# E-Business and Management Science: Mutual Impacts (Part 2 of 2)

Arthur M. Geoffrion • Ramayya Krishnan
*Decisions, Operations, and Technology Management, John E. Anderson Graduate School of Management, University of California, Box 951481, Los Angeles, California 90095-1481*
*The Heinz School of Public Policy and Management, Carnegie Mellon University, Pittsburgh, Pennsylvania 15213*
*ageoffri@anderson.ucla.edu • rk2x@cmu.edu*

This concludes a two-part commentary on management science and e-business, the theme of this two-part special issue. After reviewing the topical clusters that give organization to both parts, we sketch the papers appearing in this second part from the perspective of two key questions concerning the impact of the emerging digital economy on management science research: What fundamentally new research questions arise, and what kind of research enables progress on them. We then offer summary comments on the second question based on the papers in both parts. The principal conclusions are that, in meeting the challenges posed by the digital economy, management science researchers are (a) making greater use of parts of economics and computer science/information technology, and (b) exploiting the improving productivity advantages of empirical and methodological work in comparison with theoretical work.
(*E-Business; Information Infrastructure; Online Markets; Management Science*)

## 1. Introduction

This continues our commentary on management science and e-business, the subject of this two-part special issue.

As explained in the first part of this commentary (Geoffrion and Krishnan 2003), the papers in Part 1 (*Management Science* 2003) all spring from the transformation of the digital economy's information infrastructure brought about by technological progress in computers and communications (especially the Internet). The papers in Part 2 all deal with aspects of online markets:

• *Auctions* (Pinker et al. 2003, Pekeč and Rothkopf 2003, Snir and Hitt 2003, Carr 2003, Beil and Wein 2003). These papers study auction design. Pinker et al. (2003) survey noncombinatorial single- and multi-unit auctions with an emphasis on bidder behavior and lot-sizing issues in business-to-consumer (B2C) and consumer-to-consumer (C2C) settings; Pekeč and Rothkopf (2003) survey the theory, issues, and tradeoffs arising in combinatorial auctions; Snir and Hitt (2003) and Carr (2003) focus on procurement markets with high bid-preparation and bid-evaluation costs; and Beil and Wein (2003) on a new mechanism for multiattribute procurement auctions.

• *Other Price-Discovery Mechanisms* (Anand and Aron 2003, Hann and Terwiesch 2003). These papers study other specific price-discovery mechanisms in online markets. Anand and Aron (2003) address group buying as an alternative to conventional posted prices, and Hann and Terwiesch (2003) address name-your-own-price retailing.

• *Estimating Online Market Benefits* (Brynjolfsson et al. 2003). This paper develops a method for

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estimating the consumer surplus gains from increased product variety.

• *E-Procurement* (Kleindorfer and Wu 2003). This paper surveys its topic from a highly integrative vantage point that stresses risk management.

Papers are printed in the above order.

In summary, the papers fall into the natural thematic groupings of Table 1.

As detailed last month in Part 1, two key questions serve to focus both parts of this commentary. Both questions are framed in terms of a process view of management science that considers *research products* (including archived data, hypotheses, algorithms, insights and findings from models, modeling paradigms, software, theory, and tools and methods) to be the result of *research work* (empirical, methodological, theoretical, or precursive) stimulated by *research questions*. The two key questions are:

*Q1 (Research Questions).* What fundamentally new or revitalized research questions of importance to managers are arising from the emerging digital economy?

*Q2 (Research Work).* What kind of research work is being done to make progress on the research questions just identified?

The next section sketches the nine papers published in this issue from the perspective of these questions. Section 3 gives our summary comments on Q2 based not only on these papers, but also on the papers appearing in last month's special issue and in our earlier special issue of *Interfaces* on e-business (*Interfaces* 2001). Our summary comments on Q1, based on the same set of papers, already appeared last month (note that all of the papers in this issue are mentioned in that commentary).

**Table 1 Thematic Organization of Parts 1 and 2**

| Theme | Article |
|---|---|
| *Information infrastructure* (*Part* 1) | |
| From voluminous data to decisions | Elmaghraby and Keskinocak (2003)* |
| | Spann and Skiera (2003) |
| | Padmanabhan and Tuzhilin (2003)* |
| | Murthi and Sarkar (2003)* |
| | Boyd and Bilegan (2003)* |
| Strategic interactions | Swaminathan and Tayur (2003)* |
| | Dellarocas (2003)* |
| | Murthi and Sarkar (2003)* |
| | Elmaghraby and Keskinocak (2003)* |
| Network infrastructure | Datta, Dutta, Thomas, and VanderMeer (2003)* |
| *Online markets* (*Part* 2) | |
| Auctions | Pinker, Seidmann, and Vakrat (2003)* |
| | Pekeč and Rothkopf (2003)* |
| | Snir and Hitt (2003) |
| | Carr (2003) |
| | Beil and Wein (2003) |
| Other price-discovery mechanisms | Anand and Aron (2003) |
| | Hann and Terwiesch (2003) |
| Estimating online market benefits | Brynolfsson, Hu, and Smith (2003) |
| E-procurement | Kleindorfer and Wu (2003)* |

*Note.* Survey articles are indicated by an asterisk.

## 2. The Papers: Online Markets Cluster

For each paper, after a brief introduction, we sketch the fundamentally new or revitalized management-oriented research questions that it brings to light. We then sketch the kinds of research work that it exhibits, with particular attention to contributions from other disciplines.

### 2.1. "Managing Online Auctions: Current Business and Research Issues" (Pinker et al. 2003)

Online auctions differ from their physical counterparts in important ways, including the following: reduced transaction costs; the ease of setting their duration to suit the characteristics of the product or service being auctioned; the ability of participants to join at any time; the relative ease with which identities can be switched online; the use of advanced information technology to permit auction participants to describe complex products or services; and the ability to dynamically alter auction lot sizes. The focus of this paper is on understanding the implications of these characteristics for bidding behavior as well as for auction design, in single- and multiunit (multiple units of the same good) auctions.

*Research Questions.* The distinctive characteristics of online auctions generate new questions about equilibrium bidding strategies, revenue expectations, and auction design. Of particular interest are the following: What is the impact of design parameters such as minimum bid increment and reservation prices (secret or revealed to all participants) on realized price in a single-unit auction? In a multiunit auction, what is the optimal auction design in terms of the number of auctions to hold, the lot sizes that should be put up in each such auction, and the duration of each such auction? Empirically, what are the long-term costs and benefits in a business-to-business (B2B) context of online auctions as a procurement channel in contrast to contracting through a traditional RFQ/RFP process?

*Research Work.* This paper surveys pertinent empirical and theoretical work in the auction theory, management science, and information systems literatures. Given the ease with which real data can be collected from bidding logs in online auctions, empirical research using econometric methods can readily answer questions about bidding behavior under a variety of auction design parameters. An example is the analysis of bid time-stamps and valuations to determine the revenue impact of arrival patterns of bids with respect to hard and soft deadlines. Multiunit auctions do not conform to the assumptions used in auction theory as developed by economists. Theoretical and empirical research for these auctions requires taking bidder behavior and lot-size (and associated) inventory considerations into account, necessarily drawing on the rich literature in economics on auction theory and in management science on inventory theory. An example of such interdisciplinary work for repeated auctions is the use of empirically estimated bidder valuation distributions with a Bayesian learning mechanism to make optimal lot-sizing decisions.

Finally, recent work has discussed some potential problems with online auctions such as the significant costs associated with switching suppliers and the lack of incentives for suppliers to make relationship-specific investments. Some of these issues can be addressed using auction markets that take dimensions other than price into account (e.g., quality and reliability). Theoretical and empirical research is required to understand the short-term and long-term costs and benefits of B2B procurement auctions.

### 2.2. "Combinatorial Auction Design" (Pekeč and Rothkopf 2003)

Combinatorial auctions are a particular type of simultaneous multiunit auction in which all-or-nothing bids for combinations of items are submitted and the auction mechanism allocates sets of items to winners. Such auctions are appropriate when value interactions arise from complementarity among some items. Their practical application has been limited by the computational difficulty faced by bidders in specifying bids and by auctioneers in determining winners.

*Research Questions.* The deployment of combinatorial auctions has energized considerable work on efficient algorithms and heuristic methods for solving the winner-determination problem. Since the formulation of this problem depends on the types of bids permitted, new questions arise concerning the interaction between the bid specification restrictions and the complexity of winner determination. For example, what is the tradeoff between the expressive power of the bid specification language and the difficulty of winner determination? Can experimental evidence illuminate the usability of bid specification languages? To what extent can user interfaces incorporate decision support technologies to mitigate the complexity of bid preparation?

Typical questions posed about auctions such as equilibrium bidding strategies and revenue expectations are also of interest for combinatorial auctions. Of particular interest are bidding strategies in real combinatorial auctions, in light of the incentive to coordinate efficiently. Since signaling through bidding can facilitate such coordination but also facilitate collusive behavior, how is this accomplished in the absence of face-to-face interactions? In addition, other auction questions that are easy in simple auctions, such as resolving ties, provide design dilemmas in combinatorial auctions.

*Research Work.* This paper surveys the operations research, computer science, and economics literatures on combinatorial auction design. The winner determination problem in these auctions is a combinatorial optimization problem. Since alternative bid specification languages and mechanisms (e.g., simultaneous progressive auctions) result in different winner-determination problems, this topic has generated considerable methodological work by operations researchers, especially those with expertise in integer programming. Computer scientists have also developed algorithms and efficient heuristics to address these problems and have analyzed their computational complexity. Work on issues pertaining to mechanism design, equilibrium bidding strategies, and revenue expectation naturally draws on game theory. Behavioral economists have conducted experiments to understand the behavior of bidders. While it is clear that game-theoretic mechanism design is important to all types of research in this area, the authors also stress that much existing theoretical work neither analyzes practically relevant combinatorial auctions nor properly informs their practical design (see Roth 2001 on this point). Thus, opportunities exist to make major contributions in this area using a combination of theoretical, empirical, and experimental approaches.

### 2.3. "Costly Bidding in Online Markets for IT Services" (Snir and Hitt 2003) and "Note on Online Auctions with Costly Bid Evaluation" (Carr 2003)

Online markets are used increasingly to procure services as well as goods. These markets use reverse auctions with a buyer issuing an RFP and then evaluating bids submitted by vendors. These papers study such a market for which, due in part to lack of standardization of the services covered, both bid preparation and bid evaluation are costly.

*Research Questions.* The rapid growth in online markets for IT services revitalizes interest in the following questions. What should the buyer and vendor strategies be in such markets? What is the role of bid-evaluation costs in determining these strategies? Do higher-value projects tend to attract lower-quality providers? Do higher-value projects tend to attract more bids? Are buyers with higher-value projects less likely to award them via such auctions?

*Research Work.* Both papers use game theory to model bidding behavior and bid-evaluation behavior in equilibrium. Snir and Hitt (2003) model the case where bidding is costly and there is variation in the vendor's cost and quality. They do not explicitly model the case where bid evaluation is costly. Carr (2003) does so and establishes the more general result. Snir and Hitt (2003) draw on their results and Carr's to develop two hypotheses. They perform econometric tests on real data (nearly 5,000 observations) from an active online market for software development services and find support for their hypotheses. Such data, rarely available for offline markets, illustrates once again the generally data-rich environment for research on Internet-enabled business processes.

### 2.4. "An Inverse-Optimization-Based Auction Mechanism to Support a Multiattribute RFQ Process" (Beil and Wein 2003)

Firms are increasingly using multiattribute, multiround procurement auctions that evaluate bids on cost and noncost criteria such as quality, lead time, contract terms, supplier reputation, and incumbent switching costs. Typically a scoring rule is announced for comparing bids that essentially reduces the multiple bid attributes to a single composite dimension. The reduced transaction costs and the ease of collecting information from and about individual bidders in an Internet auction make multiround auctions more cost effective. They also make sophisticated auction designs more practical than is possible for offline auctions.

*Research Questions.* This paper exploits that opportunity and e-RFQ practices that permit scoring rules to be changed from one round to the next by asking a new question: How can the scoring rule be altered between bidding rounds so that the bidders' cost functions eventually can be deduced, thereby enabling maximization of the buyer's utility in a properly designed final round of bidding? The authors solve this problem under the assumption that bidders are myopic and do not bid strategically. Testing this behavioral assumption using real-world data or experimental data is an interesting and important question.

*Research Work.* The design of auctions has been dominated traditionally by a branch of economics (mechanism design) that assumes perfectly rational bidders and imposes incentive-compatibility constraints. As noted, this paper deviates from this tradition. The method it develops is based on inverse optimization—a technique for deducing unobserved parameters of an optimization problem from observed solutions—and is the first application of this technique to auctions. The underlying behavioral assumption could be tested empirically by analyzing either bidding logs from real multiattribute e-RFQ auctions or bidding logs from carefully constructed experiments.

### 2.5. "Group Buying on the Web: A Comparison of Price-Discovery Mechanisms" (Anand and Aron 2003)

Group buying has been around a long time, but the Web makes it much more practical than before. Indeed, this paper demonstrates at some length that it is quite widespread, in spite of the failure of some early, high-profile, online group-buying sites. Essentially, group buying offers a price-quantity schedule such that the price paid by any customer is not based on the quantity they order, but rather on the total amount that all customers order.

*Research Questions.* Different assumptions about demand uncertainty, production economies of scale, and the sequence of pricing versus production decisions lead to different practically relevant market scenarios. Questions of revitalized importance under various scenarios include: What is a monopolistic seller's profit-maximizing price-quantity schedule? How does the performance of an optimal group-buying schedule compare relative to the simpler posted-prices mechanism and under what conditions is it better? How do the answers to these questions change in the presence of competition?

*Research Work.* This paper draws on two distinct literatures: the information economics literature on price discovery under demand uncertainty, and the operations management literature on quantity discounts. It uses standard analytic modeling methods and game theory to develop theoretical predictions about group buying and the conditions under which a monopolist should prefer it over posted prices. As the first rigorous attempt to develop theory about group buying, it also generates new questions and hypotheses. Empirical research using real-world demand data from group-buying sites can be used to test the theoretical predictions of the model. There are also opportunities to move this work closer to implementation by drawing on operations research methods to determine optimal price-quantity schedules under realistic demand scenarios.

### 2.6. "Measuring the Frictional Costs of Online Transactions: The Case of a Name-Your-Own-Price Channel" (Hann and Terwiesch 2003)

Conventional wisdom has it that transaction costs and search costs are much smaller in online markets than in offline ones, but these costs need not be negligible. Frictional costs for a manual bidding process turned out to be surprisingly significant in this study—about 3.5 euros on an MP3 player and 6 euros on a PDA. The next paper (Brynjolfsson et al. 2003) deals with the complementary matter of the benefits of online markets.

*Research Questions.* Consider the frictional costs bidders encounter in an online "name your own price" channel where they may revise and re-bid during the course of negotiating with a seller (for example, Priceline.com allows consumers to re-bid for long-distance phone cards). What is the magnitude of these frictional costs? How do they affect bidding behavior? Will the ability to revise and re-bid result in many rounds of bidding as they seek to learn the reservation price of the seller and thereby dissipate his information rents? How can knowledge of these costs be useful to the seller for improving the design of the user interface? Such questions, largely about the costs associated with online markets, did not exist prior to the advent of these markets.

*Research Work.* This paper draws on economics, operations research, and econometrics, and combines theoretical and empirical work. The frictional costs are estimated based on a dynamic programming model of individual bidding behavior. Subsequently, demographic factors (education, income) and experience with the website are investigated as drivers of frictional costs. Since the real-world retailer that provided the data for the study had changed from a policy that did not permit bid revision to one that did, the work uses the data from this quasi-natural, Internet-based experiment to test the revenue implications of the policy change.

### 2.7. "Consumer Surplus in the Digital Economy: Estimating the Value of Increased Product Variety at Online Booksellers" (Brynjolfsson et al. 2003)

In many common product categories, Internet retailers are able to carry a substantially larger variety of products than could be carried in brick-and-mortar stores. This is so because inventory can be avoided at the retail level, where it would be both expensive to carry and confined by the walls of the retail outlet.

*Research Questions.* Estimating the impact of this increased product variety on consumer surplus is a research question to which the Internet gives new urgency. This question is important to Internet retailers, investors, and entrepreneurs who want to identify and quantify the value proposition from Internet-channel business models. It is also relevant for governments analyzing the impact of Internet markets on consumers, on economic measures such as the consumer price index, and on the changing nature of economic welfare itself. In addition, there are questions relating to operational issues. As product variety increases, the retailer may be able to exploit it to provide a higher-quality interaction with the user through superior recommendations or co-marketing opportunities. What should variety be in terms of breadth or depth of listings in a given category to maximize profits or welfare?

The consumer surplus generated by the increased product variety of online booksellers was, surprisingly, found to be "7 to 10 times as large as the consumer welfare gain from increased competition and lower prices in this market."

*Research Work.* The chosen research question called for a highly resourceful, empirical approach that extended a known econometric method for estimating consumer welfare. This method is not typically in a management scientist's toolkit. There are other industries (e.g., music CDs, movie rentals, computer software, and consumer electronics) where the extended method may be applicable to the same important research question. Finally, it may also be used to study markets for products that only become viable due to the ability to virtually stock a large variety of products on the Internet.

### 2.8. "Integrating Long-Term and Short-Term Contracting via Business-to-Business Exchanges for Capital-Intensive Industries" (Kleindorfer and Wu 2003)

Prior to the emergence of online B2B exchanges, the focus in procurement was on negotiation and traditional forms of contracting. B2B exchanges and spot markets offer firms an opportunity to fundamentally rethink operational decisions on capacity and production. They provide a way to improve operational performance through better supply-demand coordination, while still preserving the value of longer-term contractual relationships and investment decisions. This is particularly important for capital-intensive industries where the out-of-pocket costs of excess capacity and the opportunity costs of underutilized capacity are high. These benefits of B2B exchanges and spot markets are made possible through the risk management possibilities of options and forwards.

*Research Questions.* These risk management opportunities, enabled by online exchanges and spot markets through options on capacity and output, raise new research questions. How can supply and demand best be coordinated in the presence of options-based instruments? What are the new types of options and the mechanisms for their valuation for nonstorable and storable goods? Additional questions are industry specific. For example, for the electric power industry, what should be the optimal set of purchasing contracts to fulfill retail demand while also engaging in speculative trading for profit?

*Research Work.* This paper, like Anand and Aron (2003), argues for the fusion of two previously separate literatures, pertinent parts of operations management and financial economics (particularly option theory). This fusion will provide the means to study the new research questions relating to decisions concerning capacity, capital asset utilization, contracts, demand management, fulfillment, technology choice, and risk management. Surveying the mostly theoretical work on these questions, the paper notes that the desired disciplinary integration is not without challenges. The operations management literature does not adopt such financial basics as efficient market theory and the capital asset pricing model, and the financial economics literature does not take into account operational realities such as capacity limits and cost heterogeneity. The management science community has only begun to become aware of the opportunities promised by successful fusion.

## 3. Research Work: Important Changes Under Way

In the first part of this commentary and in the previous section, we saw that the digital economy is giving rise to many fundamentally new research questions. Here we offer summary comments relating to Q2—how research work is changing in response to these new research questions—from the vantage point of the papers in this issue, in its companion, and in our earlier special issue of *Interfaces* on e-business. We have two main observations.

### 3.1. The Changing Mix of Donor Disciplines

The nature of research work in management science ought to change slowly if the new research questions are sufficiently similar to those that have driven management science in decades past. But we know from last month's commentary that the new questions are different in their origins, which are three:

1. the proliferating technology-mediated interactions among the parties participating in the digital economy,
2. the proliferating large-scale digital data sources, and
3. an increasing number of recurring operational decisions that need to be automated.

This leads to our first observation, which is that each of these research question wellsprings calls for knowledge from certain disciplines that have long contributed to management science, yet are not universally considered in its "core." Consider each wellspring in turn.

**First Wellspring.** Interactions among rational autonomous parties almost always lead to strategic behavior. This means that parts of *game theory* (including mechanism design) are often relevant, and indeed we have seen ample evidence of this.[1] As explained in §1 of Part 1 of this commentary, all of the papers classified under "strategic interactions" use game theory (Swaminathan and Tayur 2003, Dellarocas 2003, Murthi and Sarkar 2003, Elmaghraby and Keskinocak 2003). So do most of the papers classified under "auctions" (Pinker et al. 2003, Pekeč and Rothkopf 2003, Snir and Hitt 2003, Carr 2003).[2] In addition, Anand and Aron (2003) make essential use of game theory to derive optimal group-buying price schedules, Datta et al. (2003) mention game-theoretic models of strategic behavior between providers and customers of a content distribution network, and the online appendix of Keskinocak and Tayur (2001) illustrates the use of game theory for gaining insights into multiunit Dutch auction bidding behavior and two managerial issues arising for supplier-buyer relations in the presence of a spot market.

The conspicuous appearance of game theory in more than half of the papers in this pair of special issues suggests that other topics in *economics* may also play important roles, and that is the case. For example, issues of market structure and competition from *industrial organization* (e.g., Tirole 1998) appear in Elmaghraby and Keskinocak (2003), Murthi and Sarkar (2003), and Datta et al. (2003); *econometric methods* (e.g., Greene 2002, Kennedy 1998) appear in Brynjolfsson et al. (2003), Hann and Terwiesch (2003), Murthi and Sarkar (2003), Snir and Hitt (2003), and Spann and Skiera (2003); the important role of information asymmetry from *information economics* (e.g., Levine and Lippman 1995, Shapiro and Varian 1998) appears in Anand and Aron (2003) and Swaminathan and Tayur (2003); and *financial economics* (e.g., LeRoy and Werner 2000, Luenberger 1998) makes its appearance in Kleindorfer and Wu (2003) (the study of risk management) and Spann and Skiera (2003) (the design of financial markets).

[1] Interestingly, an essentially identical argument has been made for the relevance of game theory to theoretical computer science (Papadimitriou 2001).

[2] Beil and Wein (2003) essentially assume away bidder strategic behavior.

**Second Wellspring.** We turn next to large-scale databases, much studied in *computer science*. Especially relevant are *data mining* (e.g., Fayyad and Uthurusamy 2002, Mitchell 1999), as motivated by Padmanabhan and Tuzhilin (2003) and Murthi and Sarkar (2003), and *very large databases* (VLDB[3]), as motivated by several papers cited toward the end of §4 of Part 1 of this commentary. Research products and commercial software from these fields are needed to deal effectively with many of the massive data sources now available.

**Third Wellspring.** Automating recurring operational decisions in real time or near real time was motivated at the end of §4 of Part 1 of this commentary and illustrated with five papers that all happen to be in the companion issue. Several other papers in both of these special issues also invite *real-time implementation*. This kind of automation can pose challenges beyond those of algorithmic efficiency, such as decision making with incomplete information. As mentioned in Geoffrion and Krishnan (2001), the latter topic is studied in *computer science* under the heading of *online algorithms*. Real-time implementation also calls for design that is compatible with today's standards (e.g., the XML-based standards now at the core of Web services) and with application programming interfaces for ERP (enterprise resource planning), *database*, workflow, and other host systems. History suggests that management scientists need to become familiar with such matters and to participate in implementations, or at least produce research products conducive to implementation. Otherwise, automation will occur anyway using only the most primitive decision technologies, as happened in supply chain management in the mid-1990s (e.g., Brown 2003, Sodhi 2001).

These three research-question wellsprings owe everything to the rapidly progressing information infrastructure on which the digital economy is built. That infrastructure itself is a legitimate domain for management science research. Using content delivery networks as an example (Datta et al. 2003), work on operational issues such as cache location and sizing (e.g., Breslau et al. 1999) requires considerable knowledge of the underlying network technology, as well as optimization methods. Work on pricing and related strategic issues (e.g., Hosanagar et al. 2003) draws on the economics of industrial organization to develop symbolic and numerical models taking technological aspects into account. More generally, work on operational issues, pricing, and strategic issues should interest many firms whose business includes some part of the information infrastructure (e.g., Datta et al. 2003 comes out of such a company). Doing such work requires knowing pertinent parts of computer science and information technology as well as management science, and often some economics too.

Thus it is evident that many of the research questions raised by the digital economy require an interdisciplinary approach in which other disciplines, especially parts of economics[4] and computer science,[5] have important contributions to make in concert with management science's core content. Management science researchers have ample motivation to study these disciplines: to be more self-sufficient when working without collaborators from these disciplines, to be more effective on research teams that include collaborators from them, and to set the stage for the breakthroughs that science often achieves when disciplines cross-fertilize. Many of the papers in these issues exhibit the advantages of interdisciplinary synergy, including Padmanabhan and Tuzhilin (2003), Pinker et al. (2003), Hann and Terwiesch (2003), and Kleindorfer and Wu (2003).

### 3.2. Shifting Research Productivities

Our second main observation concerning management science work on the research questions

[3] At this writing, VLDB is commonly taken to be upwards of 500 gigabytes.

[4] For example, microeconomics, econometrics, industrial organization, financial economics, game theory, and information economics. These terms can be found in the American Economic Association's subject classification index.

[5] For example, network architecture and design, spatial and statistical databases, workflow management, data mining and learning techniques, algorithms and their analysis, and multiagent systems. These terms can be found in the ACM Computing Classification System.

identified in these special issues is that there is a trend toward making greater use of computation and communication. This trait is pronounced in more than half of the papers in this pair of issues, including five of the six original research contributions. In terms of the four kinds of research work recognized in §2 of Part 1 of this commentary (empirical, methodological, theoretical, and precursive), this suggests that both empirical and methodological work are gaining at the expense of purely theoretical work (we see no clear implication for precursive work).

It is easy to understand such a trend in terms of the changing relative productivities of these three kinds of research work, because computation, data, and communication are much more important as factors of production in empirical and methodological work than in theoretical work. The cost and availability of these factors have changed enormously while technology has made thinking, the main ingredient of theoretical work, only moderately more productive per labor hour or per resource dollar. Computation used to be slow, expensive, and inaccessible, but now it is fast, cheap, and at everyone's fingertips. Data used to be difficult to obtain, awkward to share among applications, and expensive to store and communicate. But now many kinds of data are abundantly available either routinely through the kinds of sources mentioned in §4 of Part 1 of this commentary or through expedient Internet experiments as illustrated by Brynjolfsson et al. (2003), Hann and Terwiesch (2003), and Spann and Skiera (2003). Data is much easier to share among applications with the emergence of XML (e.g., Bradley 2003) and associated technologies such as XSLT (Extensible Stylesheet Language Transformations). The costs of data storage and communication have been dropping for decades at least as rapidly as the cost of computation, and at an industry-altering rate. Moreover, there is a growing wealth of computational services and software readily available via the Internet that can be of great value to researchers (e.g., Fourer and Goux 2001, Geoffrion and Krishnan 2001, Lougee-Heimer 2003). These seismic shifts in the cost and availability of computation, data, communication, and OR-related computational resources cause empirical studies and numerical methods to become more competitive every year as complements to mathematically based theoretical studies. This may not be unfortunate (Meredith 2001).

We are far from the first to make this general observation about the shifting nature of scientific work as a consequence of dramatically shifting cost-benefit ratios. Management science is not the only discipline in which computational studies with real or generated data can be effective as an instrument of discovery and as a source of useful insights and results when the unwanted assumptions needed for mathematical tractability are cast aside. Such developments have given birth to entirely new fields, including "computational economics" and "computational statistics." Focusing on just one use of computation, simulation, a recent statement of program objectives for NSF's Advanced Computational Research Program (1999) states in part:

> As pointed out in many documents and reports, computer simulation has now joined theory and experimentation as a third path to scientific knowledge. Simulation plays an increasingly critical role in all areas of science and engineering.

The preface of a recent book on computational statistics offers this view:[6]

> Computational statistics shares two hallmarks with other "computational" sciences, such as computational physics, computational biology, and so on. One is a characteristic of the methodology: it is computationally intensive. The other is the nature of the tools of discovery. Tools of the scientific method have generally been logical deduction (theory) and observation (experimentation). The computer, used to explore large numbers of scenarios, constitutes a new type of tool. Use of the computer to simulate alternatives and present the research worker with information about these alternatives is a characteristic of the computational sciences. In some ways, this usage is akin to experimentation. The observations, however, are generated from an assumed model, and

[6] Another appreciation of computational statistics by two of its pioneers (Efron and Tibshirani 1991) explains how bootstrap methods, nonparametric regression, and other modern, computationally intensive methods liberate statistics from the tyranny of traditional statistical tools designed in the days when computation was very expensive relative to mathematics.

those simulated data are used to evaluate and study the model (Gentle 2002).

Similar views of how computation complements traditional theoretical science can be found in other fields such as economics, where experimental economics and computational economics are both very well established. A senior academic economist who has played a leading role in designing major auctions and other markets has reflected at length on what his consulting experience has taught him (Roth 2001). He makes a strong case for the development of a new field that he would call "design economics." Such a field, he believes, would need to supplement game theory extensively with experimentation and computation in ways he explains and illustrates in convincing detail.

Thus, we find considerable support from neighboring fields for our second observation concerning the trend of management science research work toward computational and empirical approaches and away from the purely theoretical.

In summary, we believe that management science will continue to make good progress on the new and revitalized research questions raised by the emerging digital economy to the extent that it assimilates or partners with pertinent parts of economics and computer science/information technology and becomes more computational, in keeping with changing cost-benefit ratios.

## 4. Conclusion

This issue completes the project begun with our *Interfaces* (2001) special issue. We have been particularly concerned in this issue and its companion with (1) the nature and origins of the fundamentally new or revitalized research questions of managerial interest being raised by the digital economy, and (2) the related implications for the training and self-renewal of management scientists who wish to work on the research questions being spawned.

Last month, we dealt with (1) by noting the great variety of new research questions that arise, a variety further documented this month. We also posited that they arise from three specific wellsprings inherent in the digital economy.

In this article, we have dealt with (2) by noting the increasing importance of parts of economics and computer science/information technology to the continued success of management science. We also noted the productivity advantage to management science researchers of expending a greater share of their effort on empirical and methodological work.

This completes our two-part commentary on management science as it strives to meet the challenges presented by the emerging digital economy. It may appear, from this commentary, that the mutual impacts of the digital economy and management science on one another run mainly from the former to the latter. However, that would be far from the truth. The papers in these two issues and those in *Interfaces* (2001) document at length some of management science's significant contributions toward building a deeper understanding of the digital economy and toward helping managers with many important decisions for which there is scant experience on which to rely.

We hope that these two special issues, together with *Interfaces* (2001), will help management science researchers to recognize promising new opportunities and to identify some of the approaches most likely to be fruitful.

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