in the smaller step 3 model relating implicit optimization to factors e, s_1/D, and p.   As suggested by the findings, as of step 5, implicit optimization can be isolated within the test bed by calculating the logit of probability of friction, $-4.970 + .031s_1 + 1.000p + 5.932e - .033D - .602s_1/D$, for each experimental instance. A negative result predicts implicit optimization. 42,161 experimental instances return such a result, of which 87.7% of these are indeed instances of implicit optimization. The overall friction level of this group is only 1.006, although this model incorrectly indentifies 27 distinct economic blindspots, or instances in which friction was at least 1.20. The balance of the testbed, 21,679 instances, are assumed to involve friction, although 24.5% of these are likewise instances of implicit optimization misclassified by the regression equation.

	Step 1 Coeff.	Step 2 Coeff.	Step 3 Coeff.	Step 4 Coeff.	Step 5 Coeff.
Constant	-2.710*** [.067] (.024)	-4.216*** [.015] (.034)	-5.870*** [.048] (.003)	-7.357*** [.001] (.061)	-4.970*** [.007] (.067)
e	3.750*** [42.520] (.038)	4.415*** [82.722] (.043)	4.791*** [120.447] (.046)	5.033*** [153.455] (.048)	5.932*** [376.914] (.056)
s_1/D		.763*** [2.145] (0.010)	.828*** [2.290] (0.010)	.633*** [1.883] (0.011)	-.602*** [.548] (.017)
p			.796*** [2.217] (.013)	.838*** [2.313] (.013)	1.000*** [2.718] (.015)
s_1				.012*** [1.012] (.000)	.031*** [1.031] (.000)
D					-.033*** [.968] (.000)
Model Chi Square	12125	20628	24890	27402	35473
Nagelkerke r-Square	.240	.383	.447	.484	.591
Model Significance	.000	.000	.000	.000	.000
% Implicit Optimization Correctly Predicted	82.8	86.0	88.6	88.9	89.4
% Instances of Friction >1 Correctly Predicted	44.1	54.6	61.7	64.9	71.8
Overall % Correct	69.7	75.4	79.5	80.8	83.4

Table 3. Results of forward stepwise (Wald) regression model of implicit optimization in two-stage test bed. Odds Ratio listed in square brackets[], with standard error in curved brackets(). *** Significance 1%

Despite the statistical significance of the full model, its associated r^2 is only 59.1%, a disappointing value from the perspective of predictive power. Furthermore, the logitistic regression equation itself is difficult to interpret in broad contextual terms. Nonetheless, this analysis, coupled with a series of graphical observations, suggests a simpler scheme for discriminating between instances of implicit optimization and friction. Approximately 65% of all instances of implicit optimization in the link friction test bed can be identified through the sequential application of three intuitive rules:

- **$s_1/D \leq 0.5$**. This requirement identifies 10,260 experimental instances, each with a link friction of 1.0. $s_1/D \leq 0.5$ implies that $s_1 \leq 0.25dh_1$ indicating that the fixed cost at the first stage is no more than one-quarter the cost of holding a single lot of demand for one period. Restated, this rule identifies those instances in which fixed costs at the buyer stage are so small that the buyer's independent decision to order lot-for-lot is simultaneously the decision a central planner would reach.

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- **s_1/D ≤ .990 - .458*ln(p).** This requirement identifies 13,623 experimental instances (when applied after the first requirement), 7 of which have an associated link friction of 1.003 and the balance being perfect implicit optimization. This rule uses the factor p = s_2/s_1 to collect instances in which the environmental cost factors associated with the buyer are significantly greater than that of the supplier, thus there is little or no loss to allowing the buyer to dictate the plan.
- **s_1/D ≤ 1 - .507*e.** Applying this requirement after the two rules identifies 3,527 experimental instances with an average friction of 1.0007, as 96% of this group represents implicit optimization. This rule reflects the distinctly linear inflammatory effect that factor e (the ratio h_2/h_1) has on friction.

Application of these three rules divides the link friction test bed into two groups: the 27,410 instances identified by the rules, 99.5% of which are examples of implicit optimization, and the 36,430 remaining instances possessing overall average friction of 1.052.

5.2.2 Three-stage test bed

As observed earlier, friction ran higher and implicit optimization was not as common in the three-stage chain friction experiments. Naïve application of the three rules developed to discriminate implicit optimization in the link friction case yields less impressive results when applied to the three-stage results: the analogous "implicit optimization group" of 27,410 experimental instances would be comprised of only 65% instances of implicit optimization and possess an overall average friction of 1.026, as opposed to the overall average of 1.00009 for its two-stage counterpart.

Employing multivariate logistic regression using the Wald Forward selection method to model implicit optimization in the three-stage data does reveal some insight, highly similar to the two-stage results detailed in Table 3. The resulting logistic regression equation in the three-stage case, logit of probability of friction = -3.282   + .013 s_1 + 1.149p + 4.389e - .013D - .221 s_1/D, sorts the test bed into a group of 29,050 instances of which 75.4% are implicit optimization, and a group of 34,790 instances containing only 13.6% implicit optimization. Like the previous two-stage model, this discrimitory ability, with its associated r² of 44.6% in the three-stage case, is surpisingly disappointing from the perspective of anticipating future occurances of implicit optimization.

In contrast, a tightening of the simplified two-stage rules developed out of the original two-stage regression analysis does yield additional insight into implicit optimization in the three-stage case.   To discriminate between the majority of the instances of implicit optimization versus non-trivial chain friction in the three-stage test bed, apply the following three rules sequentially:

- **s_1/D ≤ 0.5 and s_1p_1/De_1 ≤ 0.5**. 2,007 experimental instances fit this description, each exhibiting implicit optimization. These are environmental parameters such that both the first and second level stages have insubstantial fixed costs relative to inventory costs, and will be ordering lot-for-lot regardless of whether their schedules are decided independently or centrally.
- **s_1/D ≤ .337 - .587*ln(p).** This requirement identifies 3,905 experimental instances with an average chain friction of 1.0003, 97% of which being examples of implicit optimization. This restriction identifies those experimental instances for which the relevant costs at the first level are substantially greater than those at the second and

third levels, thus "top-down" planning does little to damage system performance. Note that $p = p_1 = p_2$ in this test bed.

- **$s_1/D \leq 2 - 3.889*e$.** Subsequent application of this cut identifies 11,396 experimental instances with an average friction of 1.003, as 75% of these instances represent implicit optimization. Note that $e = e_1 = e_2$ in this test bed.

Application of these three rules divides the three-stage chain friction results into two groups, the first being 17,308 instances with an average chain friction of 1.002, 83% of these being instances of implicit optimization. The balance of the chain friction test bed, 46,532 instances, now have an average friction level of 1.074, but 26% of these instances are likewise examples of implicit optimization.

5.3 Friction as a response to environmental parameters
5.3.1 The influence of the ratio s_1/D

Fig. 2 illustrates the distinct influence of the ratio s_1/D on the issue of friction in these supply chain structures, and this ratio has already proven invaluable to modeling much of the implicit optimization observed in the test beds. As discussed previously in Section 5.1.1, the ratio s_1/D can be restated as $(2s_1)/(dh_1)$. This breakdown of the ratio is useful when one considers that the worst cases of friction in both test beds, economic blindspots that implied up to 46% increase in system costs through decentralized planning, all occured when s_1/D was near or equal to a value of 2.0. Restated, average friction was peaking in Fig. 2 when $(2s_1)/(dh_1) = 2$, or $s_1/(dh_1) = 1$, or $s_1 = dh_1$. In other words, friction is observed to peak as the cost of holding one lot of external demand at the first level balances with the fixed cost of replenishment at that level. This is significant in that this represents a scenario in which the independent planner is logically *indifferent* to placing an order for that demand lot versus consolidating that requirement with the order for one period previously. In these simulations, it was assumed that, given indifference, the decision-maker would elect to place the additional order, acting on the general principle of avoiding inventory.

Fig. 2 suggests that friction peaks again to a lesser extent when s_1/D achieves a value 6.0, which implies $s_1 = 3dh_1$. Here the independent decision-maker at the first level is indifferent with respect to cost between a policy of ordering every two periods ($\lambda_1 = 2$) versus every three periods ($\lambda_1 = 3$), and thus is assumed to implement the former policy. An earlier, preliminary study in Simpson (2007) suggested further but lesser peaks when s_1/D neared values of 12 and 20, consistent with scenarios in which the first level decision-maker is economically indifferent between replenishing every third versus fourth period and fourth versus fifth period, respectively. However, Simpson (2007) also presents evidence that this intriguing influence is highly dependant on the condition of smooth demand, as modelled here. Intuitively, these points of indifference must be experienced repeatedly to induce the associated inefficiency, and highly dynamic demand with its resulting variable order cycle conditions rapidly mute the effect.

5.3.2 The influence of parameters *p* and *e*

Fig. 3 illustrates the average response of two-stage link friction to the two other environmental parameters observed to have profound influence on that test bed: the ratios *p* and *e*, representing the ratios of the second level to first level's fixed costs and holding

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costs, respectively. Each point in this surface represents the average friction for n=280 experiments across all factor levels of s_1 and D for given levels of p and e, and this response surface is very closely modeled by the expression z (average friction) = $1.0 + 0.086e^2 + 0.002p^2 - 0.001p$ (r^2 = .843).
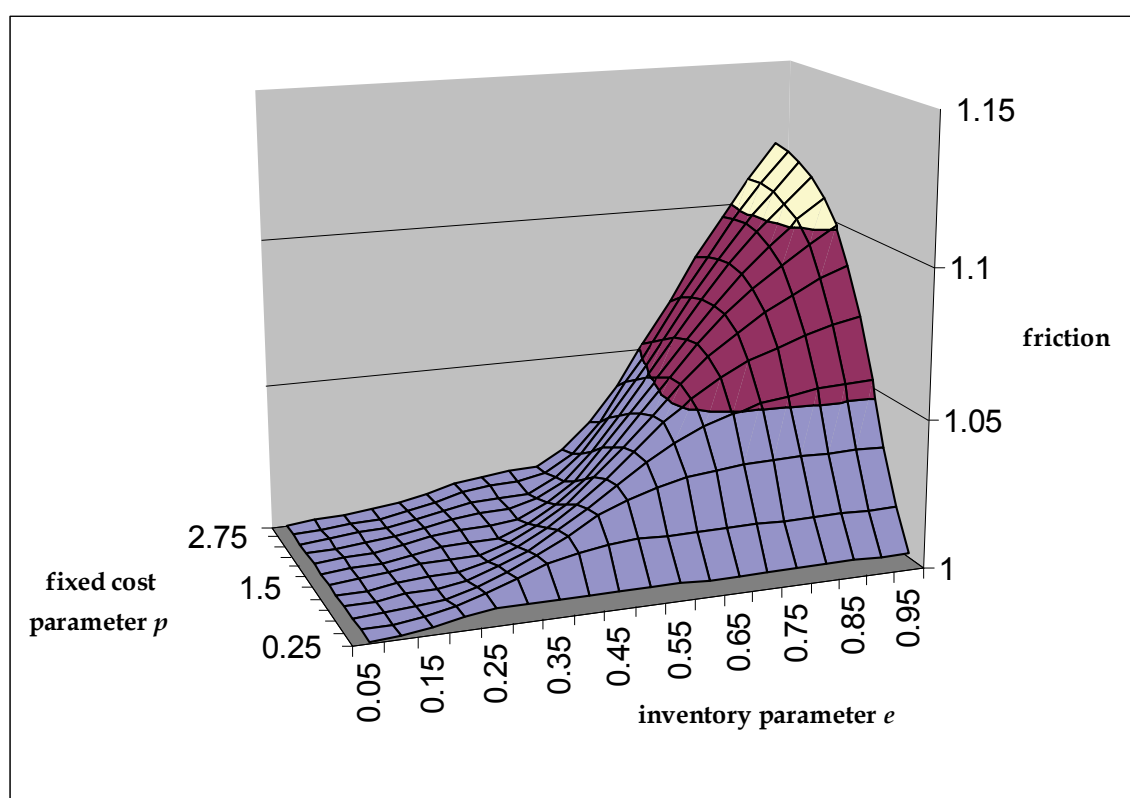

Figure 3. Response surface formed by average friction levels across environmental factor levels p and e for two-stage test bed.

Observation of the three-stage test results suggests similar relationships between these parameters and the broader effect of chain friction. In the case of the three-stage results, the response surface is closely modelled by z (average friction) = $1.0 + 0.351e^2 - 0.182e - 0.011p^2 + 0.043p$ (r^2 = .879). Furthermore, the *percent* increase between three-stage chain friction instances and their corresponding two-stage counterparts describes a highly similar response surface with respect to p and e, as shown in Fig. 4.

Further insight can be gained by looking at these two environmental parameters in isolation. Fig. 5 shows the distinctly "inflammatory" effect of the inventory parameter e: the higher the levels of this factor, the higher the observed levels of friction. Fig. 5 also indicates the intuitive result that this phenomenon is compounded by the addition of another level of planning, as the disparity between the average friction in the two-stage and three-stage experiments widens with increasing values of e.
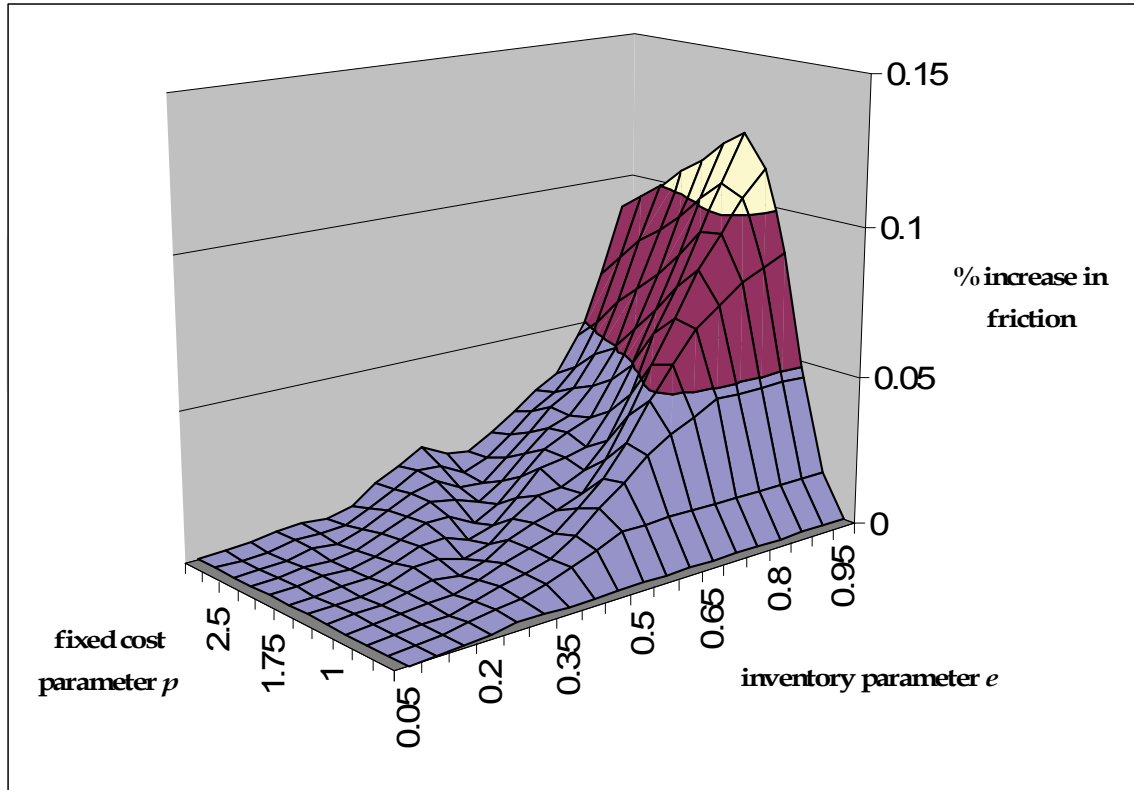
Figure 4. Response surface formed by average percent increase in friction levels when comparing three-stage to two-stage experimental instances, across environmental factor levels *p* and *e*.
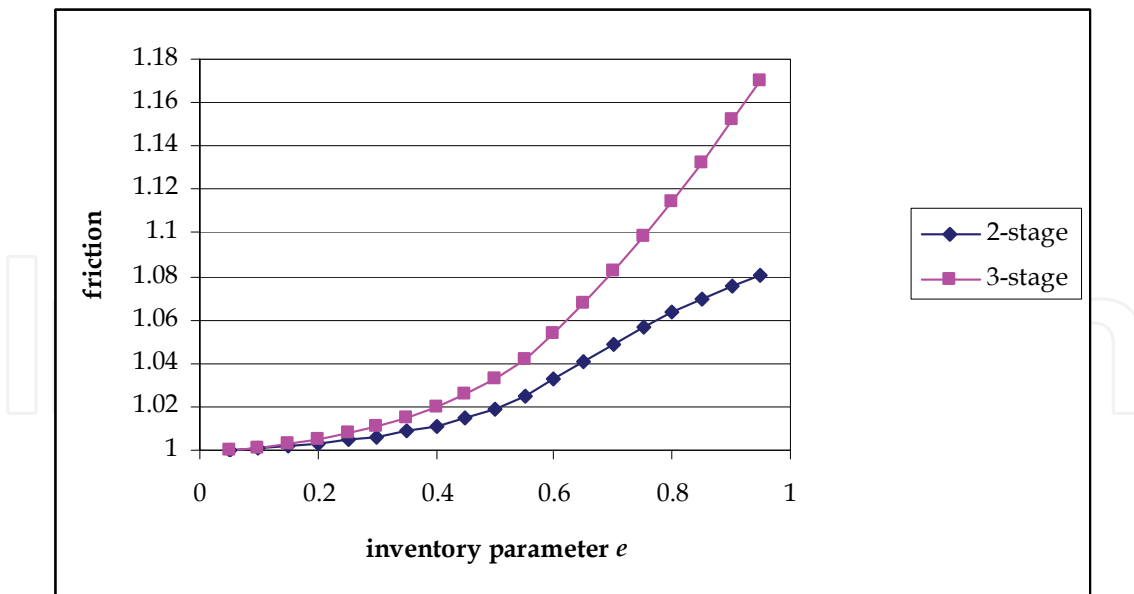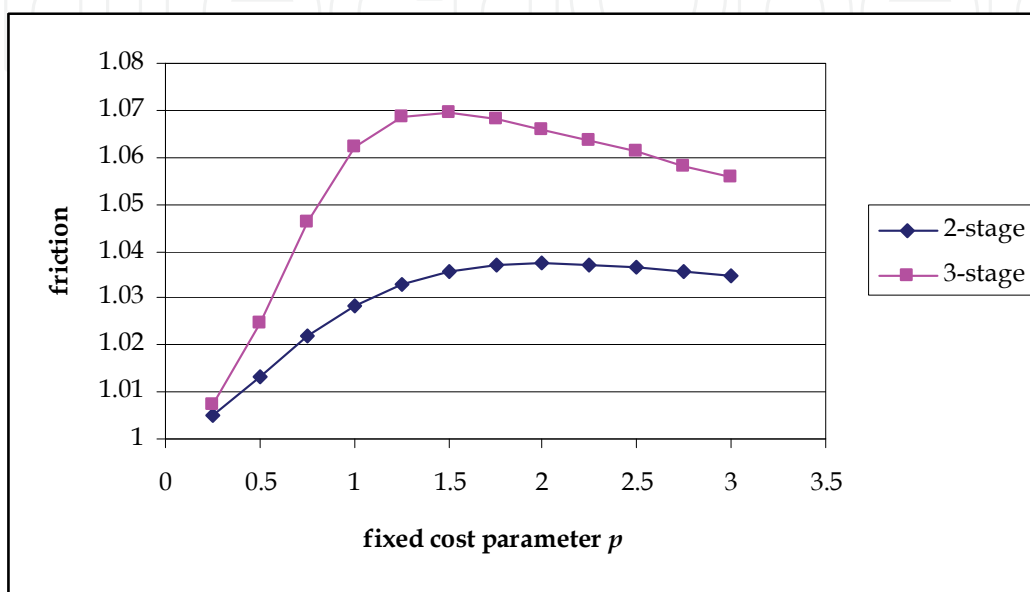

Figure 5. Average friction levels across factor level *e* for the two-stage versus three-stage results (n = 3,360 instances for each data point).

Fig. 6 illustrates average two-stage and three-stage response to the fixed cost parameter *p*, suggesting similar polynomial relationships with the issue of friction, but nonetheless in

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contrast with the ratio e. Unlike the inventory parameter e, the results do not support a strictly increasing relationship between parameter p and resulting friction.   Rather, the highest average levels of friction witnessed on Fig. 6 are associated with the values of 1.5 and 2.0, and inspection of the data reveals that the absolute highest values of friction, or economic blind spots, are associated with somewhat lesser values of p, as will be discussed in the next section. Likewise, unlike factor e in Fig. 5, the disparity between the two-stage and the three-stage results does not appear to be strictly increasing with the value of fixed cost parameter p.

Figure 6. Average friction levels across factor level p for the two-stage versus three-stage results (n = 5,320 instances for each data point).

5.4 Anticipating economic blind spots

As discussed earlier, economic blind spots are so named because independent supply chain partners could potentially fail to "see" substantial savings achievable through centralized coordination. Interestingly, the findings in the previous section suggest these instances of extreme friction are associated with the same environmental parameters in both the two-stage and the three-stage test bed.   In each case, the worst of the economic blind spots are confined to instances in which the following conditions occur simultaneously:

- $.75 \leq p \leq 1.25$
- $e \geq 0.9$
- $1.33 \leq s_1/D \leq 2.0$

These three conditions hold true for 282 experimental instances in each test bed. In the case of the two-stage test bed, average friction for this sub-group is 1.219 (in contrast to 1.030 for the entire test bed), containing of all instances of friction of at least 1.30. Within the three-stage test bed, average friction of these 282 instances is 1.310 (compare to 1.054 for all three-stage experiments), containing only 17% of the 880 three-stage experiments with chain friction of at least 1.30, but 100% of the 47 instances in which chain friction was at least 1.40.

6. Observations and conclusions

The results of this simulation study strongly suggest that certain inter-organizational supply chain partnerships could prove extremely vulnerable to the inherent inefficiency of decentralized procurement, while others could function quite comfortably in that mode, dependent on environmental factors. Thus, it is not surprising how, as discussed in Section 1, much of the existing literature exploring the relative merits of centralized planning and coordination reports distinctly mixed results. Indeed, it now becomes apparent how potentially dangerous it may be to draw conclusions from an average observation of interest in this context- the average loss from decentralized planning across these 127,680 experiments was only 4%, but this summary conceals the presence of distinct economic blind spots ranging as high as 46% increases in system-wide costs.

The new measures of link friction and chain friction discussed in Section 2 and the associated conditions of implicit optimization and economic blind spots assist in focusing attention on the relative merits of centralized planning, to rationally weigh these merits against any difficulties present in a given inter-organizational supply chain. Even in the context of the particular simplifying assumptions incorporated into the formulations of Section 3, resulting friction levels showed strong relation to both the environmental factors tested here, and complex interactions of those factors. The powerful influence of the cost factors p and e, both in the creation of instances of implicit optimization and in driving friction upwards, has interesting implications for simulation study design as well as practice. As an example, an earlier study of Simpson (2001) examined centralized versus decentralized procurement across a three level system of substantially greater complexity than the linkages modelled in Section 3, including features such as multiple products, joint order-picking costs, and time variant demand. Nonetheless, a highly centralized scheduling technique outperformed intuitive, pull-style planning by an average of only 1.8% across one group of 900 experiments, and yet this same technique lowered costs by an average of 31.5% within another group of 900 experiments. In hindsight, the only environmental difference between these two groups were the factors identified here as e_1 and e_2, these values being substantially higher in the latter case.

Section 5.4, outlining the environmental factor values most commonly associated with economic blind spots in both test beds, addresses the question posed earlier: *when* would a substantial effort to restore the operations research perspective of a system make a substantial difference in that system's performance? All three of the conditions identified in Section 5.4 have compelling interpretations. The first two, $0.75 \leq p \leq 1.25$ and $e \geq 0.9$, are indicating those experimental instances in which the fixed replenishment costs and the inventory holding costs of each of the supply chain stages are the *most similar to each other*. Restated, supply chains linking independent organizations with highly similar cost structures may see the greatest benefits from centralized interventions, or suffer distinct cost increases from independent behaviour.

However, to locate the most dramatic blind spots in this simulation study, Section 5.4 coupled the conditions of similar fixed and holding costs with a third condition, $1.33 \leq s_1/D \leq 2.0$. As discussed earlier in Section 5.3.2, the ratio s_1/D was found to be highly influential on the level of friction within a simulation, with the greatest degree of influence observed when this ratio's value was at or near a value of 2.0. This condition represents a scenario in which a buyer's fixed and inventory costs balance such that, when acting independently, this stage would be indifferent or nearly indifferent to recieving lot-for-lot replenishment

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versus replenishing two period's worth of demand requirements with each in-bound shipment. Thus, the presence of this condition of independent indifference to holding one period's worth of inventory based on cost (it is assumed that the buyer stage would otherwise favor no inventory simply on principle) strongly suggests that effort should be invested in identifying the centralized solution on behalf of system-wide performance.

As discussed earlier, there is evidence suggesting that the particular influence of s_1/D is not likely to hold beyond the conditions of level demand simulated here, in that these moments of indifference must be repeated through time to generate the inefficiency. Arguably, this is not as confining an assumption as it may first appear: supply chains supporting Just-in-Time (JIT) production will likely be supporting level production schedules, resulting in level procument patterns across in-bound partnership links. Furthermore, as pointed out by Gavirneni (2001), much of the recent re-engineering of supply chain partnerships has been in support of JIT inventory management. Thus, the issues of characterizing and identifying those supply chain relationships most vulnerable to decentralized treatment should not be considered simply a promising direction for further research, but a genuine and on-going need in the successful management of the increasingly complex systems observed in the field.

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Supply Chain

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Traditionally supply chain management has meant factories, assembly lines, warehouses, transportation vehicles, and time sheets. Modern supply chain management is a highly complex, multidimensional problem set with virtually endless number of variables for optimization. An Internet enabled supply chain may have just-in-time delivery, precise inventory visibility, and up-to-the-minute distribution-tracking capabilities. Technology advances have enabled supply chains to become strategic weapons that can help avoid disasters, lower costs, and make money. From internal enterprise processes to external business transactions with suppliers, transporters, channels and end-users marks the wide range of challenges researchers have to handle. The aim of this book is at revealing and illustrating this diversity in terms of scientific and theoretical fundamentals, prevailing concepts as well as current practical applications.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

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