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Abstract: Robert Hayes (this issue) has written provocatively about the implications of the digital economy for Operations Management (O.M.). Here I examine and illustrate a simple 4-stage framework for thinking about these implications: advances in digital technology (Stage 1) lead to business developments (Stage 2), which impact the views of O.M.-relevant thought leaders (Stage 3), which influence the conduct of O.M. activities (Stage 4). This framework provides a perspective for viewing the evolution of O.M. and indicates how educators, researchers, and practitioners can steal the march on mainstream thinking.

Keywords: Operations Management, Digital Economy, Internet, Information Technology, Professional Evolution

Life would be much easier if the world would stand still, but of course it doesn't. As the world evolves, so must the disciplines whose mission includes helping managers deal with it. Operations Management is no exception. In an insightful article, Robert Hayes (this issue) discerns some changes in the business world deriving mainly from opportunities presented by the digital technologies, and explains what these mean to the management profession and hence how O.M. must change so as to support managers in a changing world. He concludes with recommendations for modernizing O.M. education. His primary context is the information-intensive industries, especially the new ones, in contrast to the more traditional industries dealing with physical goods and services that originally gave birth to O.M. This emphasis seems appropriate since the shift of economic mass from the latter industries toward the former has been a major trend in recent times.

This article describes a causal pattern of events that is to some extent implicit in Hayes' paper, and uses this pattern to organize some complementary examples and observations. It provides a framework for thinking about the kinds of issues Hayes raises, and for other purposes to be mentioned later.

The causal pattern has four stages (Fig. 1):

Stage 1: Digital Technology Advances. Everything begins with scientific and engineering (including software engineering) advances like integrated circuits, telecommunication technologies (including Internet technologies), and Java.

Stage 2: Digital Technology-Based Business Developments. Stage 1 advances create commercial opportunities, which lead to new business developments and to management attention to issues associated with such developments. Many business developments in recent years arose in this way, although of course there are also other drivers besides digital technology such as socio-political factors that cause the world of affairs to change. These developments, together with the reallocation of management attention they cause, create the impetus for the next stage.

Stage 3: Changes in Thought Leaders' Views on Practical Managerial Challenges and Issues. The thought leaders I have in mind, typically influential academics, consultants, and pundits, are those to whom the O.M. community pays attention and who conceptualize and reconceptualize the nature of practical managerial work in light of current business developments. Some write and speak from the perspective of the O.M. community and some from other perspectives (e.g., general management or strategy). Of particular interest are their identification, conceptual development, and discriminating assignment of relative importance to the panoply of practical challenges and issues managers face as a result of the business developments of Stage 2. Their views influence research, educational activities, and practice in O.M. (as well as other disciplines).

Stage 4: Changes in Research, Educational Activities, and Professional Practice. What goes on in the O.M. community changes over time for a variety of reasons, including the views of Stage 3 thought leaders. The segment of "practice" referred to here is that which is open to being guided by current, applicable, O.M.-related research and education.

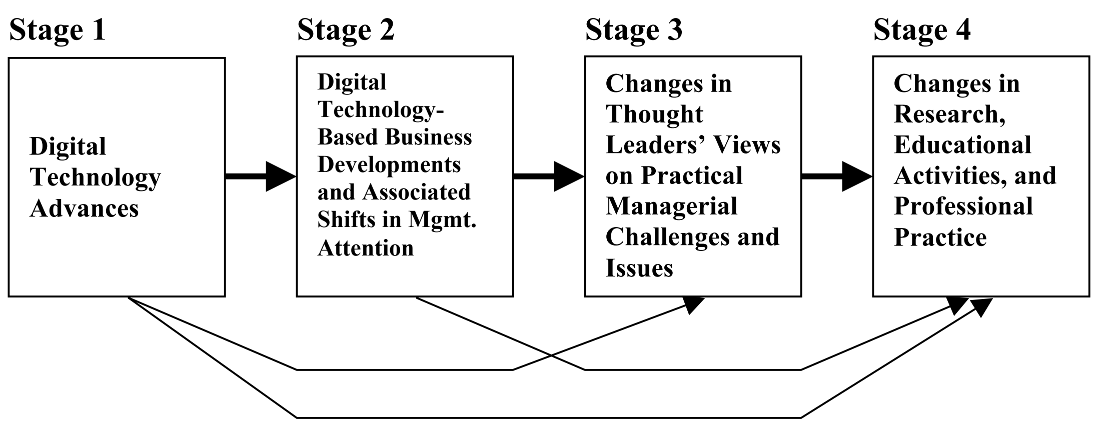

Figure 1. A Causal Pattern That Helps to Drive Progress in O.M.

Thus advances in digital technology (Stage 1) lead to business developments (Stage 2), which impact the views of thought leaders (Stage 3), which influence the conduct of O.M. activities

(Stage 4). There is delay from each stage to the next. Most of the causality is serial, but it is also possible for Stage 1 to impact Stages 3 and 4 directly, and for Stage 2 to impact Stage 4 directly. Moreover, there is feedback influence from some stages to earlier ones (not shown in Fig. 1); for instance, one hopes that Stage 4 O.M. activities occasionally affect thought leaders' views and have some impact on events and managerial attention-share at Stage 2. Examples come later.

Does this causal pattern account for all progress in O.M.? Definitely not. There is a good deal of momentum at work also: research tends to beget similar research, courses tend to beget sequel courses and to follow research, and professional practice tends to proceed in accepted channels. Resource-seeking is another driver: research tends to follow funding sources, teaching tends to respond to curricular demands, and professional practice tends to respond to markets for services. However, since Stages 1-3 strongly influence resource availability, one might regard resource-induced changes in O.M. as the causal pattern operating on a material rather than intellectual plane.

Moreover, other causal patterns influence O.M. research, education, and professional practice. One such begins with the long-term transformation of the U.S. economy from manufacturing-based to service-based. This is discussed at length in [Geoffrion 1992], one conclusion of which was that OR/MS -- a close relative of O.M. -- has been slow to make the necessary adjustments in academic research and education, though much swifter in professional practice.

Probably O.M. academics have been slow to evolve under the causal pattern of Figure 1 as well. If they are to lead rather than follow, then they need to monitor not only Stage 3 changes, but also Stage 2 and perhaps Stage 1 as well in an effort to overcome the usual lags. It takes time to develop new theory, techniques, and tools to meet new needs and exploit new technological opportunities, so O.M. should look *upstream* of Stage 3 changes.

Thus we have one of the general uses of the causal pattern: to indicate how educators, researchers, and practitioners can steal the march on mainstream thinking if they wish to move to the forefront or stay there. A second general use is to provide a perspective for thinking about current developments that may lead to a better understanding of why they are occurring and what might ensue. A third is to provide structure for the plots of stories, well known to be one of the most powerful devices for communication (a recurring challenge for everyone in academia, research, and practice).

In what follows, I comment on each of the four stages in turn, each time beginning with a very brief recap of Hayes' observations followed by some supplementary ones of my own. The final section illustrates the causal pattern and one of its uses.

Stage 1

Hayes uses *information technology* (IT) as a general rubric for what is here called *digital technology*. This change of terminology, which perhaps is not essential, is prompted by personal preference, his emphasis on information-intensive industries, and a recent estimate [Lyman and Varian 2000] that over 93% of all information produced in 1999 worldwide was in a digital format. This proportion is growing.

Besides IT, Hayes specifically mentions CAD and the items listed in my initial definition of Stage 1 as notable advances. To be more explicit, one could add such advances as **magnetic storage technology** [Lyman and Varian 2000], **public-key cryptography** [RSA Security Inc. 2000], and **XML** [Flynn 2001]. The first is responsible for the cost of disk drives dropping from more than $5,000 per gigabyte a decade ago to less than $3/GB today. This has been crucially important for personal computers and servers, and has enabled many data-intensive business developments. The second is at the core of much of the security required for e-business activity. The third is a metalanguage for identifying the semantic content of Web pages, and is expected to greatly impact O.M. business processes (among others).

Stage 2

Many of the business developments that spring from or are heavily impacted by digital technology are evident, including the computer hardware/software/peripherals industries, the telecommunications industry, the industries devoted to information goods and services, and all the business activity aimed at facilitating or actually conducting e-business. Hayes observes that production processes and their interconnections tend to be highly flexible in such information-intensive industries, with products changing rapidly and often being customized. He observes that information-intensive networks play an important role for many such products and services, leading to major managerial issues relating to network effects, network alliances and partnerships, product complementarities, outsourcing, and enabling standards among others.

There are at least a few other technology-based business developments that warrant attention. One is the advent of **enterprise software**, especially ERP, which has been adopted by about half of all large companies in the U.S. and Europe and has been both boon and bane to O.M.: boon because of the resulting business process standardization and the large amount of data newly made available for analysis, and bane because it steamrollered much model-based application software into oblivion. See [Sodhi 2001] for additional discussion of this topic and [CACM 2000, ISF 2000] for recent in-depth surveys.

Another important development is the emergence of **intranets**, that is, private networks for internal information dissemination and coordination that use Internet technology [King 2000]. Given the added importance of coordination activity in recent times, and the availability of this totally new platform for hosting O.M. application software, intranets seem destined for a bright future. The same is true for **extranets**, which are essentially intranets that link an organization to a selected subset of its customers, suppliers, and other partners. Using intranets and extranets to field model-based applications is becoming increasingly common. [Cohen et al. 2001] describes one popular multi-tier architecture and typical applications. United Parcel Service has used a similar architecture to reduce their maintenance and support costs by 80% for two “very complex” applications while still increasing their use [Levis 2001]. A different architecture is used by MasterCard International, which offers its neural-network-based RiskFinder fraud-detection system to

MasterCard issuers via two cooperating extranets: one a global transaction processing network known as Banknet, and the other a network called MasterCard OnLine that supports operational relationships with MasterCard member banks [Alliston 2001].

A third development is the proliferation of **data warehouses** and **data marts** (collections of transaction data specifically structured for querying and reporting) [Greenfield 2001], which are enabled by the advances in magnetic storage technology mentioned earlier and which in turn enable many kinds of data-driven O.M. applications and analyses.

Stage 3

Hayes himself is a thought leader in O.M., and his paper is a nice example of Stage 3 thinking. I agree with his observations on how the challenges and issues facing management have changed with progress in digital technology and consequent business developments. He summarizes these changes succinctly in a single table that obviates the need for further review here.

He discusses at length the many profound consequences of the very low unit reproduction costs (after the first unit) of information goods, in contrast with high first-unit costs. He also points out that the distribution costs of such goods are small and independent of distance. For a fuller picture of the distinction between information-goods economics and physical-goods economics, one should also note: 1) the absence of most inventory costs, 2) the absence of most capacity limits on reproduction and distribution, and 3) the negligible time consumed by most reproduction and distribution operations. It might seem that these almost magical characteristics of information goods all but eliminate most of the kinds of managerial questions that O.M. has traditionally addressed, but this is not the case.

For example, distribution costs and time delays can be negligible but in many cases are not: content delivery networks -- a new and important kind of Stage 2 business development that serves digital content from caches in order to improve response speed (among other benefits) -- are a major cost category where used and raise significant managerial questions that are amenable to analysis [Geoffrion and Krishnan 2001]. For another example, information obsolescence costs are an inventory cost category that can be significant and worthy of serious managerial attention (e.g., [Bashyam and Karmarkar 2001] shows that the database obsolescence rate in at least some business information service firms figures prominently in optimal firm behavior and market segmentation). For particular categories of information goods, close examination may well show that there are other cost categories, capacity limits, and time delays (more on this below) substantial enough to raise serious and analyzable managerial questions, particularly in real-time operations where the time and resources available to execute essential business processes usually are severely limited.

To better understand the management challenges and issues posed by the digital economy for physical as well as information goods and services, I want to draw attention to several important aspects of the Internet itself as a medium for economic activity.

One aspect is that it changes customer expectations for how quickly they will be gratified. This began in B2C e-commerce with nearly instant information access over the Web, extended to expectations of quick delivery for physical goods (hence the increased popularity of package-mode transportation services), and has led to similarly altered expectations in parts of the B2B sector. Increased customer expectations have contributed to the prominence of quality-of-service issues for Internet infrastructure and of real-time performance requirements for the decision components of business process software, both topics discussed in detail in [Geoffrion and Krishnan 2001].

Another aspect of the Internet as an economic medium is the dematerialization of physical supply chains it is causing for some information goods that traditionally have taken physical form. This is a Stage 2 development. For example, the essential content of financial products, greeting cards, music CDs, packaged software, postal mail, printed matter (books, journals, magazines, manuals, newsletters, newspapers, and such), tickets, and videos can be delivered digitally over the Internet, and other products (like photographic film) have close digital substitutes. Not only products dematerialize, but also some services. Consider these examples in which people avoid travel by using personal computers to: participate in distance learning, go to traffic school on the Web, take computer-based entertainment, and rely on information-rich Websites rather than industrial showrooms or retail outlets for researching purchases. Not only is there diminished use of transportation in such cases, but this also changes fundamentally the way some business is conducted. Organizations dealing in such products and services are facing serious issues of transition and of how to integrate physical operations with the new digital ones. Clearly O.M. needs to address these issues in the dematerializing industries.

A third aspect of the Internet that commands managerial attention is the need to defend e-business infrastructure, companies, and transactions against new kinds of fraud, theft, and vandalism. Some of this is the proper domain of computer science, but some falls within a broadened scope of O.M. For example, tools for guarding against Internet credit-card fraud are in wide use [Demby 2000], and trust-based systems are used in some online markets [Kollock 1999]. Both lend themselves to modeling [CyberSource 2001, Dellarocas 2001].

A fourth aspect is the opportunity presented by the Internet to do much more sophisticated dynamic pricing (including yield and revenue management [Smith et al. 2001]) than is practical for traditional mediums of economic activity [Geoffrion and Krishnan 2001]. Pricing has often been considered outside the usual domain of O.M., but the digital economy has been breaking down the customary fences between management disciplines as it forces models to become more inclusive in scope. In particular, collaborations between marketing and O.M. specialists are becoming increasingly common. So it seems likely that pricing decisions will increasingly be made dynamically and jointly with capacity, procurement, production, and distribution decisions.

These are only some of the more important challenges and issues newly facing management as the Internet gains prominence as a medium for economic activity.

Stage 4

In the last paragraph of his paper, Hayes recommends specific changes in what an introductory O.M. course should cover. Briefly: 50% on traditional O.M. topics with an increased service orientation, 25% on project management, and 25% on managing cross-company operations. He does not explicitly advocate changes in research or professional practice other than to recommend more academic attention to project management.

My comments on Stage 4 are strongly influenced by the experience of co-editing a special issue of *Interfaces* (March-April 2001) on OR/MS in e-business. Based on a keen awareness of Stage 1 advances and Stage 2 developments, and with considerable attention to the managerial concerns of Stage 3, this issue focused strongly on practice – what has been done and what could be done -- rather than on research or education. Yet the implications for research and education are quite clear, as sketched in this brief summary adapted from [Geoffrion and Krishnan 2001] of that issue:

1. Research, education, and practice should build on the six notable strengths of OR/MS (and hence potentially of O.M.) identified as matching the needs of the digital economy, namely the abilities to: exploit the unprecedented abundance of data, cope with complexity in design, planning and operations, manage risk and deal with uncertainty, achieve a deep understanding of business processes and issues, experiment without risk, and automate entire classes of recurrent decisions.
2. Education, including continuing professional education, should incorporate parts of microeconomics and such new decision technologies as auction design, constraint programming, data mining, dynamic pricing and revenue management, and techniques useful for adding real-time intelligence to automated business processes.
3. Education, including continuing professional education, should provide an acquaintance with some of the principal information technologies underlying e-business and enterprise software, since these are becoming important O.M. implementation contexts, and with the main architectures and distributed computing technologies used to deploy O.M. applications over the Internet and Web.

The reader will notice that there is no apparent intersection between Hayes' recommendations and mine in the context of education. This is partly because our respective recommendations are not properly comparable: he addressed a single introductory course, while I have in mind an entire O.M. curriculum or at least a coherent bundle of O.M. courses. There would not be room in an introductory O.M. course for much of what is recommended above, although some of that material could be covered in other introductory courses on economics, quantitative methods, and IT. In any case, the strengths mentioned under point 1 might serve as one of the integrating themes of an introductory course, and some of the managerial contexts (at least) associated with points 2 and 3 might be introduced without adding to total course bulk by deftly altering the choice of cases when the case method is used. Changing cases can also move an introductory O.M. course in the direction Hayes advocates.

Examples

So far I have discussed the four stages individually. Now I offer two brief longitudinal examples to show the causal pattern in action for specific seminal advances in digital technology, and a final example showing one way in which to use the causal pattern.

The first example begins at Stage 1 with dramatic advances in magnetic storage technology. For more than a decade, disk storage density has been increasing fast enough to about halve the cost per gigabyte each year to the point where storage cost is becoming inconsequential in many applications. Among the Stage 2 consequences is the advent of content delivery networks (CDNs) [Stardust.com 2001], as mentioned in the discussion of Stage 3 and as discussed in some detail in [Geoffrion and Krishnan 2001]. Akamai, Digital Island, and their rivals play a role in delivering information goods much like FedEx and its rivals play in delivering physical goods. Just as (Stage 3) thought leaders in supply chain management had to recognize the management challenges and issues inherent in the availability of overnight delivery services – for example, managing the tradeoff between carrying spares inventory and relying on overnight delivery when needed – so too Stage 3 thought leaders who focus on information-intensive industries must recognize the management challenges and issues inherent in the availability of CDNs – for example, managing the tradeoff between the costs of using them and benefits such as faster delivery and reduced requirements for conventional wide-area network bandwidth [Christy 2000].

As quite recent developments, CDNs have yet to have much Stage 4 impact in O.M., but this will come even as CDN services devolve to network service providers over the next few years. Most of the impact has been in the computer science and IT/network management communities, as would be expected. One change in professional practice that is known to have occurred is the extensive application of OR optimization technology by leading content delivery service providers to do distributed load balancing (e.g., see U.S. patent 6,108,703 licensed to Akamai).

The second example begins at Stage 1 with the invention of the Web in 1990 as a new way to use the then-22-year-old Internet. The Web did not catch the public's attention until 1993 with the remarkable success of the Mosaic browser. Two years later the Web began to take off as a serious commercial platform, with e-commerce revenues passing $1 billion in 1996 for the first time. Among the many Stage 2 consequences of the Web was online auctions beginning with California's Automated Credit Exchange, which has been successfully conducting a kind of combinatorial auction in air emission permits since 1995 as the world's first Internet-based B2B exchange. eBay launched in 1995, and its rapid success as a person-to-person auction site helped lead to rapid recognition of the Web's potential for B2B auctions. Numerous auction sites emerged [Lucking-Reiley 2000], many with the help of venture funding, and a massive shakeout is now in progress. All this activity attracted a great deal of attention from Stage 3 thought leaders (e.g., [Johnson 2001], [Tapscott, Ticoll, and Lowy 2000]).

The Stage 4 impact of online auctions is swelling rapidly. One measure of research interest comes from the submission statistics for two special issues that Krishnan and I are guest editing for *Management Science* on OR/MS research in an e-business context. Of 115

submitted proposals for papers, the most popular topic was auctions with 18. For comparison, supply chain management was second most popular with 15 submissions. This suggests that online auctions are receiving much research attention. They are receiving considerable attention from analytically sophisticated practitioners too, judging by some of the auction implementations mentioned in [Geoffrion and Krishnan 2001]; these include OptiBid (www.logistics.com/products/shipper/optibid.asp), a system used by Home Depot [Elmaghraby and Keskinocak 2000], systems designed by Market Design Inc. (www.market-design.com), and systems built by Net Exchange (www.nex.com).
Online-auction content is increasingly finding its way into O.M. courses.

As mentioned earlier, the causal pattern of Fig. 1 has at least three uses: to indicate how educators, researchers, and practitioners can anticipate future mainstream thinking in their communities, to provide a broad perspective for thinking deeply about current developments, and to provide a basis for structuring the plots of stories for professional communications. Either of the two examples above could be adapted to illustrate any of these uses, but instead I will illustrate the first use with a fresh example centered on dynamic pricing. This notion was introduced near the end of the discussion of Stage 3.

It suffices for present purposes to define *dynamic pricing* as the sort of e-pricing described by [Baker et al. 2001] for on-line transactions. According to this article, it comes in three varieties: (a) better posted prices through on-line testing; (b) better and faster changes in posted prices in response to market conditions, costs, demand, inventory, and competitors' behavior; and (c) better price discrimination through better real-time segmentation.

Dynamic pricing is increasingly common, obviously well suited as it is to the Internet (especially the Web) as an interactive sales medium. My thesis is that dynamic pricing, perhaps especially the second and third varieties mentioned above, becomes ever more worthy of attention by the O.M. community as B2C and B2B Internet sales increase. This seems to be a point of convergence of Marketing and Operations Management as management disciplines. Pricing is becoming less like a class of decisions made episodically by marketing specialists, and more like an operational process in which pricing decisions are dynamically integrated with the traditional steps of the on-line sales process and also with operating data and decisions that have been traditional O.M. concerns.

Granting my thesis, consider how the O.M. community can find the motivation to work on dynamic pricing and its integration with more traditional O.M. concerns. According to our causal pattern, Stage 3 writings, talks, and interactions provide an important motivation. These are indeed in evidence (e.g., [Baker et al. 2001], [Johnson 2000], [Kyte 2001]), though too seldom with an O.M. spin. But the motivation could have come earlier had O.M. paid attention to the Stage 2 developments wherein dynamic pricing was pioneered and used by an increasing variety of industries. And it could have come earlier still to anyone who thought seriously about the interactive and real-time possibilities inherent in the Stage 1 advances that enabled dynamic pricing, mainly the Internet and Web.

The vitality of the O.M. community, like every community focused on management, depends importantly on our willingness to regularly spend some time "outside" of ourselves listening and looking upstream to the Stage 2 venues of the value that we potentially can provide, and perhaps even to Stage 1. Prof. Hayes has done us a service in this regard, and I hope that my amplifications will help to structure the opportunity-laden challenges we face and place O.M.'s usual preoccupations in broader perspective.

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