An Operations Cyberinfrastructure:
Using Cyberinfrastructure and Operations Research
to Improve Productivity in the Enterprise

Report on a Workshop held in Washington, D.C.
August 30-31, 2004

Sponsored by the National Science Foundation

Abstract/Summary

Science and engineering are being revolutionized by a *cyberinfrastructure (CI)* that promises to provide hardware and software support for a wealth of new discoveries and innovations. The report of the National Science Foundation's Blue-Ribbon Advisory Panel on Cyberinfrastructure has identified diverse areas of science and engineering that are poised to benefit from this revolution.

Our workshop formulated the concept of an *Operations Cyberinfrastructure (OCI)*, which will achieve far-reaching benefits for enterprise-wide applications by harnessing advanced sensing, data analysis, modeling, simulation, and optimization technologies. These benefits will be realized by integrating the financial, economic, and strategic objectives of an enterprise with the design of supply networks, product life cycles, and market environments. The field of *Operations Research (OR)* provides the integrating methodology for these diverse considerations and the scientific underpinning for the decision-making process. The OCI will combine OR methodology with the computational and knowledge-exchange capabilities of CI, producing tools for better planning and operational decision-making in a broad variety of enterprises.

We conclude that timely action is critical to the establishment of a successful Operations Cyberinfrastructure, and that NSF initiatives will be necessary to stimulate basic research on OCI standards, protocols, and applications before development can be taken over by more commercial entities. NSF initiatives in this area should include significant funding for basic OR research that is tied to development of an OCI, for research in the development of CI tools that are particularly relevant to an OCI, and especially for research projects at the interface of OR and CI. We further recommend that funding for OCI-related projects be leveraged by funds for other NSF programs in CI, information science, engineering, and social, behavioral, and economic sciences.

An Operations Cyberinfrastructure:
Using Cyberinfrastructure and Operations Research to Improve Productivity in the Enterprise

Report on a Workshop held in Washington, D.C.
August 30-31, 2004

Sponsored by the National Science Foundation

Introduction

Science and engineering are being revolutionized by a *cyberinfrastructure (CI)* that promises to provide hardware and software support for a wealth of new discoveries and innovations. The report of the National Science Foundation's Blue-Ribbon Advisory Panel on Cyberinfrastructure (the *Atkins Report*) has identified diverse areas of science and engineering that are poised to benefit from this revolution.[1] Our workshop addressed a related and vitally important topic: an *Operations Cyberinfrastructure (OCI)* that will have far-reaching benefits for the organization and operation of complex enterprises.

The Operations Cyberinfrastructure offers innovations in harnessing advanced sensing, data analysis, modeling, simulation, and optimization technologies to support enterprise-wide applications. These benefits will be realized by integrating the financial, economic, and strategic objectives of an enterprise with the design of supply networks, product life cycles, and market environments. The field of *Operations Research (OR)* provides the integrating methodology for these diverse considerations and the scientific underpinning for the decision-making process. The OCI will combine OR methodology with the computational and knowledge-exchange capabilities of CI, producing tools that facilitate better planning and operational decision-making in a broad variety of enterprises.

The potential impact of OCI research is rooted in a potent combination of models, algorithms, storage capabilities, and computational power. Virtually all physical production activities — from conceptual product design, supply network configuration, and production planning through operations, inventory management, delivery, maintenance, and retirement — can leverage new research at the interface of CI and OR. Similarly, many service enterprises can benefit from better organization and interpretation of the information that is their lifeblood. An OCI thus has major implications throughout the economy for gains in productivity and revenue.

Design and implementation of an effective OCI will require not only OR and Computer Science expertise, but also collaborations with economists and

---

[1] Areas cited in Section 2.6 of the Atkins Report include Atmospheric Science, Forestry, Ocean Science, Environmental Science and Engineering, Space Weather, Computer Science and Engineering, Information Science and Digital Libraries, Biology/Bioinformatics, Medicine, Physics, Astronomy, Materials Science and Engineering, and Social and Behavioral Sciences.

engineers in many areas. In just the specific topics discussed in this report, there are key roles for researchers in electrical engineering, design engineering, medical informatics, and financial/economic modeling, to name just a few.

This report describes our vision of an OCI to support enterprise-wide applications. We first elucidate the importance, challenges, and potential benefits of an OCI for enterprise-wide applications, and then take a more detailed look at applications in four areas: supply-network management, product lifecycle informatics, service enterprises, and product and enterprise design.

Why Cyberinfrastructure and Operations Research Matter for Enterprise-Wide Applications

Everyone is familiar with infrastructures: road systems, rail networks, power grids. An infrastructure does not produce goods or services itself; rather, it makes a wide range of productive activities possible. The interstate highway infrastructure does not itself carry out supply-network management, for example, but it permits the development of supply-network management systems that would not be possible otherwise. Indeed, it paves the way for phenomena that were not foreseen when it was built, such as crossdocks and suburban sprawl. The effectiveness of infrastructures depends critically on *standards* (track gauges and standard time for railroads, bridge heights for highways, voltages for power grids) and on *accessibility* to a broad base of users.

Among the major infrastructures of modern life, cyberinfrastructures constructed from computers, data networks, software, and communications standards are among the newest and most elaborate instances. The Internet and the Web are the best known examples. Like other infrastructures, they facilitate myriad applications — the Web's use for unexpected purposes is already legendary — and they depend critically on software standards such as IP, HTTP, and HTML.

Operations Research also has the characteristics of an infrastructure, in the sense that it is a collection of theory, algorithms, and software that underpins and facilitates productive activity. In essence, OR tools bridge the gaps between information, knowledge, and decision-making. OR has had major impacts in design, manufacturing, services, and supply-network management, all of which are discussed in detail later in this report. Like other infrastructures, OR tools serve many purposes that were not envisioned by their creators.

To achieve their full potential for enterprise-wide applications, however, OR tools require high-quality data in the form of current, comprehensive information and knowledge. OR tools also require computational platforms that allow large, difficult mathematical problems to be formulated and solved, often in real time. Cyberinfrastructure can help with both these needs. In supply networks, for example, CI can collect data from sensors and suppliers and transmit orders, while OR tools organize the data and make decisions. In engineering design, CI can provide access to diverse and distributed databases and to powerful computing platforms, while OR facilitates data mining, exploration of larger scenario spaces, and handling of uncertainty in the design process.

In short, OR and CI add a great deal of value to each other. An Operations Cyberinfrastructure, which synthesizes CI and OR, could yield even greater benefits for enterprises of all types.

Challenges and Benefits in Operations Cyberinfrastructure for Enterprise-Wide Applications

The potential benefits are great, but there remain substantial research challenges in creating the OCI that we envision. Current weaknesses in the key criteria of standards and accessibility currently prevent OR from truly filling the role of an infrastructure. Although hundreds of excellent OR software tools have been produced by academia and industry, they communicate with each other and with their applications in ad hoc ways and through awkward interfaces. Individual OR researchers and practitioners have ready access to only a small fraction of available tools, and are able to implement and validate far fewer ideas than they can generate. The OR community is consequently not well positioned to exploit or adapt to new computing resources, in particular the high-performance, distributed computing resources commonly associated with CI.

Many of the dangers of foregoing or under-funding CI initiatives cited in the Atkins Report[2] echo the experiences of the OR community. OR problems are pervasive and yet there is a low degree of sharing. CI tools can help the development of core OR, as well as the Operations Cyberinfrastructure, by enabling research collaborations across institutions, locations, time, and fields of endeavor. CI expertise is also needed to ensure that data and software acquired at great expense and effort are available for future researchers. Incompatible software tools and structures that isolate the OR community (and isolate researchers from each other within the community) need to be replaced, and OR researchers must take the lead in fostering interoperability. There must be investment in the maintenance of successful OR products so that time and talent is spent in breaking new ground rather than in reproducing past efforts. All of these activities need to play a role in OCI development.

Prospective users of OR approaches often express frustration at the difficulties in accessing OR techniques. The same CI mechanisms that speed the development cycle *within* the OR research community will also facilitate outreach to the user community, but other CI features specifically aimed at users should also be considered. Initiatives along these lines could include a web-based modeling and analysis library that provides introductory but scalable demonstrations of OR algorithms and applications.[3]

The OCI will also improve decision-making within enterprises, replacing slower, less-informed decisions by real-time, fully informed decisions based on sophisticated OR models and algorithms implemented in tandem with CI knowledge-gathering and computational capabilities. The OCI will thus act as an enabler for innovations in products and services, including new customization strategies. It will address challenges in design optimization, total supply-network management, product lifecycle informatics, and service enterprises, none of which are addressed directly in the Atkins report's focus on scientific and engineering challenges. We believe that CI has a great deal to offer these and other enterprise application areas, and that OR is the key to realizing the potential of these contributions.

In the remainder of this report, we elaborate on the implications of the proposed OCI thrust in four key enterprise-wide application areas:

---

[2] See in particular the middle paragraph on page 4 of the Executive Summary.
[3] See for example the NEOS Guide, http://www.mcs.anl.gov/otc/Guide, which is however limited to optimization.

> ➤ Supply-network management
>
> ➤ Service enterprises
>
> ➤ Product and enterprise design
>
> ➤ Product lifecycle informatics

We conclude with a summary of our recommendations.

We view timely action as critical to the establishment of a successful Operations Cyberinfrastructure. We foresee that NSF initiatives that will be necessary to stimulate basic research on OCI standards, protocols, and applications, before development can be taken over by more commercial entities.

Supply-Network Management

The term *supply chain* was coined to describe an enterprise-wide view of commercial activity. A company's supply chain includes everything from design and production to transportation and warehousing to marketing and delivery. Indeed, the image of a "chain" of supply has become inadequate; today a manufacturer must manage a ***supply network*** that involves many interactions between its parts at all levels. Although the company owns only some portions of its supply network and outsources the rest, it must manage the entire network in order to maintain its competitiveness. The time scales of the decision-making in this management process range from multi-year analyses down to real-time pricing and reordering decisions. Issues to be addressed include the critical issues related to costs and profits as well as the challenges of maintaining resiliency in the face of supply and demand uncertainties and unpredictable disruptions.

In the past, firms took advantage of product architectures to gain competitive advantages in producing increased variety at lower costs, but today advances in supply-network management that improve time and responsiveness are yielding some of the greatest competitive advantages. The diverse challenges of supply-network management require diverse tools, however. Models drawing on statistical, simulation, and optimization techniques must communicate with each other, with varied data sources, and with human analysts at different levels and locations. This level of integration has been approached by costly and specialized proprietary systems, particularly at large, well-integrated companies such as Wal-Mart and Dell, but has remained out of the reach of most researchers and practitioners. A comprehensive Operations Cyberinfrastructure has great potential to bring the same benefits to enterprises at all levels, with widespread economic impacts..

The open nature of an OCI will permit much faster integration of research ideas into practice, making new supply-network management ideas available to a broader variety of companies, again with greatest benefit to relatively small ones. In addition, many enterprises, both existing and new, will take advantage of the advances through other mechanisms including the SBIR. In particular, the emerging web services standards that serve as the underpinning of an OCI will let people make quick and reliable connections between diverse analytical methods and data sources, freeing time for experimentation with new computational ideas and new software components. The most dramatic effects will be seen in the use of approaches that have previously posed the greatest

challenges, such as optimization under uncertainty, distributed simulation and optimization, global optimization on noisy data, and optimization of simulations.

The steadily increasing demand for customization of products also creates challenges and opportunities for supply-network research in an OCI. While outsourcing remains profitable, it increases complexity of the supply network further; management of the interfaces between suppliers threatens to become expensive and inefficient. By dispersing engineering and production geographically, manufacturers increase the number of places their interfaces and multi-tier supply networks can break down, with consequences that include hidden logistical and inventory costs and increased lead times.

These trends have made the current product design and development process extremely iterative and communication-intensive. The manufacturers that perform a majority of the design function are reliant on suppliers while they prototype and move their products towards production. It takes significant time and cost to develop a stable, reliable supply network for a product, and heavy coordination is required between the different tiers. Once formed, these supply networks tend to be rigid and unresponsive to dynamically changing customer needs, leading to high inventory costs. The majority of these inventory costs are borne by the lower-tier suppliers who are already under pressure to cut costs. Tools developed and distributed in an OCI could enhance the flexibility, responsiveness, and efficiency of the supply network.

The increasing confluence of design, modeling, analysis, and implementation problems for complex enterprise systems creates a demand for theoretical investigations of system integration frameworks, which should form an important part of OCI research. Coordination models based on game theory, financial and econometric modeling, and control theory are having a large impact on supply chain management research, replacing earlier piecemeal studies. Another fast emerging issue, closely related to product design, is the development of design-time consumer driven supply networks. Because it incorporates a wide array of theoretical and analytical methodologies and tools, an OCI initiative will offer an ideal framework for such inter-disciplinary research.

Service Enterprises

The service sector has been the focus of much CI activity during the past decade. It has also historically been a major venue for OR research and practice. From the viewpoint of the service sector, the leading function of CI is to acquire, store, transform, and transmit information. OR techniques can then be used to manage and interpret this information, to optimize procedures for collecting it, and to provide decision support for users of the information. The synthesis of these technologies in the OCI could lead to important improvements in the quality of services delivered in this sector.

An economic taxonomy of the service sector usually classifies services as being Business-to-Business (B2B), Business-to-Consumer (B2C), Financial Services, Healthcare, and Transportation. In some cases, Educational services are also considered as service enterprises. While there is no commonly accepted definition of "service," one system-theoretic definition that applies broadly is the following: a service is an action or a series of actions undertaken in response to a request to change a customer's "state" either at the time of the request (now) or in the future.

6

Service enterprises, especially those providing B2B services, have been growing at a phenomenal rate. Companies like IBM and General Motors, which used to be primarily manufacturing organizations, now view themselves as service providers. B2B services help each company maintain its focus on what it does best, thus providing for greater overall efficiency.

Electricity markets illustrate the potential relationship between the data-gathering capabilities of CI and its successful integration with OR tools. Today, many states have separated electricity generation from electricity transmission, which has become the domain of independent system operators (ISOs). While there have been studies of the economic behavior of agents within a deregulated electricity market, studies of the impact of such markets on electricity transmission have been impractical, because each ISO has access to data only within its specific region. In the absence of easily available, interoperable models of portions of the power grid, it is not possible to predict how certain market transactions might affect the overall stability of the grid. However, if we could create a test-bed that mimics power flows for each ISO, studies of the impact of markets on transmission would become feasible. The integration of electricity market models with nonlinear power flow models will require general-purpose tools that can be plugged together without revealing sensitive network data; this integration of tools will become possible with the development of the OCI.

Development of sensor networks and the pervasive connectivity between physical infrastructure and cyberinfrastructure provide an opportunity for business transformation. However, these areas will not develop without critical research at the interfaces between the OCI and Enterprise research. Examples of such transformations include RFID in the supply network and the use of intelligent sensors for maintenance of machines. The OCI's contributions to the services sector promise to deliver significant savings and cost reductions to other sectors, including the entire product lifecycle from concept through delivery, retirement, and recycling.

Data and network security services are emerging as a necessity for applications in both manufacturing and service areas. Related issues to which OR tools are critical involve network reliability models under complete or partial information. An OCI has obvious potential to contribute in these matters, particularly by enabling hybrid approaches such as combination of experimental component testing with analytical modeling and real-time interactions.

Product and Enterprise Design

An OCI will have major consequences for the practice of design (see Figure 1). Our presentation in this section considers two approaches to the topic, first product design and then enterprise design.

Product Design requires extensive collections of data and knowledge to be conjoined with various algorithms in complex and application-specific ways. Bringing together these components is costly and time-consuming, and has therefore tended to be limited to enterprises that have vast resources or whose operations are common enough to be covered by standard software packages. To handle the complexity of the design process for today's products, the new environment offered by the OCI must provide modelers, analysts, and decision-makers with a suite of analytical capabilities covering the entire design and modeling life cycle.
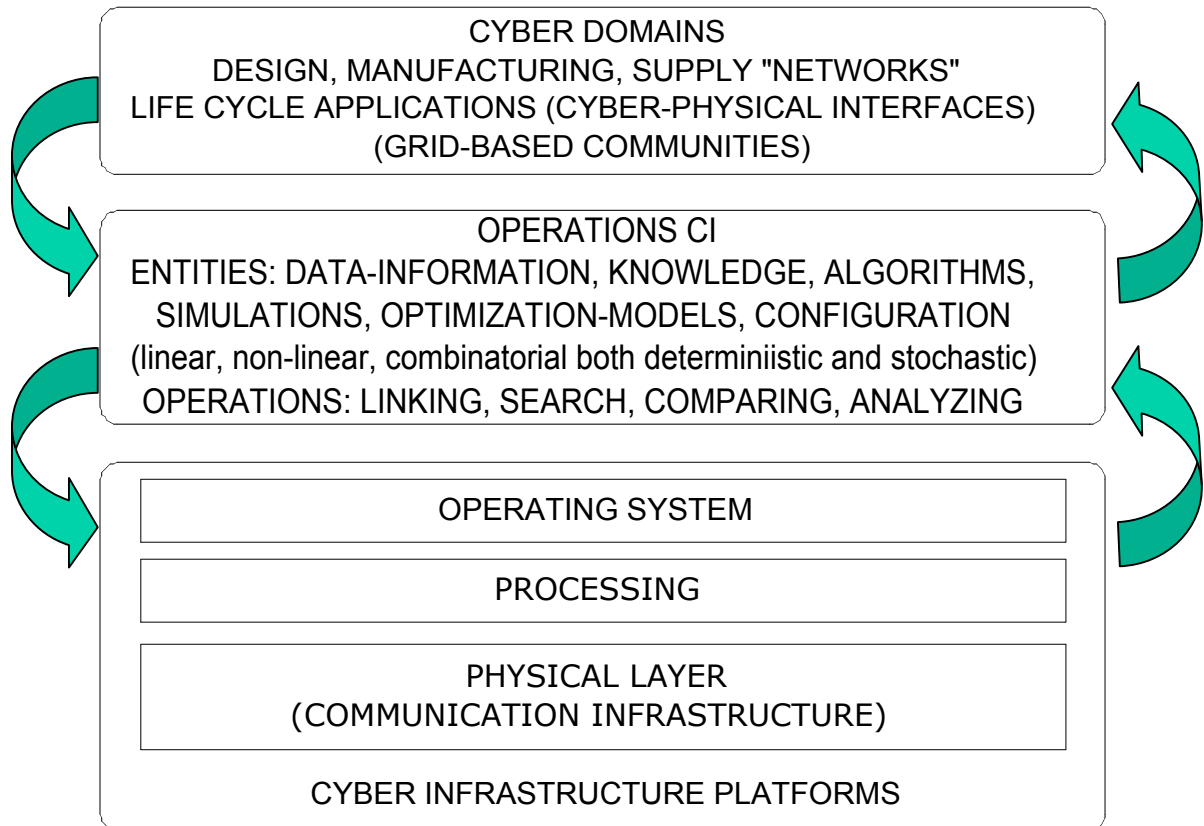
Figure 1: Combining top-down and bottom-up approaches at multiple levels and scales.

The OCI will take advantage of new Web services standards to allow data and algorithms to be combined more readily, encouraging design research and the use of design tools in a broader variety of enterprises. Specifically, the OCI will foster better storage and organization of the data repositories essential to product design, by linking a wide range of distributed databases and defining standards for accessing them. At the same time, it will provide access to more powerful algorithmic tools for data searching and mining, as well as to the advanced computational platforms that are conventionally associated with CI. The result will be to facilitate more complex design procedures, particularly for situations in which uncertainty of data or requirements must be accommodated. Examples include designing for flexibility to allow objects to adapt to their environment, and exploration of larger scenario spaces, possibly using paradigms and algorithms from stochastic optimization. In summary, CI features will provide much more widespread access to tools for solving complex design tasks.

OCI-related research in product design can help with issues related to product differentiation, product proliferation, and product standardization. How can we utilize OR models for postponement analysis to exploit standardization and common features of the design, yet facilitate product differentiation and customization? Research in OR theory and practice is required to answer this question. In particular, strategic research should be conducted on multi-tiered, multi-level, multi-objective, and network-centric design capabilities. Risk-utility

trade-offs for analyzing payoffs in various decision-making environments under highly dynamic product design scenarios is another potential focus area. The CI aspects of this research may involve the Web's ability to offer complex semantic capabilities to facilitate communication of data between OR tools and the applications they serve.

The OCI will be instrumental in dealing with system integration issues arising in physical, logical, and virtual system layers. In addition, it opens the door for multi-disciplinary exploration in the study of design, bringing together tools from computer science, electrical and computer engineering, mechanical engineering, industrial and systems engineering, and management science. OCI research should also explore the implications of emerging technologies in nano- and biosciences for innovation in product structures, issues of scale, and complexity management in product design.

With increasing focus of design and development on mass customization and customer-oriented products and services, traditional system design boundaries are blurring and even vanishing. The OCI offers opportunities to explore web-based technologies in such areas as product customization. In particular, it can shed new light on constraint satisfaction problems, which arise in distributed, decentralized, and autonomous environments, especially when complex product-process-resource platforms are present. Further development of the constraint-satisfaction approach may lead to enterprise applications that can integrate a wider range of collaboration efforts, from design to prototyping and manufacturing.

Enterprise Design encompasses physical entities such as electrical grids and communications networks, but also virtual entities such as alliances and markets. We see strong roles for an OCI in the design of both kinds of entities.

In the case of physical enterprises, OR tools can be used at the operational level. For example, robust operation of data communication networks or the electrical power grid could be performed by decentralized, real-time control procedures. Such procedures require effective placement of sensors and communication/handling of sensor data (CI issues) as well as the development of efficient OR models and algorithms that compute appropriate responses to dynamically changing network conditions. It is believed, with good reason, that decentralized control methodologies offer the best hope for continuing robust operation of the network after major disruptions. Clearly, in the case of data networks and the electricity grid, there are national security implications to this research.

OR expertise can play a key role in design of policies, pricing, and subscription mechanisms to facilitate smooth and fair operation of markets and to regulate information-sharing alliances in such areas as health care and product design. OR also can provide support tools that assist potential market participants with individual decision-making. (We discussed the case of electricity markets already in the Services section above.)

OR techniques are valuable in detecting disruptions and other environmental changes and in adapting enterprise designs in response. In this context, CI plays a crucial role in supplying up-to-the-second market information and in providing universal, reliable access to decision support tools.

Product Lifecycle Informatics

Within the interrelated processes of design, manufacturing, and supply-network management, there are a number of areas where the overall productivity of the enterprise can be transformed. CI components such as network support, computing grids, and data storage and analysis systems are not sufficient by themselves to cope with the complexity of modern production and manufacturing enterprises. Embedding of OR into CI will create new possibilities for handling large complex systems at multiple scales.

Management of product manufacturing enterprises is one class of problems that can benefit enormously from a synthesis of OR and CI. The resulting OCI will allow us to develop mechanisms whereby key issues at the enterprise level, the factory level, and the individual product level can be addressed in new and more effective ways. This end-to-end approach in product lifecycle and manufacturing, as implemented and delivered through an OCI, has the potential to lift productivities to very high levels.

While an OCI cannot directly manufacture products, it can be viewed as the "central nervous system" for an enterprise, providing the framework for connections from concept through design to process planning, factory operations, services, retirement, and recycling/reuse. For example, machine sensors can proactively link to production planning systems to support maintenance and self-assessment, with consequent financial impact at all levels: process, factory, supply network, and customer service. Factory operations can be linked together and therefore be responsive to a more demand-driven network. Supply networks of diverse size and scale can be linked by infrastructures that are able to reconfigure and respond quickly.

The present Internet is data- and information-driven, and information overload has become a significant problem in complex product and manufacturing networks. The OCI will be the key to extracting, synthesizing, and exploiting the information most relevant to the production enterprise; it will manage the enterprise's networks for design, production, and supply concurrency, configuration management, and decision support.

Hybrid approaches that combine experimental component testing with modeling (including real-time interactions) will allow simulation and testing of complex production systems. OR can provide complex optimization technologies as an adjunct to simulation and modeling components; CI will provide the computational capabilities for solving the large-scale distributed optimization and constraint problems that result from the OR formulations.

There is an urgent need for OR-centric enterprise resource planning (ERP) models to promote integrated decision-making in the enterprise. Existing ERP tools sorely lack this capability, because they lack essential CI and/or OR features such as sophisticated modeling capabilities and computational tools. An understanding of human factors at many levels of the manufacturing and decision-making process — the "human in the loop" — is also lacking in the current generation of tools. The OCI will enable tight integration of human factors (including social science and industrial engineering research) with CI and OR tool sets and methodologies. ERP tools can thus be taken to a new level of usefulness, with significant benefits for productivity across the enterprise.

The computing and communication resources available on a CI platform will enable users to perform modeling and optimization at a scale far beyond

their current capacities. Perhaps the most exciting possibility here is the potential to apply modeling and optimization techniques to manufacturing enterprises on a global scale.

Finally, we note that the OCI will allow us to avoid replication of costly resources among several domains such as design, manufacturing, services, and modeling tools in optimization and simulation.

Conclusions and Recommendations

The power of operations research to bridge information, knowledge, and decision-making fits naturally with the standards, accessibility, and computational resources characteristic of cyberinfrastructures. In this report, we have described how OR and CI can be brought together to create a multilevel *Operations Cyberinfrastructure (OCI)* that has major implications for productivity gains in design, manufacturing, and service enterprises throughout the economy (Figure 2).

System Level	*Functionality*	*Examples*
User Interaction & Interfaces	*Working level of interaction standards with users and user systems*	*Interface to various computing environments that enable access from various current and future operating platforms*
Applications	*Core tools for design, analysis, manufacture and supply chain coordination, etc. (proprietary, open source, and shared)*	*CADD, structural analysis programs, flow visualization, simulation tools, enterprise management, collaborative communications, optimization, configuration*
Community Resources	*Algorithms and analytical tools available to the applications and user levels Platform for community tool development & management*	*Data analysis tools, image processing, statistical analysis functions, data mining, search functions, language translators, optimization languages*
System Interoperation Architecture	*Low level operating software and standards, security, and communication protocols*	*Frameworks for interaction, communications, and resource sharing: Data, Information, Models, Knowledge*

Figure 2: Functions and examples of an Operations Cyberinfrastructure, distinguished by system level.

Timely action is of the essence if we are to take full advantage of the OCI's potential for revolutionizing the conduct of complex enterprise-wide

applications. Opportunities exist *now* for establishing compatible, non-proprietary approaches to knowledge archiving, data exchange, and — most important — interconnection of diverse OR analytical methods. As the Atkins report has suggested with respect to CI generally, missed opportunities for building the OCI now will be much harder to make up later, once poorly structured local cyberconnections, incompatible standards, and proprietary tools have come to dominate the field.

Basic research will play an essential role in the development of the OCI, in part because the OCI will connect and assist researchers in the development of new tools, but more importantly because much remains to be learned about how an OCI should be constructed for maximum impact on its large community of potential users. We see the evolution of the OCI as following the pattern set by other cyberinfrastructures that have come to be universally recognized. The initial risky steps will have to be taken by funded research, because commercial enterprises lack the expertise or are overly tied to proprietary investments in computing and productivity tools. Once OCI standards and protocols have been established and have proven their value in initial applications, the broad value of the OCI will become evident while its apparent risk fades, and commercial entities will increasingly assume the effort of further development.

An NSF initiative in this area should include significant funding for basic OR research that is tied to development of the OCI. It should also include research in the development of CI tools that are particularly relevant to the OCI and, possibly most important, research projects at the interface of OR and CI. Each research project of the latter type should be motivated by one or more significant enterprise-level applications, and should aim to develop and implement algorithms and tools that can be leveraged across the OCI. Typical research projects that could be supported under such an initiative could be, for example,

> ➢ development and implementation of an algorithm for solving a particular logistics problem that arises frequently in supply-network applications, with a commitment to making the resulting computational tool available through a Web server,

> ➢ construction of a modeling and analysis library to demonstrate the use of relatively new OR approaches (for example, stochastic optimization or optimization of simulations) in solving important problems in enterprise-wide applications; and

> ➢ development of methodologies and cybertools for design-time supply network design.

The value of these types of projects has already been seen in, for example, the success of the NEOS optimization server.[4] However, in contrast to earlier projects, an OCI initiative will have to address many more interactions among a much broader variety of tools, giving rise to correspondingly more difficult challenges in CI design.

Grantee meetings should be held regularly to ensure coordination across the OCI research portfolio. The portfolio should include wide coverage of the most significant OR and CI research areas, but should not include "loose end" projects that do not contribute to some aspect of OCI development. By its very

---

[4] See http://www-neos.mcs.anl.gov/neos.

nature, the OCI is an integrative entity, so the research program for its development should be similarly integrated.

Funding for OCI-related projects should be leveraged by funds for other NSF programs in CI, information science, engineering, and social, behavioral, and economic sciences. When appropriate, collaborators from areas outside of OR and CI who could contribute to OCI development should be included in funded research teams. Examples of such participants could include human-factors researchers (for human-in-the-loop modeling of manufacturing processes), economists (for modeling behavior of participants in an online market), design engineers (for product design applications), electrical engineers (for applications involving the power grid and electricity markets), and medical informaticists (for modeling of information-sharing alliances in health care).

In supporting OCI initiatives, NSF should consider the creation of a modestly scaled research center to act as an "umbrella" organization for the CI-OR effort. Such a center would undertake community-building activities such as maintaining an OCI advisory board, coordinating standards, and organizing periodic meetings, in addition to supporting OCI research at its host institution(s).

To ensure a sufficiently interdisciplinary funding mix, however, the majority of OCI support should consist of single-investigator and small-team grants directly from NSF programs. Smaller grants, administered directly by NSF program managers, have historically provided NSF with excellent return on investment. Strong, capable program managers, assisted by an advisory panel of CI and OR researchers to help with proposal evaluation and project monitoring, will be able to provide appropriate guidance. We are confident that the OCI project mix can be assembled and configured to seed, sustain, and leverage OCI development and to have a significant impact on productivity of the enterprises.