The Future of Systems, Man, and Cybernetics: Application Domains and Research Methods

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***Abstract*—Several important application areas that will dominate systems, man, and cybernetic (SMC) efforts for at least the next decade, together with the methods that will require further research and development in order to appropriately address these application domains, are considered herein. More specifically, four broad and pervasive system domains are examined: service systems, infrastructure and transportation systems, environmental and energy systems, and defense and space systems. Given the nature of these four application domains, a number of new *systems* [i.e., holistic-oriented, including system-of-systems (SoS)], *man* (i.e., decision-oriented, including decision informatics), and *cybernetic* (i.e., adaptive-oriented, including real-time control) methods are identified and their further development are discussed. Clearly, the IEEE Society on Systems, Man, and Cybernetics has a great future; its systems, man, and cybernetic methods are relevant for addressing challenging problems arising in system domains that are becoming dominant in this 21st century. However, the methods must be refined and expanded to meet the changing needs of the 21st century; from a system to a system-of-systems vision, from a disciplinary to a multidisciplinary outlook, from a mass production to a mass customization focus, from a steady state to a real-time perspective, and from an optimal to an adaptive approach.**

***Index Terms*—Cybernetics, decision informatics, defense systems, energy systems, environmental systems, infrastructure systems, real-time control, service systems, space systems, system-of-systems (SoS), transportation systems.**

I. MOTIVATION

IN MANY respects, the contents herein could be regarded as the third paper to consider the past, present, and future of the IEEE Society on Systems, Man, and Cybernetics (SMC). The two earlier papers by Palmer *et al.* [39], [40] addressed the topic mostly from an historical perspective, while this paper takes a uniquely prospective look at several representative application domains that will dominate SMC research for at least the short and medium terms, as well as the methods that will require further research and development in order to appropriately address pressing domain-related problems.

Given the infinite number of possible application domains, it is obvious that only a few of them can be investigated in this paper. In particular, four broad and pervasive system domains are considered: service systems, infrastructure and transportation systems, environmental and energy systems, and defense and space systems. Other domains that could have been examined include human factors, sensors and robotics, marketing systems, homeland security, health systems, and medical mechatronics. Likewise, it is impossible to explore the complete range of possible research methods that are required; nevertheless, given the nature of the application domains being considered, a number of new systems (i.e., holistic-oriented), man (i.e., decision-oriented), and cybernetic (i.e., adaptive-oriented) methods are identified and their further developments are discussed. Additional research methods that could have been addressed in this paper include adaptive risk assessment, machine learning, soft computing, systems security and reliability, risk and uncertainty analysis, system-of-systems (SoS) simulation, and multiagent systems. The four broad application domains and their dependence on the three sets of systems, man, and cybernetic (SMC) methods are summarized in Table I. The application domains and research methods are considered in the next two sections, respectively, while some concluding insights are provided in Section IV.

II. APPLICATION DOMAINS

The four application domains discussed in this section are indeed broad and, to some extent, overlapping. For example, transportation can be considered to be a part of services, while defense overlaps with services, transportation, and energy. Nevertheless, the essential characteristics of each domain are highlighted, especially from a systems, man, and cybernetic (SMC) perspective.

A. Service Systems

The importance of the services sector cannot be overstated [54], [56]; it employs a large and growing proportion of workers in the industrialized nations. As reflected in Table II, the services sector includes a number of large industries; indeed, services employment in the U.S. is at 82.1%, while the remaining four economic sectors (i.e., manufacturing, agriculture, construction, and mining), which together can be considered to be the "goods" sector, employ the remaining 17.9%. Alternatively, one could look at the distribution of employers for graduates from such technological universities as Rensselaer Polytechnic Institute (RPI); not surprisingly, as indicated in Table III, there

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TABLE I
DOMAINS AND METHODS

Systems, Man, and Cybernetics Methods	Application Domains			
	Service Systems	Infrastructure & Transportation Systems	Environmental & Energy Systems	Defense & Space Systems
<u>Systems (Holistic-Oriented) Methods</u>:				
• **Design**: Manufacturing, Services, Complexity, Life-Cycle	✓	✓	✓	✓
• **Interface**: Human Factors, Cognition	✓	✓	✓	✓
• **Integration**: Global, System of Systems	✓	✓	✓	✓
<u>Man (Decision-Oriented) Methods</u>:				
• **Strategic/Knowledge**: Value Systems, Simulation, Optimization	✓	✓	✓	✓
• **Tactical/Information**: Risk/Conflict Analysis, Game Theory	✓	✓	✓	✓
• **Operational/Data**: Decision Informatics, Software Agents	✓	✓	✓	✓
<u>Cybernetics (Adaptive-Oriented) Methods</u>:				
• **Data**: Fusion, Mining, Visualization, Support Vector Machine	✓	✓	✓	✓
• **Modeling**: Fuzzy Logic, Neural Networks, Genetic Algorithms, Bayesian Networks, Continuous Machine Learning	✓	✓	✓	✓
• **Control**: Supply Chain, Demand Chain, Enterprise Management	✓	✓	✓	✓

TABLE II
SCOPE AND SIZE OF U.S. EMPLOYMENT

INDUSTRIES	EMPLOYMENT (M)	Percent
Trade, Transportation & Utilities	26.1M	19.0%
Professional & Business	17.2	12.6
Health Care	14.8	10.8
Leisure & Hospitality	13.0	9.5
Education	13.0	9.5
Government (Except Education)	11.7	8.5
Finance, Insurance & Real Estate	8.3	6.1
Information & Telecommunication	3.1	2.2
Other	5.4	3.9
SERVICES SECTOR	**112.6**	**82.1**
Manufacturing	14.3	10.3
Construction	7.5	5.5
Agriculture	2.2	1.6
Mining	0.7	0.5
GOODS SECTOR	**24.7**	**17.9**
TOTAL	**137.3**	**100.0**

Source: *Bureau of Labor Statistics,* April 2006

TABLE III
REPORTED JOBS BY GRADUATING STUDENTS

ECONOMIC SECTOR	CLASS OF 1984-1985	CLASS OF 2004-2005
Services	29%	69%
Manufacturing	71	29
Agriculture	0	0
Construction	0	2
Mining	0	0
TOTAL	**100**	**100**

Source: *Career Development Center*, Rensselaer Polytechnic Institute

has been a complete flip of employment statistics within the past 20 years—from 71% being hired into manufacturing jobs in 1984–1985 to 69% entering into the services sector in 2004–2005. Moreover, such traditional manufacturing powerhouses like General Electric and International Business Machines have become more vertically integrated and are now earning an increasingly larger share of their income and profit through their services operations. Yet, university research and education have not followed suit; the majority of research is still manufacturing- or hardware-related and degree programs are still in those traditional disciplines that were established in the early 1900s. Clearly, services research and education deserve SMC's critical attention and support in this 21st century when the computer chip, information technology, the Internet, and the flattening of the world [11] have all combined to make services—and services innovation—the new engine for global economic growth.

What constitutes the services sector? It can be considered "to include all economic activities whose output is not a physical product or construction, is generally consumed at the time it is produced, and provides added value in forms (such as convenience, amusement, timeliness, comfort, or health) that are essentially intangible. . . " [42]. Implicit in this definition is the recognition that services production and services delivery are so integrated that they can be considered to be a single, combined stage in the services value chain, whereas the goods sector has a value chain that includes supplier, manufacturer, assembler, retailer, and customer. In fact, Tien and Berg [55] call for viewing services as an SoS that require integration with other systems and processes, over both time and space; they make a case for further developing a branch of systems engineering that focuses on problems and issues that arise in the services sector. In this manner, they demonstrate how the traditional systems approach to analysis, control, and optimization can be applied to an SoS that are each within the province of a distinct service provider. They underscore this special focus not only because of the size and importance of the services sector but also because of the unique systems engineering opportunities that can be exploited in the design and joint production and delivery of services.

The following discussion considers, respectively, the emergence of electronic services, the relationship to manufacturing, and the movement toward mass customization of both goods and services.

1) Emerging Services: Prospectively, it is perhaps more appropriate to focus on emerging e(lectronic)-services. The e-services are, of course, totally dependent on information technology; they include, as examples, financial services, banking, airline reservation systems, and consumer goods marketing. As discussed by Tien and Berg [55], e-service enterprises interact or "coproduce" with their customers in a digital (including e-mail and Internet) medium, as compared to the physical environment in which traditional or bricks-and-mortar service enterprises interact with their customers. Similarly, in comparison to traditional services, which include low-wage jobs, e-services typically employ high-wage earners—and such services are more demanding in their requirements for self-service, transaction speed, and computation. With regard to data sources that could be used to help make appropriate service decisions, both sets of services rely on multiple data sources; however, the traditional services typically require homogeneous (mostly quantitative) sources, while e-services increasingly require nonhomogeneous (i.e., both quantitative and qualitative) sources. Paradoxically, the traditional service enterprises have been driven by data, although data availability and accuracy have been limited (especially before the pervasive use of the Universal Product Code and the more recent deployment of radio frequency location and identification—RFLID—tags); likewise, the emerging e-service enterprises have been driven by information (i.e., processed data), although information availability and accuracy have been limited, due to a data-rich, information-poor (DRIP) conundrum [51].

Consequently, while traditional services—like traditional manufacturing—are based on economies of scale and a standardized approach, electronic services—like electronic manufacturing—emphasize economies of expertise or knowledge and an adaptive approach. Another critical distinction between traditional and electronic services is that, although all services require decisions to be made, traditional services are typically based on predetermined decision rules, while electronic services require real-time, adaptive decision-making; that is why Tien [51] has advanced a decision informatics paradigm, one that relies on both information and decision technologies from a real-time perspective. High-speed Internet access, low-cost computing, wireless networks, electronic sensors, and ever-smarter software are the tools for building a global services economy. Thus, in e-commerce, sophisticated and integrated services are combining product (i.e., good and/or service) selection, order taking, payment processing, order fulfillment, and delivery scheduling into a seamless system, all provided by distinct service providers.

TABLE IV
SERVICES VERSUS MANUFACTURED GOODS

FOCUS	SERVICES	MANUFACTURED GOODS
Production	***C***o-Produced	***P***re-Produced
Variability	***H***eterogeneous	***I***dentical
Physicality	***I***ntangible	***T***angible
Product	***P***erishable	"***I***nventoryable"
Objective	***P***ersonalizable	***R***eliable
Satisfaction	***E***xpectation-Related	***U***tility-Related
Life Cycle	***R***eusable	***R***ecyclable
OVERALL	***CHIPPER***	***PITIRUR***

2) Relationship to Manufacturing: The interdependences, similarities, and complementarities of services and manufacturing are significant. Indeed, many of the recent innovations in manufacturing are relevant to the service industries. Concepts and processes such as cycle time, total quality management, quality circles, six-sigma, design for assembly, design for manufacturability, design for recycling, small-batch production, concurrent engineering, just-in-time manufacturing, rapid prototyping, flexible manufacturing, agile manufacturing, distributed manufacturing, and environmentally sound manufacturing can, for the most part, be recast in services-related terms. Thus, many of the engineering and management concepts and processes employed in manufacturing can likewise be used to deal with problems and issues arising in the services sector.

Tien and Berg [55] provide a comparison between the goods and services sectors. The goods sector requires material as input, is physical in nature, involves the customer at the design stage, and employs mostly quantitative measures to assess its performance. On the other hand, the services sector requires information as input, is virtual in nature, involves the customer at the production/delivery stage, and employs mostly qualitative measures to assess its performance. Of course, even when there are similarities, it is critical that the coproducing nature of services be carefully taken into consideration. For example, in manufacturing, physical parameters, statistics of production, and quality can be more precisely delineated; on the other hand, since a service operation depends on an interaction between the process of producing the service and the recipient, the characterization is necessarily more subjective and different. Consequently, since services are to a large extent subject to customer satisfaction and since, as Tien and Cahn [57] postulated and validated, "satisfaction is a function of expectation," service performance or satisfaction can be enhanced through the effective "management" of expectation.

A more insightful approach to understanding and advancing services research is to consider the differences between services and manufactured goods. As identified in Table IV, services are, by definition, coproduced; quite variable or heterogeneous in their production and delivery, physically intangible, perishable if not consumed as it is being produced or by a certain time (e.g., before a flight's or train's departure), focused on being personalizable, expectation-related in terms of customer satisfaction, and reusable in its entirety. On the other hand, manufactured goods are preproduced, quite identical or substitutable in their production and use, physically tangible, "inventoryable"

TABLE V
RESEARCH TAXONOMY FOR DEMAND AND SUPPLY CHAINS

	DEMAND	
SUPPLY	**Fixed**	**Flexible**
Fixed	**Unable To Manage** Price Established (At Point Where Fixed Demand Matches Fixed Supply)	**Demand Chain Management (DCM)** Product Revenue Management Dynamic Pricing Target Marketing Expectation Management Auctions
Flexible	**Supply Chain Management (SCM)** Inventory Control Production Scheduling Distribution Planning Capacity Revenue Management Reverse Auctions	**Real-Time Customized Management (RTCM)** Customized Bundling Customized Revenue Management Customized Pricing Customized Modularization Customized Co-Production Systems

if not consumed, focused on being reliable, utility-related in terms of customer satisfaction, and recyclable in regard to their parts. In mnemonic terms and referring to Table IV, services can be considered to be "chipper," while manufactured goods are "pitirur." Although the comparison between services and manufacturing highlights some obvious methodological differences, it is interesting to note that the physical manufactured assets depreciate with use and time, while the virtual service assets are generally reusable, and may, in fact, increase in value with repeated use and over time. The latter assets are predominantly processes and associated human resources that build on the skill and knowledge base accumulated by repeated interactions with the service receiver, who is involved in the coproduction of the service. Thus, for example, a lecturer should get better over time, especially if the same lecture is repeated.

In services, automation-driven software algorithms have transformed human resource-laden, coproducing service systems to software algorithm-laden, self-producing services. Thus, extensive manpower would be required to manually coproduce the services if automation were not available. Although automation has certainly improved productivity and decreased costs in some services (e.g., telecommunications, Internet commerce, etc.), it has not yet had a similar impact on other labor-intensive services (e.g., health care, education, etc.). However, with new multimedia and broadband technologies, some hospitals are personalizing their treatment of patients, including the sharing of electronic records with their patients [9], and some institutions are offering entire degree programs online with just-in-time learning capabilities [50].

3) Toward Mass Customization: Tien *et al.* [58] provide a consistent approach to considering the customization of both goods and services—by first defining a value chain and then showing how it can be partitioned into a supply chain and a demand chain, which, in turn, can be appropriately managed. Of course, the key purpose for the management of supply and demand chains is to smooth out the peaks and valleys commonly seen in many supply and demand patterns, respectively. Although only depicting a simple two-by-two, supply versus demand, matrix, Table V provides an insightful understanding of supply chain management (SCM, which can occur when demand is fixed and supply is flexible), demand chain management (DCM, which can occur when supply is fixed and demand is flexible), and real-time customized management (RTCM, which can occur when both demand and supply are flexible and where real-time mass customization is possible).

Table V identifies several example SCM, DCM, and RTCM methods. The literature is overwhelmed with SCM findings (especially in regard to manufacturing), is only recently focusing on DCM methods (especially in regard to revenue management), and is devoid of RTCM considerations, except for a recent contribution by Yasar [60]—he combines two SCM methods (i.e., capacity rationing and capacity extending) and two DCM methods (i.e., demand bumping and demand recapturing) to deal with the real-time customized management of, as examples, either a goods problem concerned with the rationing of equipment to produce classes of products or a services problem concerned with the rationing of consultants to coproduce classes of services.

The shift in focus from mass production to mass customization (whereby a service is produced and delivered in response to a customer's stated or imputed needs) is intended to provide superior value to customers by meeting their unique needs. It is in this area of customization—where customer involvement is not only at the goods design stage but also at the manufacturing or coproduction stage—that services and manufacturing are merging in concept [56].

Finally, it should be noted that customization is both an enabler and a driver for services innovation. After a detailed review and analysis, Tien [53] suggests that innovation in the services area—especially in e(lectronic)-services—are facilitated by nine major innovation enablers (i.e., decision informatics, software algorithms, automation, telecommunication, collaboration, standardization, customization, organization, and globalization) and motivated by four innovation drivers (i.e., collaboration, customization, integration, and adaptation). Not surprisingly, all four drivers are directed at empowering the individual—that is, at recognizing that the individual can, respectively, contribute in a collaborative situation, receive customized or personalized attention, access an integrated SoS, and obtain adaptive real-time- or just-in-time input.

B. *Infrastructure and Transportation Systems*

Transportation and its concomitant information and physical infrastructures constitute a sizeable part of the services sector and provide a rich source of intellectually challenging SMC-related research topics that have considerable potential for real-world impact. Such systems involve the movement of people and goods, enabled by a physical infrastructure comprised of roads, bridges, seaports, airports, pipelines, sea lanes, air lanes, canals, and vehicles (e.g., automobiles, trucks, buses, trains, airplanes, bicycles, etc.), all enabled by an underpinning information infrastructure (i.e., traffic control systems, traffic congestion sensors, etc.) that serves to maintain and manage the physical infrastructure. The economic and social impacts of transportation are enormous, especially in regard to freight or the movement of goods.

The U.S. spends roughly 45% of the cost of transportation on the movement of goods. Roughly $1 trillion or 9% of the nation's GDP is generated by the freight or logistics industry, the industry that moves and stores goods. Approximately 27% of the nation's GDP is created by the movement of goods across the nation's international borders. Trucks provide for nearly 60% in shipment volume and nearly 82% in shipment revenue in the transportation sector, making the trucking industry the dominant mode for freight movement. Trucking is a major employer in the U.S., with 9.7 million people being employed in trucking or trucking-related jobs in 1998. Further information about the freight transportation industry can be found in Nagarajan *et al.* [36].

A prime reason for moving freight (including commodities, work in progress, or finished goods) is to serve the extended enterprise, a network of independent companies with the intent to respond to customers with better, less expensive products and faster-to-market technologies. Goods, information, and money flow in this network, and these flows are often called the supply chain, the design of which involves the determination of how value is added. Value can be added either internally by the lead company in the enterprise or by an outside supplier. If the decision is to outsource, then supplier selection also becomes an issue. Supply chain management involves managing the flow of goods (e.g., determining routes, schedules, and warehousing facilities) and adding value to these goods (e.g., manufacturing and packaging).

In order to identify relevant technical challenges associated with the logistics and supply chain industries that can be addressed by SMC tools and techniques, it is important to understand the trends and forces that are affecting, and are affected by, these industries, as discussed later.

1) Outsourcing: As mentioned earlier, supply chain design involves determining whether or not a company or enterprise should assume responsibility for manufacturing a particular component or providing a specific service in its supply chain; alternatively, one could outsource the products or service functions. Logistics is one of the first functions to be outsourced for a variety of reasons. Rarely will a manufacturer consider logistics as a core competency, although companies that consider supply chain management a core competency (e.g., Dell) often have a resultant competitive advantage. Private fleets are rarely as cost effective as for-hire carriers since private carriers typically do not have access to back-hauls that the for-hire carriers have. The value of outsourcing the logistics function becomes more pronounced as supply chains become more complex as a result of, say, offshoring (where the manufacturing is performed offshore). These facts have led to the establishment of a third-party logistics (3PL) industry, an industry of companies—many of which do not have assets such as trucks, ships, and trains—that can handle the freight transportation and warehousing between an origin (e.g., a supplier) and a destination (e.g., an assembly plant) in a supply chain. The 3PL industry has experienced phenomenal growth in the U.S. in the 1990s and is poised to experience the same level of growth in China.

The decision to outsource is typically based on the fact that there is a supplier who can make a particular component less expensively and/or at a higher quality than can be made by the original equipment manufacturer (OEM). Expense must include both the cost to manufacture and the cost to transport and warehouse the component for the next stage in the production process. The trend of outsourcing offshore is enabled by good quality, by inexpensive offshore manufacturing (often due to low labor and/or material costs), and by a global logistics industry, all dependent on an efficient global web that can move goods cheaply and reliably around the world. As manufacturing has gone offshore and global, so has the need for freight transportation. The impact of being able to manufacture offshore inexpensively has had a tremendous geopolitical and economic impact. For example, China is now considered the "world's largest factory" in that it produces more than 50% of the world's cameras, 30% of the air conditioners and televisions, 25% of the washing machines, almost 20% of the refrigerators, more than 33% of the digital video disk-read-only memory (DVD-ROM) drives and personal, desktop, and notebook computers, and about 25% of its own mobile phones, color televisions, personal digital assistants, and car stereos. As a consequence, a freight transportation company can gain and retain customers if it has a global reach. Global strategic expansion can also enable domestic growth. Freight moved from, say, China to the U.S. also has to be moved within the U.S., and, therefore, represents potential domestic business. Hence, a strategy for increasing a company's freight business in the U.S. can be achieved by capturing U.S.-bound freight offshore, transporting it to the U.S., and then inserting it into the company's U.S. domestic freight network (i.e., "feed the beast"). The next stage for system expansion for a freight transportation system that is well developed in the U.S. and that has expanded to move goods between the U.S. and foreign countries is emerging in the offshore market itself, a phenomenon that is anticipated in fast-growing China.

2) Vertical Integration, Consolidation, and Congestion: Once the decision is made to outsource logistics, there is a tendency to look for 3PLs that can provide a complete logistics solution (i.e., "one-stop shipping"). Such a customer requirement has led to an expanded set of services that are offered by the freight transportation industry. For example, the United Parcel Service (UPS), historically a package express company, now has expanded its services in the following manner:

1) For Toshiba, UPS picks up computers in need of repair, and then also repairs them.
2) For Papa John's, UPS schedules and dispatches their truck drivers for the pickup and delivery of pizza supplies (i.e., tomatoes, pizza sauce, cheese, etc.).
3) For Nike, UPS inspects, packs, and delivers their shoes and manages their warehouse.
4) For Jockey, UPS fills the order, bags it, labels it, and delivers it, all from a UPS-owned warehouse.
5) For Hewlett-Packard, UPS manages their replacement parts and repair divisions in Europe and Latin America.

Other integrated service providers include the U.S.-based FedEx and DHL, and the Japan-based Nittsu. It should also be noted that increased geographic span and service expansion, coupled with economies of scale, are moving the industry toward greater consolidation.

Infrastructure congestion in the U.S. is increasing as offshoring grows, as domestic freight movement increases due to the normal growth of the U.S. domestic market, and as U.S. freight transportation infrastructure remains constant. This congestion is occurring at sea and at air cargo ports, rail lines, canals, and highways. Congestion increases not only the length of lead time (i.e., the time needed to go from origin to destination), but it also increases lead time variability. The resulting productivity and environmental impact can be profound and is, of course, usually negative. Under robust assumptions, the amount of safety stock needed to maintain a certain customer service level increases as a function of both the mean and the variance of the lead time. Thus, congestion requires a greater level of inventory; hence, a greater inventory holding cost.

3) Supply Chain and Information Technologies: Global supply chains that move goods across national boundaries, through many time zones and across several oceans and continents, are invariably complex and offer heightened opportunities for supply chain disruptions. Some of these disruptions are due to the expected variations in, as examples, demand, congestion, and weather. However, low probability, highly disruptive events (e.g., labor strikes, terrorist attacks, major accidents, extreme weather conditions, etc.) can occur and represent a significantly greater management challenge. How to best design resilient supply chains and freight transportation strategies that are "robust" or "adaptive" and degrade gracefully under such circumstances is a topic of considerable interest in the freight transportation industry. Some mitigating ideas include the use of multiple suppliers and the practice of postponement to help "shock-proof" supply chains and ensure a quicker return to normal operations following a major disruption.

The freight transportation industry can benefit from many advances in a variety of technologies, especially information technologies that allow for real-time control of supply chains, based on real-time system information. Clearly, a decision informatics [51] approach to managing supply chains represents the next level of supply chain productivity, including efficiency, resiliency, and other desirable supply chain characteristics (e.g., stability), all challenges for the community of SMC researchers. The value of information in the freight transportation industry has been assumed to be significant, although this is not always the case. Nevertheless, timely information has been credited with reducing cost in the long haul less-than-truckload (LTL) segment of the U.S. trucking industry, with being essential to the efficient scheduling and tracking of valuable and always on-the-move assets, and with reducing inventory levels and providing for just-in-time supply chains.

In practice, it is essential to have real-time information concerning inventory levels; production rates; vehicle, vessel, or trailer operating characteristics (i.e., position, speed, direction, temperature, oil pressure, and tire pressure); driver alertness; traffic congestion; and weather. A related challenge that the industry faces is how to fuse and transform the incoming sensor data into information so that informed decisions can be made in a real-time manner, all in the face of data that may be delayed and/or corrupted by incorrect sensor readings. The concomitant decision support system must be based on models of sequential decision-making that can explicitly take into consideration possible uncertainties and noise-corrupted observations. Such adaptive, real-time models tend to be much more computationally demanding than the current generation of supply chain systems software that relies on optimal, mathematical programming solutions.

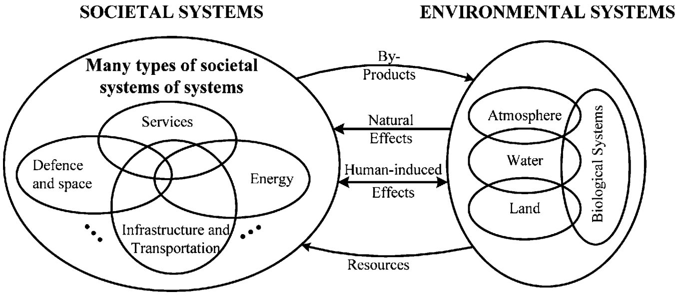

Fig. 1. Societal and environmental systems.

C. Environmental and Energy Systems

General relationships existing between societal and environmental systems are explained first. After highlighting the importance of maintaining sustainable relationships between these two crucial SoSs, the urgent necessity of having sustainable connections between energy and atmospheric systems is explained. Finally, opportunities are put forward to systems thinkers and others to thwart the dangerous buildup of carbon dioxide (CO_2) in order to mitigate global warming.

1) Societal and Environmental Systems: Biological life on earth can be classified into two main categories: animal life (i.e., zoological species) and plant life (i.e., botanical species). Both of these categories of species survive and thrive within the environmental systems that exist on planet earth. As shown on the right-hand side of Fig. 1, land, water, and atmosphere are three crucial environmental systems upon which biological systems are dependent. When environmental systems intersect in a meaningful way at a given location on the globe, the resulting system is often referred to as an ecological system. For instance, a river basin often forms a natural ecological system within which human activities and their environmental impacts can be better understood and sustainably maintained. The pathways in which water travels in its various forms through the atmosphere, land, and bodies of water is called the hydrological cycle—see Hipel and McLeod [23, Section 1.4] for a definition and associated references. Moreover, all of these environmental systems are highly interconnected, possessing many positive and negative feedback loops; indeed, one can certainly refer to each one of them as an SoS. For example, the Gulf Stream brings warm water from the tropical areas of the Atlantic Ocean, northward past the coastline of Europe where it heats the atmosphere and land, thereby controlling climatic conditions such as temperature and precipitation patterns; then, cold water from the Arctic sinks and returns in a southerly direction in the Atlantic Ocean, thereby keeping this "conveyor belt" of water in continuous circulation.

The left side of Fig. 1 identifies some important examples of societal systems that are discussed in this paper: services, infrastructure and transportation, energy, and defense and space systems. As can be seen, these and other kinds of societal systems overlap with one another via highly dependent structures designed by humans to serve their needs and desires. All societal systems, for instance, are completely reliant upon access to energy systems, without which they would cease to operate or exist. For example, transportation systems would grind to a halt if cars, trucks, trains, aircraft, and ships could not obtain fuel from appropriate energy sources. Other basic services or infrastructure systems, such as supplying water to the residential, agricultural, industrial, and commercial sectors of society, could not function without having electrical energy sources to deliver water through pipes.

As depicted by the arrows connecting the societal and environmental systems in Fig. 1, these two sets of systems directly affect one another, although, in general, societal systems are ultimately at the mercy of environmental systems. In particular, the resources arrow indicates that all societal systems must obtain resources from the various environmental systems in order to survive and flourish. For example, all industrial products, such as cars, planes, and computers, are built using raw materials extracted from nature. Even services, like legal practices and psychological counseling, which largely involve thinking and utilizing concepts from information technologies, require resources from the environment inasmuch as those humans creating and benefiting from these activities must be housed and fed. Whatever the case, every type of societal system produces unwanted by-products that are, unfortunately, dumped into the environment as partially treated or untreated wastes. Cities, such as Victoria and Halifax in Canada, Rio de Janeiro in Brazil, and all of the coastal cities of China, knowingly discharge huge quantities of untreated sewage into the oceans. In response to such human-induced activities, natural systems may react in unforeseen and violent ways. For example, heavy rainfall in mountainous areas that have been deforested as a result of poor logging practices can cause unexpected landslides, bringing about high losses of human life and property. In some cases, such as earthquakes, tsunamis, and volcanic eruptions, the destructive actions of nature upon societal systems are, of course, not the fault of human activities, although preventative measures, such as constructing earthquake-proof buildings and having effective warning and evacuation plans in place, can mitigate the effects of these natural disasters.

2) Sustainable Systems: Continuing increases in human populations on planet earth mean that more and more societal systems are being created to serve these populations. Consequently, valuable resources such as water, minerals, metals, and agricultural land are being consumed by society, resulting in a concomitant increase in the volume and complexity of by-products. The exploding increase in the number of synthetic products made by an array of newly created chemicals could have a number of unsuspected negative consequences on both human health and the environment. Accordingly, there is a vast array of opportunities for systems engineers to address the complex and interconnected problems affecting the earth's societal and environmental systems. Of overriding import is the development of systems methodologies for creating and maintaining sustainable relationships between societal and environmental systems. Resources must be utilized in a responsible manner, consistent with environmental, ethical, economic, and other societal principles. The by-products of human activities should be minimized, recycled whenever possible, and properly treated, with any remaining residues being responsibly stored. Suitable agreements, policies, laws, and effective implementation mechanisms are required at the local, regional, provincial, national, and international levels to ensure the sustainability of these critical, life-sustaining SoSs. Adaptive decision-making, coupled in an integrative manner with informatics and many other systems techniques, is essential for sustainably managing the SoSs and their interrelationships depicted in Fig. 1 in real-time as well as within short-, medium-, and long-term perspectives.

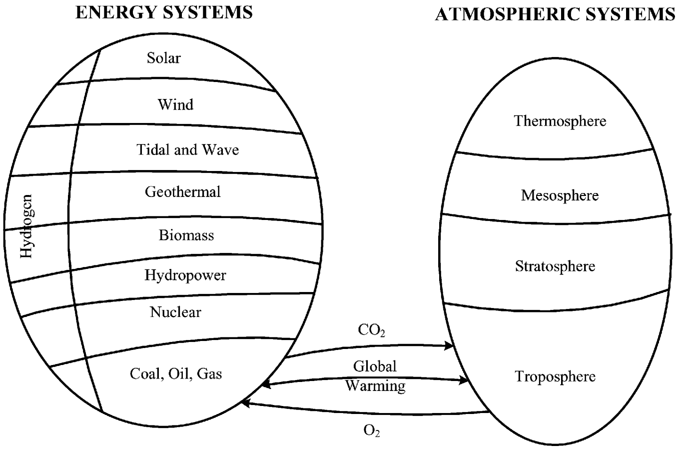

Fig. 2. Energy and atmospheric systems.

3) Energy Systems, Atmospheric Systems, and Global Warming: To highlight why systems thinking approaches are urgently needed to tackle a near and present danger now being played out between societal and environmental systems, consider the serious situation illustrated in Fig. 2, between energy systems from the societal domain and atmospheric systems from the environmental domain. As depicted on the left in Fig. 2, humans design, operate, and maintain a range of systems for producing energy to satisfy the energy demands of many different kinds of societal systems. Of particular importance in the development of modern civilization has been the extensive extraction, processing, and utilization of fossil fuels (i.e., coal, oil, and gas) for heating, cooking, lighting, agriculture, industry, transportation, and other purposes. The widespread burning of coal started in England about 700 years ago and became an increasingly key energy source with the initiation of the industrial revolution in the late 18th century; in fact, the 19th century has been coined the century of coal. The 20th century is considered the century of oil, in which first the Americans and Europeans and then the Asians and people in the rest of the world developed an enormous appetite for driving automobiles. By the year 2025, gas may overtake oil as the world's most important fossil fuel source.

In 2005, the U.S. consumed almost 21 million barrels of oil per day, followed by China and Japan at 6.5 and 5.4, respectively, with India in sixth place at 2.6. With the emergence of China and India as industrial superpowers, the competition and demand for oil and other fossil fuels is bound to increase

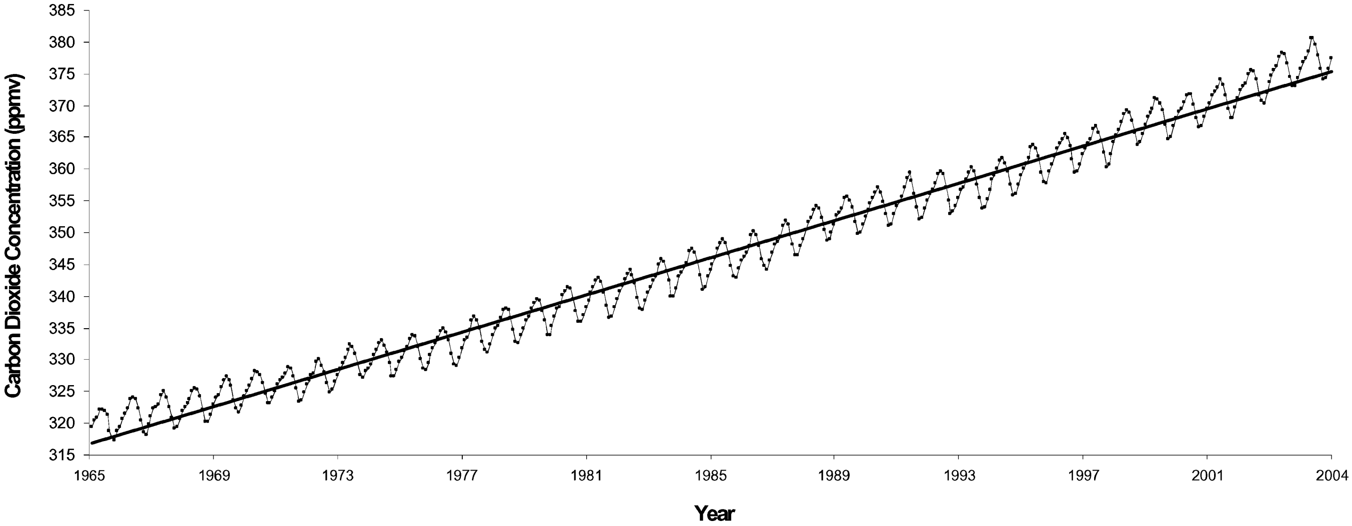

Fig. 3. Monthly concentrations of atmospheric carbon dioxide. *Note*. Carbon dioxide volume in parts per million, as measured at the Mauna Loa Observatory in Hawaii for the period from January 1965 to December 2004 with a linear trend line superimposed on the plot of the data.

dramatically. Unfortunately, when fossil fuels are burnt, CO_2 is released into the atmosphere, and, in today's world, the quantity of CO_2 emitted is enormous. Carbon dioxide is the most abundant of about 30 other known greenhouse gases, including methane and nitrous oxide, which trap heat near the earth's surface in the troposphere, as shown on the right in Fig. 2. Capturing heat in the lower troposphere causes global warming and climatic change well beyond that which could be expected through natural processes, devoid of human influences. Overall, it is estimated that CO_2 emissions resulting from human activities cause about 80% of global warming. More specifically, CO_2 released as by-products from electricity production and transportation systems is the biggest culprit in global warming, with coal-fired power generation plants being the worst offenders. Ironically, the stratosphere, which is located from about 12 to 50 km above the earth's surface, is, in fact, cooling because of the destruction of the ozone layer and the creation of ozone holes precipitated by the release of chlorofluorocarbons (CFCs), a synthetic chemical produced solely by humans.

The carbon budget refers to the amount of carbon stored in the various environmental systems shown on the right in Fig. 1. As indicated earlier, a crucial controller and harbinger of climatic change is the amount of CO_2 present in the lower part of the troposphere. Prior to 1800, at the start of the industrial revolution, there were 280 parts per million (ppm) of CO_2 in the atmosphere. In 1958, Charles David Keeling measured 315 ppm of CO_2 atop Mauna Loa on the Big Island of Hawaii. Except for some missing values during the first few years of record, continuous measurements of monthly CO_2 values at the Mauna Loa site are available up until the present time [30]. Fig. 3, showing the famous "Keeling Curve," displays the average monthly concentrations of CO_2 in parts per million, as measured at the Mauna Loa Observatory from January 1965 until December 2004 [30]. The sinusoidal curve reflects the seasonal variations in CO_2 concentrations. In particular, the regeneration of plant life in the spring in the large land masses of the northern hemisphere causes more CO_2 to be absorbed while the decaying of plants and tree leaves in the fall releases CO_2. However, what is particularly disturbing about this curve is that these seasonal variations are wrapped around a distinctive upward trend line, one that is dramatically increasing over time.

There is now almost universal consensus that the effects of greenhouse gases and climatic change upon societal and environmental will be devastating. Scientific analysis of measurements from tree rings, ice cores, and other natural evidence permits scientists to make fairly accurate estimates of CO_2 levels, atmospheric temperatures, and associated climatic effects far into the past. Scientists also know that going from 300 to 600 ppm of CO_2 concentration can heat the atmosphere from 3 to 6 °C. In addition, since 1990, nine out of the ten warmest years ever recorded have occurred, with 1976 and 1998 being the years of exceptional change.

The question naturally arises as to what will happen if society continues with "business as usual" and atmospheric CO_2 concentrations continue to spiral out of control as shown in Fig. 3. Knowledgeable experts from around the globe have some pretty dire predictions—see, as examples, Diamond [5], Flannery [8], Gore [13], International Panel on Climatic Change [25], and Kolbert [32]. Of prime concern is the effect upon the biological systems shown on the right in Fig. 1. There is now no doubt that there will be mass extinctions of plants and animals and many of the societal systems shown on the left in Fig. 1 could be greatly weakened, if not obliterated. In fact, in the late 1980s, the disappearance of the golden toad in Costa Rica was the first proven case of extinction caused by climatic change. Extreme climatic conditions are a key characteristic of climatic change and are already well underway as evidenced by severe droughts (e.g., in Africa and Australia), devastating hurricanes (e.g., Hurricane Katrina in 2005), and increasing coastal floods (e.g., due to the melting of the polar ice caps and glaciers).

4) Timely Opportunities: The foregoing bleak picture of the devastation that global warming can wreak upon the societal and environmental systems provides a unique window of opportunity for systems engineers, in particular, and citizens of the world, in general, to take timely and determined actions to forestall the catastrophic effects of climactic change, while simultaneously allowing the societal systems on the left in Figs. 1 and 2 to function within a sustainable framework. As in a systems approach to creative problem solving, a clear vision and mission are required. Certainly, CO_2 levels must be brought under control and, fortunately, scientists have also worked out exactly what has to be accomplished on a global scale. Specifically, society requires a 70% reduction in CO_2 emissions below 1990 levels by 2050 in order to stabilize the earth's climate [8]. Additionally, annual emissions of all greenhouse gases must be decreased to at least 80% of current 2006 levels [49]; this will cause the atmosphere to contain about 450 ppm of CO_2, which, in turn, would cause world climate to stabilize in 2100 at a temperature that would be 1.1 °C higher than today, with some locations heating up by as much as an additional 5 °C. One should keep in mind, however, that 450 ppm of CO_2 in the atmosphere is a level which is far higher than any that has occurred in the last 650 000 years.

Because virtually all CO_2 emissions are connected with the extraction, processing, distribution, and utilization of energy within societal systems, energy systems must be properly designed and managed to meet the 450 ppm of CO_2 requirement. Fortunately, the technical solutions for meeting such a requirement are already known, and the associated costs are manageable. The left side in Fig. 2 lists the main energy sources that are currently available; the top five sources—solar, wind, tidal and wave, geothermal, and biomass—constitute renewable energies, among which only biomass has CO_2 emissions that, fortunately, can be controlled. Nuclear power generation is completely free of CO_2 emissions, although one must ultimately dispense of the nuclear residual wastes. In 1996, Japan became the first nation to start using third-generation nuclear reactors, and planning for a fourth-generation reactor is well underway. Even fossil fuels present a viable option for providing energy in the long term if large-scale CO_2 sequestration technologies can be successfully implemented [26], [43]. Two popular carbon dioxide sequestration techniques that are being considered are pumping compressed CO_2 deep into the oceans and concentrated CO_2 into the ground (i.e., geosequestration). Carbon dioxide from coal-fired power stations can be injected into oil formations to increase pressure and thereby assist in the recovery of oil and gas. Through reforestation and the practice of sustainable agriculture and animal husbandry, the earth's vegetation and soils can likewise act as carbon sinks. One far-out suggested solution to CO_2 sequestration is to fertilize the southern oceans with iron filings, a limiting nutrient for the growth of plankton, which can capture CO_2 and sink to the bottom of the ocean when they die.

Innovative design and modeling procedures considered in Section III can be employed for comparing alternative energy generation methods. An innovative technical design is not complete, realistic, meaningful, or, for that matter, ethical, unless it reflects the value systems of stakeholders and is directly linked with proper proactive policy, governance, implementation, and regulatory systems, at the local, provincial, national, and international levels—to ensure that the vision, mission, and goals are met in an adaptive, integrative, and real-time manner. As noted earlier and from a very general viewpoint, there are tremendous opportunities for systems thinkers and other professionals to design systems that can guarantee and maintain sustainable relationships between the societal and environmental systems depicted in Fig. 1. Moreover, some of the major difficulties in sustainable relationships that may arise in the future, perhaps related to the planting of genetically altered seeds or the spread of yet-to-be identified viruses, may be largely unknown and become recognizable only after they emerge. Consequently, both precautionary and proactive systems must be in place to adaptively tackle real-time problems that are presently unforeseen as well as dilemmas that are already visualized. System-wide policies may consist of both carrots (i.e., incentives) and sticks (i.e., mandates), and may deal with the problem from both a supply-side and a demand-side perspective.

The 1997 Kyoto Protocol, an agreement among nations of the world to reduce greenhouse gas levels, is a step in the right direction. However, the biggest emitter of CO_2, the U.S., as well as Australia, have not signed the Kyoto Protocol and critics complain that the protocol "lacks teeth" and permits relatively large polluters like China and India to keep on polluting, at least in the short run while their economies develop. Various carrots (e.g., carbon trading, tax incentives) and sticks (e.g., strict enforcement procedures, economic penalties) have been suggested as components of a CO_2 reduction agreement. As argued by Hipel and Obeidi [24], economic agreements—such as those falling under the World Trade Organization (WTO) and the North American Free Trade Agreement (NAFTA)—could be modified to reflect environmental, societal, and other types of concerns. Alternatively, these highly criticized economic agreements, which underpin globalization, could be replaced by fair and ethical treaties that are economically, environmentally, and socially viable. More importantly and as argued by Gore [13] and Glasby [12], political will is required to control greenhouse gases. The 1987 Montreal Protocol, however, is an example of a successful environmental treaty; it has been able to minimize the ozone holes over the poles by banning the use of chlorofluorocarbons (CFCs) and other ozone-depleting substances.

D. *Defense and Space Systems*

In recent years, there has been a growing recognition that significant changes need to be made in the defense and space or aerospace industries; they are undergoing a major transformation. Today, major defense and aerospace manufacturers in the U.S., including, but not limited to, Boeing, Lockheed-Martin, Northrop-Grumman, Raytheon, and BAE Systems, all recognize the critical importance of large-scale systems integration. In some cases, these companies have even established entire business units dedicated to systems integration activities. As examples, consider the vision statements of three of the major aerospace companies [1]:

— "*To be recognized as the world's premier systems engineering and technology enterprise*," Lockeed Martin Corporation in 1995;

- "… aspire to be one of the most admired technology companies in the world, and a "System of Systems" integrator," Raytheon Corporation in 2000; and
- "*To be the leading systems company, innovating for a safer world*," BAE Systems in 2005.

Similar vision statements can be obtained from other corporations like Boeing, Northrop-Grumman, and General Dynamics. A well-managed military complex, which adheres to systems integration principles, is needed to produce a wide variety of military equipment required by the armed forces to meet their defensive and offensive capabilities. When a government or a coalition of nations decides to launch a military campaign, or must respond to aggression by other nations, an entire "life-cycle" of events must be planned and executed in a systematic manner. For example, in World War II, both the British and American military employed the systems science principles of operations research to assist them in defeating Germany and Japan. Moreover, after the unconditional surrender of Germany in 1945, the Western Allies occupied Western Germany and systematically disarmed the Germans. Under the brilliant leadership of the U.S., the Western Allies launched the famous Marshall Plan to not only rebuild Western Germany but also all other devastated areas of Western Europe and Japan. A sound constitution was established when the Federal Republic of Germany was formed just after the war and today a united and democratic Germany is the economic engine of the European Union. Likewise, under their clever military campaign of "island hopping," the U.S. decisively defeated Japan and under the inspired leadership of General Douglas MacArthur created a strong form of parliamentary democracy in Japan. Currently, Japan is the largest democracy in Eastern Asia and is an economic superpower within which its economic wealth has been reasonably well distributed among its citizens.

Unfortunately, the foregoing type of "life-cycle" systems approach has not been followed by the current U.S. administration, which launched an attack against Iraq in March 2003, ignoring the advice of some of America's closest allies (including Canada, Germany, and France). The superb military equipment, which the U.S. defense industry built for the armed forces, performed according to specifications and the American military met its immediate obligations by expeditiously defeating the Iraqi military, while suffering few losses. However, after this quick military victory, no viable plan was in place to carry out the entire "life-cycle" or long-term plan of occupying and rebuilding a defeated nation in a systematic manner.

In the space domain, the National Aeronautics and Space Administration (NASA)'s International Space Station (ISS), which is being developed by Boeing and is considered to be the largest and most complex international scientific project in history is, in essence, an SoS. When ISS is completed around 2010, it will be comprised of more than 100 major components carried aloft by 88 space flights. With contributions from over 16 nations, the ISS will include systems concerned with thermal control, life support, guidance, navigation, control, data handling, power, communications, and tracking. Components from the international partners include: a Canadian-built, 55-ft-long robotic arm and mobile servicing system used for assembly and maintenance tasks; a pressurized European laboratory called *Columbus*; a Japanese laboratory called *Kibo*, with an attached exposed exterior platform for experiments; and two Russian research modules—an early living quarters called the *Zvezda* Service Module with its own life support and habitation systems, and a Soyuz spacecraft for crew return and transfer.

Obviously, defense and space systems have similar concerns and are focused on the integration of a range of systems into a viable SoS. Clearly, sophisticated, real-time- and adaptive SoS methods are required to deal with these complex systems. For example, Nilchiani and Hastings [37] argue for designing in flexibility in space systems so that they could adapt to change. Equally evident is the fact that such methods are within the purview of the IEEE Society on Systems, Man, and Cybernetics.

III. RESEARCH METHODS

As summarized in Table I, the required methods for dealing with the four application domains can be appropriately grouped into three categories: systems, man, and cybernetics. Thus, SMC, as a professional society, does indeed have an exciting future; it includes critical methods for addressing at least the four domains considered herein.

A. Systems

Systems design, interface, and integration constitute the foundation upon which systems research methods can be supported and broadened in scope.

1) Design: Design, or creative problem solving, constitutes the philosophical foundation upon which all engineering disciplines, including systems, man, and cybernetics, can flourish and mature. The design process permits humans to employ the imaginative or "right brain" component of their intelligence in concert with their analytical or "left brain" capabilities to creatively solve, often in an iterative manner, tough problems, ranging from designing intelligent transportation systems to effective government policies. The information technology revolution has permitted the analysis part of design to be largely replaced by computers. For example, a human can tentatively imagine the main features of an advanced transportation vehicle having certain capabilities for satisfying transportation objectives, which can then be rigorously analyzed and viewed graphically using a computer-aided design (CAD)/computer-aided manufacturing (CAM) program. Based on this analytical and visual feedback, the vehicle can be redesigned and analyzed again in an iterative manner until a satisfactory design is achieved that meets specified performance (i.e., human interface, environmental, fuel efficiency) criteria.

Several considerations should be borne in mind when one undertakes a systems design. First, the current holistic viewpoint of designing a system should be expanded in scope to encompass SoSs, which reflect the features of the various types of problems referred to in the Section II application domains. Attractive research opportunities exist for developing sound methodological and theoretical bases to properly model and analyze SoSs.

Second, as proposed by Hipel and Fang [20], multiple participants and their associated value systems should be entertained when investigating any SoSs. For example, when designing an energy policy, the viewpoints of all stakeholders should be "hardwired" into the policy so that the interests of producers, distributors, customers, regulators, environmentalists, and other relevant stakeholders are fairly addressed. When designing a service system for purchasing or selling on eBay, distributed multiagent demands must be met when negotiating sales among real people, purchasing software agents, or some mixture thereof. Third, any type of system, whether it be a societal system or an automated corrective system (e.g., in response to a power failure), should possess an ethical design. Hence, health systems that penalize customers for being sick by charging higher rates, should be deemed illegal in any civilized society. Fourth, of great import in many situations is to design systems that can operate in real-time, by having instant and ongoing access to vast arrays of constantly updated data from which decision-support information can be immediately obtained. In some cases, split-second decisions may have to be automatically made for isolating a problem in a system, such as an electrical distribution network, in order to prevent system collapse. In other situations, like a suspected launch of nuclear missiles against a nation, humans will have to make the final crucial decision as to whether the attack is real and if the country should activate its defensive systems and/or launch a counterstrike at the offending country. Fifth, one should be cognizant that most system problems involve a high level of uncertainty and risk for which systems methodologies such as fuzzy sets [61], information-gap theory [3], [19], grey sets, rough sets, and probability and statistics are crucial. Sixth, virtually every systems design problem is multidisciplinary in nature and requires an integrative and adaptive approach. Finally, one should recognize that the ultimate purpose of good design is to produce good decisions to benefit stakeholders in a fair manner.

2) Interface: System interface could include the interactions between software agents, between humans and machines, between subsystems, between systems (i.e., in an SoS manner), between humans, or between any of the earlier-mentioned components. Human factors constitute a discipline that deals with many of these interactions. However, another critical interface concerns how humans interact with information. In developing appropriate human–information interfaces, one must pay careful attention to a number of factors. First, human–information interfaces are actually a part of any decision-support model; they structure the manner in which the model output or information is provided to the decision-maker. Cognition represents the point of interface between the human and the information presented. The presentation must enhance the cognitive process of mental visualization, capable of creating images from complex multidimensional data, including structured and unstructured text documents, measurements, images, and video.

Second, constructing and communicating a mental image common to a team of, say, emergency responders facilitates collaboration and leads to more effective decision-making at all levels, from operational to tactical to strategic. Nevertheless, cognitive facilitation is especially necessary in operational settings that are under high stress.

Third, cognitive modeling and decision-making must combine machine learning technology with a priori knowledge in a probabilistic data mining framework to develop models of an individual's tasks, goals, interests, and intent. These user-behavior models must be designed to adapt to the individual decision-maker so as to promote better understanding of the needs and actions of the individual, including adversarial behaviors and intent. If not appropriately developed, cognitive models can introduce errors in interactive behavior and result in an unreal perspective [14]. Such a priori knowledge must also be represented in a manner as compatible as possible with the manner in which the knowledge source would like to represent the knowledge. If the knowledge source is a human, then the precise probabilities or value functions may require knowledge acquisition techniques foreign to the source and, hence, may produce unreliable knowledge descriptions. This suggests the need for more natural forms of knowledge capture and representation, as well as decision-support methodologies that are constructed on the basis of natural models of knowledge representation.

3) Integration: System integration refers to the progressive linking and testing of system components to merge their functional and technical characteristics into a comprehensive, interoperable system. For example, in a fully integrated SoS, each system can communicate and interact with the entire SoS, without any compatibility issues. For this purpose, an SoS needs a common language. Without having a common language, the SoS components cannot be fully functional and the SoS cannot be adaptive in the sense that new system components cannot be appropriately integrated into the SoS without a major effort. Integration also implies a seamless interaction among the components [28].

A system of systems often consists of transformational, network-centric components with software-intensive characteristics. The emphasis is on interoperability and a need for the system of heterogeneous systems to perform optimally and to realize a common objective [6]. The concept of an SoS arises from the need to more effectively implement and analyze large, complex, interdependent, and heterogeneous systems working in a cooperative manner. The SoS paradigm presents a new school of thought in systems engineering. The driving force behind the desire to view these systems as an SoS is to achieve higher capabilities and performance than would be possible with traditional stand-alone systems. While the expectation of an SoS is that it would perform in a synergistic manner, few real-world applications are available [41].

Just like a system can be considered to be a metasubsystem, an SoS can be envisioned as a metasystem [46]. For example, a Boeing 747 airplane system can be considered to be an element of an airport SoS; similarly, a rover on Mars is not itself an SoS, but a robotic colony or swarm exploring the red planet is an SoS. In the U.S. Department of Defense (DoD), many efforts are underway to utilize SoS as a technology where national and regional security can best be attained. As an example, in 2005, the U.S. Army announced a joint project with Boeing on the creation of the System of CA, Systems Integration

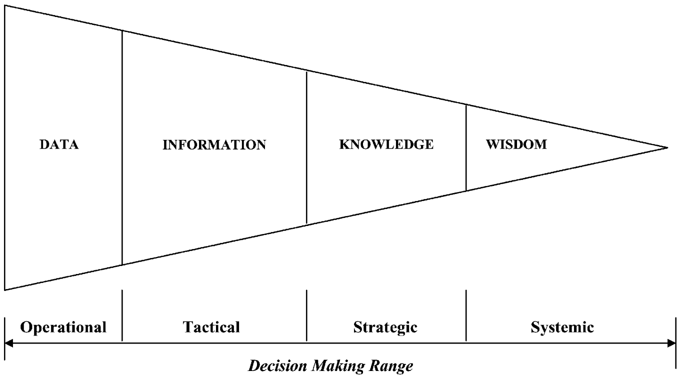

Fig. 4. Decision-making framework.

Laboratory (SoSIL) in Huntingdon Beach, where all 18 platforms in a network-centric warfare scenario can be simulated and tested. The facility should allow soldiers and civilian experts to work together to develop, test, and evaluate the future combat systems (FCS) network that can connect vehicles and planes on the battlefield. The high-tech facility should also be able to link suppliers and subcontractors nationwide, in real-time manner [28].

B. Man

The man- or human-related methods included in this section are focused on decision-making. Other human-related methods like human factors and human–information interfaces are addressed in Section III-A. Before discussing decision-making at the strategic, tactical, and operational level, it may be helpful to provide an example context for such a discussion. A defense- and services-related example is provided by Tien [52], who views urban disruptions (i.e., terrorist acts, natural disasters, and accidental incidents) from a decision perspective when dealing with the various stages of a disruption, including the preparation for a major disruption, the prediction of such a disruption, the prevention or mitigation of the disruption, the detection of the disruption, the response to the disruption, and the recovery steps that are necessary to adequately, if not fully, recuperate from the disruption. In this context, at the strategic level (which includes the preparation and recovery stages of a disruption), decisions must be made in terms of months, if not weeks; at the tactical level (which includes the prediction and prevention stages of a disruption), decisions must be made in terms of days, if not hours; and at the operational level (which includes the detection and response stages of a disruption), decisions must be made in real-time. Hagen and Brown [16] provide another services-related, decision problem—within a law enforcement context.

One could consider the different decision-making levels in terms of a data, information, knowledge, and wisdom continuum [51]. As depicted in Fig. 4, data represent basic transactions captured during operations, while information represents processed data (e.g., derivations, groupings, patterns, etc.). Clearly, except for simple operational decisions, decision-making at the tactical or higher levels requires, at a minimum, appropriate information or processed data. Fig. 4 also identifies knowledge as processed information (together with experiences, beliefs, values, cultures, etc.), and wisdom as processed knowledge (together with insights, theories, etc.). Thus, strategic decisions require knowledge, while systemic decisions require wisdom.

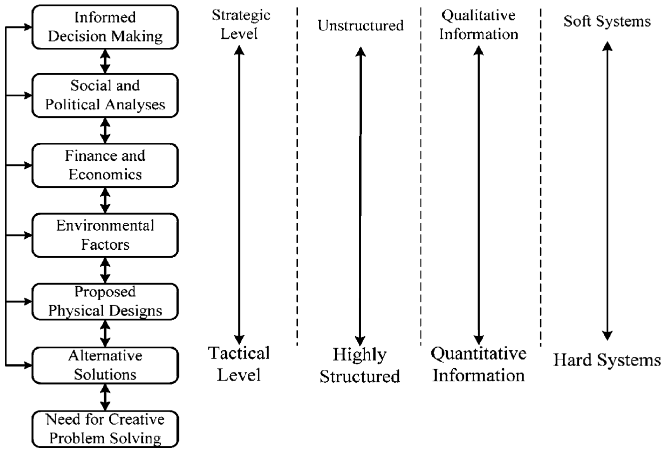

Fig. 5. Decision-making framework.

1) Strategic: Strategic decision-making is usually distinguished from tactical and operational decision-making by the organizational and financial impact of the decisions (i.e., the impact of a strategic decision being significantly greater than those at the tactical and operational levels); by the "clock speed" (i.e., major strategic decisions usually do not arise as often as tactical and operational decisions and the amount of time available for strategic decision-making is usually greater than for tactical and operational decision-making, sometimes significantly so); by the complexity or scope of the decisions (i.e., strategic decisions—in contrast to tactical and operational decisions—must also take into consideration political, legal, social, and ethical issues).

As an example, technology investment is a strategic decision. In terms of a freight system, the fundamental question is: would an investment in an information infrastructure that is designed to provide data in near real-time, be worth the investment? Two possibilities come to mind. First, would equipping all tractor trailer trucks with location identification systems and two-way communication systems between driver and dispatcher be worthwhile doing? Studies indicate that information thus obtained has sufficient value for the national trucking industry, which has invested in such systems during the past 15 years. Second, would putting radio frequency location and identification—RFLID—tags on products manufactured in China and moved to the U.S. be able to improve the efficiency of their movement across the Pacific? Interestingly, since the Pacific movement is predictable and the added asset visibility provided by such RFLID tags does not significantly influence or expedite supply chain decisions, there is no value in the data generated.

Fig. 5 portrays a flexible procedure for considering strategic decision-making from a systems engineering perspective. As an example, consider the situation in which a country wishes to design a long-term energy policy for meeting future energy demands, based on multiple stakeholder objectives for, say, the year 2020. The left column in Fig. 5 contains the main factors that must be considered for selecting a suitable design. Besides a sound physical design, any alternative solution, such as a nuclear power plant or a wind farm, must be evaluated with respect to environmental, financial, economical, political, and social considerations or objectives. Keeney [31] suggests a value-focused thinking approach for cleverly determining short- and long-term goals. Whether one employs value-focused thinking, brain-storming sessions with stakeholders, surveys, or some other appropriate procedure, one can arrive at a range of meaningful alternatives and criteria for evaluating these alternatives [2], [4], [18]. Criteria such as political and societal impacts may be nonquantitative in nature, while economic, risk [17], and certain environmental data may be quantitative in nature. As described by Hipel *et al.* [21], [22], appropriate techniques from systems engineering [45], [47], [59] and operations research can be employed throughout the design or decision-making process to identify the alternatives, to rank the alternatives, and to select the best alternative or some combination thereof. Thus, the final energy policy may well be a combination of nuclear, hydropower, wind, solar, and fossil fuel generation in combination with CO_2 sequestration methods, along with policies for encouraging the development of energy-efficient products, homes, manufacturing facilities, and transportation systems.

As indicated in the top-left cell in Fig. 5, the output from all of the systems analyses furnishes information and insights to assist decision-makers in eventually reaching an overall informed decision. The feedback arrows drawn on the left in Fig. 5 indicate that additional studies can be executed, as required, to procure a better understanding of the problem. In fact, this type of systems approach to enlightened decision-making provides a valuable basis for enhancing discussion and cooperation among decision-makers that may result in a win/win situation for everyone concerned. The right side in Fig. 5 depicts characteristics that are embodied within the hierarchical framework of the decision-making process. In particular, as one goes from the tactical level of decision-making to the strategic level, the problem changes from being highly structured, quantitative, and hard, to being unstructured, qualitative, and soft. Due to these and other reasons, one must choose an appropriate set of systems tools to investigate all relevant aspects of the system or SoS systems being studied. When modeling strategic interactions among decision-makers, especially at the strategic level where information tends to be unstructured, more qualitative, and soft, one can employ the Graph Model for Conflict Resolution [7], [24] or Conflict Analysis [10]. By properly taking into account all key aspects of decision-making, society can arrive at decisions that are more equitable to all parties involved and fall within a sustainable development framework.

2) Tactical: Tactical decision-making is concerned with making wise decisions to tackle more medium-term problems and associated objectives. The basic decision-making process depicted in Fig. 5 could also be employed for making decisions in the not-too-distant future. For example, after deciding upon a long-term energy strategy as described in the previous paragraphs, the procedure could be utilized to make decisions about all of the issues involved in building a nuclear power plant at a specific location over a period of five years. Issues to be addressed include selecting the type of nuclear power plant, such as an advanced, heavy water reactor design; choosing an optimum safety system; determining how to store nuclear wastes and eventually disposing of them; adopting reliable security systems; minimizing environmental impacts; obtaining finance at a low interest rate; minimizing environmental impacts; minimizing different types of risk [17]; and maximizing employment opportunities for the local community.

As pointed out earlier, appropriate decision-making techniques developed in the fields of systems engineering and operations research can be effectively utilized in regard to tactical decisions. More specifically, systems engineering focuses on all levels of decision-making, including the strategic and tactical levels; on unstructured and complex problems; on qualitative and quantitative data; on soft and hard systems; on the integration of technical, institutional, cultural, financial, and other inputs; on multiple conflicting objectives; and, more recently, on an SoS viewpoint. When tackling real-world problems, systems engineers have at their disposal a tool box of both societal and physical system models from which they can select appropriate techniques to use within the decision-making framework shown in Fig. 5. As one goes from the operational to the tactical to the strategic level of decision-making, one tends to use more societal systems models and fewer physical systems models. Moreover, as indicated in the earlier design discussion in previous paragraphs, many of these system models recognize the multiple participant-multiple objective characteristics of real-world problems, especially from an SoS perspective.

3) Operational: Decision-making is not only about making the right decisions; it is also about making timely—and, therefore, adaptive—decisions. This is especially true at the operational level, where humans must react in seconds and software programs must react in milliseconds. As an example, real-time, information-based decision-making—which Tien [51] calls decision informatics—is needed for enhancing the production and delivery of services, especially emerging e-services. As shown in Fig. 6, the nature of the required real-time decision (e.g., regarding the production and/or delivery of a service) determines, where appropriate, and from a systems engineering perspective, the data to be collected (possibly, from multiple, nonhomogeneous sources) and the real-time fusion/analysis to be undertaken to obtain the needed information for input to the modeling effort, which, in turn, provides the knowledge to support the required decision in a timely and informed manner. The feedback loops in Fig. 6 are within the context of systems engineering; they serve to refine the analysis and modeling steps.

Thus, operational decision-making or decision informatics is supported by two sets of technologies (i.e., information and decision technologies) and underpinned by three disciplines: data fusion/analysis, decision modeling, and systems engineering. Data fusion/analysis methods include data mining, visualization, data management, probability, statistics, quality, reliability, fuzzy logic, multivariable testing, and pattern analysis; on the other hand, real-time data fusion/analysis is more complex and requires additional research. Decision modeling methods include

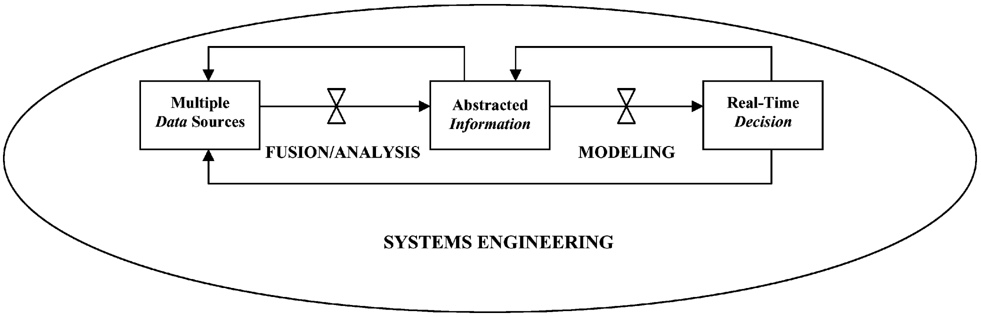

Fig. 6. Decision informatics paradigm.

discrete simulation, finite-element analysis, stochastic methods, neural networks, genetic algorithms, optimization, etc.; on the other hand, real-time decision modeling, like real-time data fusion/analysis, also requires additional research, especially since all steady-state models become irrelevant in a real-time environment. Systems engineering includes cybernetics or, as indicated in Section III-C, feedback and control; it integrates products, processes, and operations from a holistic perspective, especially human-centered systems that are computationally intensive and intelligence-oriented. Similarly, undertaking systems engineering within a real-time environment requires additional thought and research.

It should be noted that the decision informatics paradigm depicted in Fig. 6 is, as a framework, generic and applicable to most, if not all, decision problems. In fact, since any data analysis or modeling effort should only be undertaken in support of some kind of a decision (including the design of a product or a service), all analyses and modeling activities should be able to be viewed within the decision informatics framework. Thus, the framework can be very appropriately applied to critical issues in regard to a particular service, infrastructure, transportation, environmental, energy, defense, or space system. Additionally, the adaptive nature of decision informatics is very much akin to the evidence-based medicine that is becoming increasingly popular in health care.

C. Cybernetics

Cybernetics is derived from the Greek word "kybernetics," which refers to a steersman or governor. Within a system, cybernetics is about feedback (through evaluation of performance relative to stated objectives) and control (through communication, self-regulation, adaptation, optimization, and/or management). Thus, it relies on data, models, and control.

1) Data: Sensors acquire data; they could be in the form of humans, robotic networks, aerial images, radio frequency signals, and other measures and signatures. In regard to tsunamis, for example, seismographs, deep ocean detection devices with buoy transmitters, and/or tide gauges can all sense a potential tsunami. More recently, data warehouses are proliferating and data mining techniques are gaining in popularity. No matter how large a data warehouse and how sophisticated a data mining technique, problems can, of course, occur if the data do not possess the desirable attributes of measurability, availability, consistency, validity, reliability, stability, accuracy, independence, robustness, and completeness. Indeed, 9/11 might have been thwarted if a more robust and system-oriented passenger screening system were in place instead of the 1998 initiated CAPPS program (which employed a computer-based formula to identify potential terrorists based on a number of variables), a system that had already experienced a drastic cutback, and, moreover, had not been uniformly used by the airlines. Hopefully, most of these deficiencies have been corrected in the current Transportation Security Administration's CAPPS II system.

In most situations, however, data are useless unless access to and analysis of the data are in real-time. In developing real-time, adaptive data processors, one must consider several critical issues. First, as depicted in Fig. 6, these data processors must be able to combine (i.e., fuse and analyze) streaming data from sensors and appropriate input from knowledge bases (including output from tactical and strategic databases) in order to generate information that could serve as input to operational decision-support models and/or provide the basis for making informed decisions. Second, as shown in Fig. 6, the type of data to collect and how to process it depend on what decision is to be made; these dependencies highlight the difficulty of developing effective and adaptive data processors or data miners. Further, once a decision is made, it may constrain subsequent decisions, which, in turn, may change future data requirements and information needs. Third, inasmuch as the data processors must function in real-time and be adaptable to an ongoing stream of data, genetic algorithms, which equations can mutate repeatedly in an evolutionary manner until a solution emerges that best fit the observed data, are becoming the tools of choice in this area.

2) Models: At the strategic or policy level, there are a number of appropriate models that can support decisions. As examples, Kaplan et al. [29] developed a set of complex models to demonstrate that the best prevention strategy to a smallpox attack would be to undertake immediate and widespread vaccination. Unfortunately, models, including simulations, dealing with multiple systems are still relatively immature and must be the focus of additional research and development. Such SoS models are quite complex and will require a multidisciplinary approach.

At the tactical level and as Larson [33] details, there is a range of decision models for, say, response planning. Indeed, response is about allocating or reallocating resources, which is the essence of operations research—a science that helped the U.S. minimize shipping losses during World War II, brought efficiencies in production, and developed optimal scheduling of personnel. Another set of critical emergency response models includes those that can simulate, as examples, the impact of an airliner hitting a chemical plant, the dispersion of radioactive material following the explosion of a dirty bomb, and the spread of illness due to a contaminated water supply.

At the operational level, there is a need for real-time decision-support models. In such a situation, it is not just about speeding up steady state models and their solution algorithms; indeed, steady state models become irrelevant in real-time environments. In essence, it concerns reasoning under both uncertainty and severe time constraints. In addition to the discussion in Section III-B, the development of operational decision-support models must recognize several critical issues. First, in addition to defining what data to collect and how they should be fused and analyzed, decisions also drive what kind of models or simulations are needed. These operational models are, in turn, based on abstracted information and output from tactical and strategic decision-support models. The models must capture changing behaviors and conditions and adaptively—usually, by employing Bayesian networks [48]—be appropriately responsive within the changing environment. Second, most adaptive models are closely aligned with evolutionary models, also known as genetic algorithms; thus, they function in a manner similar to biological evolution or natural selection. Today, computationally intensive evolutionary algorithms have been employed to coordinate airport operations, to enhance autonomous operations in unmanned aircrafts, and to determine sniper locations while on patrol in Iraq. Third, computational improvization is another operational modeling approach that can be employed when one cannot predict and plan for every possible contingency. (Indeed, much of what happened on 9/11 was improvized, based on the ingenuity of the responders.) Improvization involves reexamining and reorganizing past knowledge in time to meet the requirements of an unexpected situation; it may be conceptualized as a search and assembly problem, influenced by such factors as time available for planning, prevailing risk, and constraints imposed by prior decisions [35].

3) Control: Control is perhaps the most critical challenge facing SoS designers. Due to the difficulty or impossibility of developing a comprehensive SoS model, either analytically or through simulation, SoS control remains an open problem and is, of course, different for each application domain. Moreover, real-time control—which is required in almost all application domains—of interdependent systems poses an especially difficult problem. Nevertheless, several potential control paradigms are briefly considered as follows.

First, as illustrated in Fig. 7, hierarchical control of an SoS assumes that it can be characterized by a finite set of subsystems, say n, each of which could be separately optimized by a classical optimal control approach employing, for example, a linear quadratic regulator based on either continuous- or discrete-time basis. Through an iterative process of modeling the interactions between the coordinator system and the n subsystems, a convergent optimal solution could be obtained. In a real-time implementation of hierarchical control, a number of additional issues need to be resolved. For example, data transmission among the systems that constitute an SoS could be achieved through the use of extensible markup language (XML) to code or decode data exchanges between them.

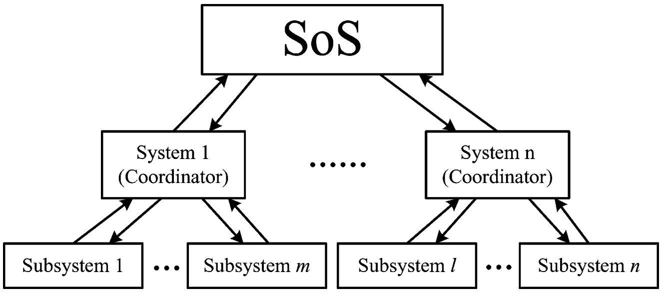

Fig. 7. Hierarchical structure for control of an SoS.

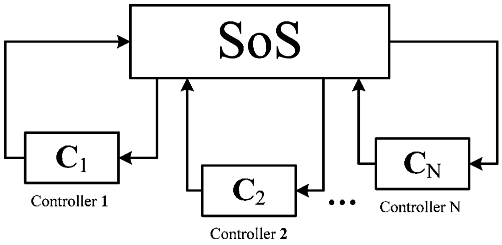

Fig. 8. Decentralized structure for control of an SoS.

Second, as illustrated in Fig. 8, decentralized control of an SoS assumes that it can be characterized by a great multiplicity of input and output variables, with each subset of variables or system exercising local control. For example, an electric power grid (i.e., an SoS) has numerous substations (i.e., systems), with each substation being responsible for the operation of a portion of the grid. The designer of a decentralized SoS needs to determine a control structure that assigns system inputs to a given set of local controllers, each of which observes only local system outputs. In essence, decentralized control attempts to avoid difficulties in data gathering, data storage, and system debugging. As in the case of hierarchical control, while the literature is filled with classical, steady state approaches to decentralized control [27], it is lacking in real-time considerations.

Third, the cooperative control of an SoS assumes that it can be characterized by a set of interconnected systems or agents with a common goal. Classical techniques of control design, optimization, and estimation could be used to create parallel architectures for, as an example, coordinating underwater gliders [38]. However, many issues dealing with real-time cooperative control have not been addressed, even in non-SoS structures. A critical issue concerns controlling an SoS in the presence of communication delays to and among the SoS systems.

Fourth, autonomous control of an SoS assumes that it can be characterized by a set of "intelligent systems" that can be implicitly or autonomously controlled. Although the concept of autonomous or intelligent control was first introduced three decades ago by Gupta *et al.* [15], the control community has only recently paid substantial attention to such an approach, especially in regard to a variety of industrial applications (e.g., cameras, dishwashers, automobiles, etc.) . Most of these applications are due to Zadeh [62] and involve fuzzy logic, neural networks, evolutionary algorithms, and soft computing [63]; the strength of these methods is in its ability to cope with imprecision, uncertainties, and partial truth. Moreover, the methods can be used to process information, adapt to changing environmental conditions, and learn from the environment; thus, they are adaptive and, to a large extent, responsive to real-time input. However, additional research is required before autonomous control can make full use of an incoming data stream, including taking into consideration the possible future state of an SoS.

IV. CONCLUDING INSIGHTS

As regards the system domains considered in this paper, it is seen that the systems are becoming increasingly more complex; indeed, each reflects an SoS, together with all the attendant life-cycle design, human interface, and system integration issues. Whatever system—whether it be a service, infrastructure, transportation, environmental, energy, defense, or space system—is designed, developed, analyzed, and/or refined, there is a critical need to assess the resultant outcome or performance through appropriate metrics. In a profit-driven environment, such financial metrics as revenue growth or return on equity are typically employed. However, Reichheld [44] has advanced a deceptively simple metric, by asking "How likely is it that you would recommend this product, service, or system to a friend or colleague?" This customer-centric metric has been shown to be highly correlated with achieving long-term profitable growth. Nevertheless, although assessment metrics are not explicitly addressed in Section III, it is obvious that they must be carefully developed and validated so as to ensure their ability to assess such issues as satisfaction, convenience, privacy, security, equity, quality, productivity, safety, and reliability.

As a critical aspect of complexity, modern systems are also becoming increasingly more human-centered, if not human-focused; thus, products and services are becoming more personalized or customized. Certainly, services coproduction implies the existence of a human customer; transportation is a service in support of the global society; the environment and energy provide the infrastructure for enhancing quality of life; and defense and space systems safeguard human existence. The implication in regard to SMC methods is profound; indeed, such methods must truly be multidisciplinary—they must include techniques from the social sciences (i.e., sociology, psychology, and philosophy) and management (i.e., organization, economics, and entrepreneurship). As a consequence, SMC researchers must expand their systems (i.e., holistic-oriented), man (i.e., decision-oriented), and cybernetic (i.e., adaptive-oriented) methods to include and be integrated with those techniques that are beyond science and engineering. For example, higher customer satisfaction can be achieved not only by improving service quality but also by lowering customer expectation. In essence, systems, man, and cybernetics is an integrative, adaptive, and multidisciplinary approach to creative problem solving that takes into account stakeholders' value systems and satifies important societal, environmental, economic, and other criteria in order to enhance the decision-making process when designing, implementing, operating, and maintaining a system or an SoS to meet societal needs in a fair, ethical, and sustainable manner throughout the system's life cycle.

Given the application domains addressed in Section II, the underlying theme in regard to the systems, man, and cybernetic methods presented in Section III is about decision-making. This should not be a surprise, since the employment of any data analysis, modeling, or control approach must be responsive to the decision requirements. In fact, systems design is about making decisions among different alternative design scenarios. Moreover, Mankins and Steele [34] show that even strategic planning is worthless unless it is about decision-making or making choices; they advocate following a continuous, decision-oriented planning approach. More importantly, because of the dynamic nature of today's complex SoS (e.g., electronic services, transportation, energy, defense, and space), the decision-making must occur in a real-time, adaptive manner. Thus, whereas steady state methods can be applied to dynamic but predictable electromechanical systems, adaptive methods must now be developed and applied to dynamic but unpredictable human-centered systems. Adaptive methods include Bayesian networks, neural networks, evolutionary algorithms, soft computing, and decision informatics; they must support decision-making in an environment where there is a continuous stream of sensor-based data. Such methods are by their very nature computationally intensive; they rely on information technology and sensor-based data; and they serve to continually abstract reliable information from fused data so that informed decisions can be appropriately made. The resultant systems must be agile, resilient, robust, flexible, and evolutionary.

In sum, the IEEE Society on Systems, Man, and Cybernetics has a great future; its systems, man, and cybernetic methods are relevant for dealing with the challenging system domains that are becoming dominant in this 21st century, including service systems, infrastructure and transportation systems, environmental and energy systems, and defense and space systems. However, the methods must be redeveloped to meet the changing needs of the 21st century; from a system to an SoS vision, from a disciplinary to a multidisciplinary outlook, from a mass production to a mass customization focus, from a steady state to a real-time perspective, and from an optimal to an adaptive approach.

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