An Attempt at Complex System Classification

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May 2002

I. Summary

This paper searches for a useful taxonomy or classification scheme for complex Systems. There are two aspects to this problem: 1) distinguishing between Engineering Systems of interest to ESD (ES) and other Systems, and 2) differentiating among Engineering Systems. The first of these has been approached through general interaction with other ESD faculty and use of the ESD definitions. This analysis leads to a proposed specific set of ES which are human designed, have high technical and human complexity and are real, open, dynamic, have hybrid system states and have both autonomous and human-in–the loop subsystems or elements.

The second aspect has been approached by top-down and bottom-up analysis. A top-down approach consists of reviewing past system classification schemes starting with taxonomies proposed in the context of General Systems Theory from the 1950's and assessing their usefulness with the proposed list of ES. Such schemes prove to be of limited value in our search because they tended to be formulated from a mechanical technology viewpoint and more importantly because they could not anticipate the emphasis herein on systems with both technical and human complexity.

The proposed or testbed list is also useful in the bottom-up approach, since it gives specific cases for qualitative and quantitative analysis of various system attributes. The qualitative and preliminary quantitative study indicates that functional types are the most useful technical attribute for classification differentiation. Information, energy, value and mass acted upon by various processes are the foundation of the technical types building on prior work by Hubka, Pahl and Beitz and Van Wyk.

A meta-model for Engineering Systems is suggested in the form of a multi-layer network whose goal it is to fulfill human wants and needs by enabling the flow of goods and services between sources and sinks. This description essentially combines and extends the attributes suggested by the bottom-up approach to be most useful in classification.

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II. Introduction

We have three inter-related reasons for attempting a system classification study at this time. First, by analogy with other fields, a classification framework has often been a major step forward, and a significant accelerator of development of the field. Thus we are attempting a possible small "foundation" contribution in the field.

Second, by developing a framework for classification of complex systems, we may help delineate the "intellectual boundaries" of engineering systems. The differentiation of ES from other complex systems is most important to fulfill this purpose. Such delineation may be of interest within MIT in differentiating ESD from engineering departments, the Sloan School, and other areas, as well as outside MIT in the broader academic setting. We presume that such boundaries will be open and blurred as are those defining other fields.

Our third reason for attempting to classify complex systems—the reason we believe is most important—is to contribute to the engineering and design of such systems. Achievement of this goal could be facilitated by differentiation between different classes of ES. As the modern world relentlessly evolves towards a highly interactive and interdependent complex set of complex systems, the improvement of our ability to design such systems is becoming crucial. However, classification frameworks tend to be more challenging at high levels of complexity and thus we expect limitations on the potential application of any framework we propose.

III. Approach

Our overall approach has been to develop a "testbed" list of complex systems (aka, systems of interest to ESD). The process for developing the list, the basis for decisions whether to include a specific system, and the specific systems in our list are in the next section. We use this list to assess the utility of prior classification frameworks, and then to extend them and develop new ones. Figure 1 shows schematically our overall approach.

In order to explore promising classification schemes for Engineering Systems, we simultaneously pursued a top-down and a bottom-up strategy. The top-down strategy consists of surveying past suggestions for a classification of complex Engineering Systems, generically considering the attributes of Engineering Systems and the kinds of processes that they are involved in, as well as suggesting a meaningful classification scheme based on systems theory. The bottom-up approach consists of qualitatively assessing a wide variety of system attributes for each entry in the testbed list of Engineering Systems to learn about the systems. The bottom-up approach also involves actual quantitative observation of a few specific instances of Engineering Systems by gathering quantitative data about some of their attributes. Both aspects of the bottom-up approach are used to begin to discover some suggestive and interesting groupings.

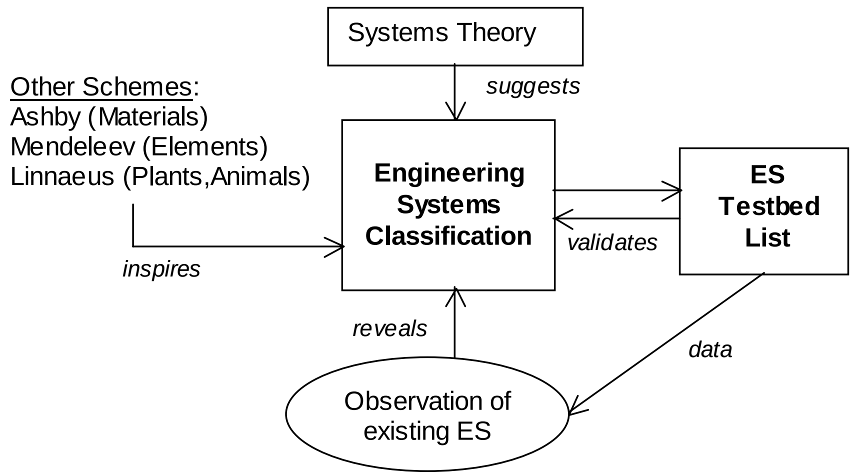

Figure 1. Approach for finding a classification of Engineering Systems

In order to evaluate possible classification frameworks, we have developed a set of criteria for determining whether a given classification framework is useful. The first criterion is that it work for the systems we are trying to learn how to more effectively engineer (hence the list as “testbed”). To have utility, a framework must first and foremost be able to differentiate among systems on our list and separate them into distinct groupings. In addition, valuable classification schemes would help by defining categories where different engineering methods and approaches are most useful. A useful framework would also possibly help define potential fundamental issues and principles of importance in various categories suggested by the framework. Finally, a useful scheme might suggest the most viable modeling and representation techniques to apply in different categories.

IV. Specific Engineering Systems of Interest to ESD

The need for a “testbed” set of engineering systems led first to finding (not surprisingly) that no list was known. An informal list was started and discussed with a few other ESD faculty and generally spirited discussion about criteria for inclusion ensued and some new systems were added. Concerned that a list derived in this way was likely to be narrower in scope than desired for our study, we enlarged the participation with two successive mailings to all ESD faculty. We received much valuable input on both rounds which helped make the list more comprehensive and helped tighten our thinking about inclusion decisions.

Since our approach involves actual “bottom-up” observation of engineering systems (as well as application of “top-down” theory and speculation), we require specific instances of engineering systems. Many inputs were generic which we either did not use or converted to a specific instance for the second round of e-mail. We also found that focus on specific instances sharpened the decision process on inclusion. Indeed, some generic input can be considered as a suggestion for a possible category in a classification framework.

We attempted to incorporate all input from the other faculty in our decisions whether to include specific instances in our proposed list. To a very large extent, this input was consistent with the ESD definition of Engineering System(s) [9]. Our working definitions of *engineering system*, *complex system*, and *system* are as follows:

> **Engineering System:** a system designed by humans having some purpose; large scale and complex engineering systems which are of interest to the Engineering Systems Division, will have a management or social dimension as well as a technical one.
>
> **Complex System:** a system with numerous components and interconnections, interactions or interdependencies that are difficult to describe, understand, predict, manage, design, and/or change.
>
> **System:** a set of interacting components having well-defined (although possibly poorly understood) behavior or purpose; the concept is subjective in that what is a system to one person may not appear to be a system to another.

In the few cases where faculty input may have differed, we followed these definitions as the primary the basis for the separation of the specific systems listed in Table 1 into two sets: Engineering Systems of interest to ESD (ES from herein) and Other Interesting Systems.

Table 1. Engineering Systems Distinguished From Other Systems

Engineering Systems of Interest to ESD **ES**	**Other Interesting Systems** Legend: N = Natural Systems T = Insufficient Technical Complexity H = Insufficient Human Complexity P = Provisionally Classified
• Airbus 318-321 Airplane Family System • AOL instant messaging community/communication system • AT&T Telecommunication Network • Automotive Products and Plants of Toyota Motor Company System • Baltimore Harbor (P) • Big Dig (central Artery Project, Boston) • Boeing Supply Chain System • Boeing-777 Aircraft System • Boston Fire Alerting Prevention and Fighting System • Boston Globe Print Media System	• AIDS activist health care system/ prevention system (T)(P) • Amazon basin ecosystem (N) • Andromeda galaxy (N) • Ant Colony (N) • ASME JOURNALS Academic peer review system (T) • Atmosphere / Global weather system (N) • Boston Public Library (T,P) • Central Nervous System (N) • General Electric Dispute Resolution System (T,P) • German political system (T)

Engineering Systems of Interest to ESD **ES**	**Other Interesting Systems** Legend: N = Natural Systems T = Insufficient Technical Complexity H = Insufficient Human Complexity P = Provisionally Classified
(Newspapers, Magazines) • China's Three-Gorge Dam • Chinese "People" Air Transport System (PRC) • CNN Global News Gathering and Distribution System • CVS Computerized Drug Store Chain (P) • General Motors Cost and Accounting System • Exxon Mobil Enterprise Resource Planning (ERP) System • Microsoft Corporation Knowledge Management System • Xerox Corp. Preventative Maintenance System (P) • General Electric Quality Control & Operating System • Cray-1 Computer System • Department of Defense Acquisition System (USA) • eBay trading system (P) • Amazon.com system (P) • European Union Roadway System • FAA/IATA Certification System • Federal Express (or UPS) North American Package Delivery System • Federal Reserve System (P,T) • Ford XY Platform Products and Plants System • Exxon Mobil Fossil Fuel Drilling, Refining and Distribution System • GE Polycarbonate Manufacturing and Distribution System • General Motors (GM) Supply Chain • Geosynchronous Orbital (GEO) Belt Satellite Systems • Global Air Traffic Control System • Global Air Transportation System • Global Freight Transportation System	• Embryonic Stem Cell (N) • Fruit Fly (N) • Elephant (N) • GRE (Graduate Record Examination) System (T) • Human (homo sapiens) (N) • Human Brain (N) • Kidney/Urinary Tract System (N) • Microorganism (Bacterium) (N) • Milky Way (N) • MIT Engineering Systems Learning Center (T) • Name Tracking of Terrorism Attack Casualties (P) • NASA Deep Space Network (DSN)(H,P) • NBA (NFL, NHL, MLB) sports system (T) • Pentium V Microprocessor as a System(H) • Planet Earth, Planet Mars (N) • Salt Lake City 2002 Olympic Games (T) • Solar System (N) • Stanley Electro-Mechanical Drill (T,H) • Universe (N) • Virus (N) • Volkswagen New Beetle System (T,P) • Whale communications system (N) • Wolf Pack (N) • Wright Brothers Wind Tunnel (MIT Aero-Astro) (T,H) • Arms Control Negotiation and Treaty System(T,P) • Boston City Police (T,P) • Earth Climate System(N) • International Police (Interpol) (T,P) • Olympic Competition System (T) • Rain Forest system(N) • Sunday River Sky Resort (T) • Tribal hunting village economic

Engineering Systems of Interest to ESD **ES**	**Other Interesting Systems** Legend: N = Natural Systems T = Insufficient Technical Complexity H = Insufficient Human Complexity P = Provisionally Classified
• Reuters Global News Distribution Service • Global Positioning System (GPS) • Global Satellite Launching System • Global Wireless Communication System • Gotthard Transalpine Tunnel (Switzerland) (H,P) • Health Care System of France • Hudson River Watershed Water Supply System • Human genome project • International Banking and Monetary Transfer System • International Space Station (ISS) • Global Internet • Java Software System • JSF System (Joint Strike Fighter) • Linux/UNIX Operating System • Iridium Low Earth Orbit Communication Constellations • Company XYZ Marine freight transportation • Tokyo Metropolitan Area • Mexico City Transportation System • MGH health care system • Military Air Transport System • MIT Facilities System • MIT Information Technology System (incl. Athena) • MIT Life-Long Learning Systems (P) • NASDAQ Trading System • National Defense System • New York City Subway System • Newark Airport • Pentium V Microprocessor System • Pilgrim Nuclear Power Plant, Plymouth, MA • NYPD security system (P) • Pratt and Whitney XYZ Gas Turbine	system(T) • United Nations System (T) • Federal Reserve System (T,P) • System International (SI system of units) (T)

Engineering Systems of Interest to ESD **ES**	**Other Interesting Systems** Legend: N = Natural Systems T = Insufficient Technical Complexity H = Insufficient Human Complexity P = Provisionally Classified
Family System • Rohm and Haas IC "Blocker" Manufacturing System • Shanghai Freight Transport System • U.S. Social Security System • South Pole International Research Station • Space Satellite Guidance and Navigation System • Star Alliance (United, Lufthansa, Singapore Airlines…) (P) • Sun XYZ Server Family System • Synchrotron (Quantum Physics Experimental System) • Synthes-Norian Bone Surgery System (P) • U.S. Aerospace Industry • U.S. Agricultural Food Production and Distribution System • U.S. Air Traffic Control System • U.S. Aluminum production and recycling system • U.S. Government Environmental Regulatory System • U.S. Government OSHA Systems • U.S. Navy XYZ Aircraft Carrier Battle Group • U.S. Power Grid System • Windows NT Operating System • Wixom (Ford) Automotive Assembly Plant System • Xerox Family of Photocopiers System • XY Rocket Engine Product Verification (Test) Systems • ZF XYZ Continuous Variable Transmission System	

As shown in Table 1 above, systems not designed by humans are labeled “natural,” and are not included in the ES list—our first sorting principle. However, some of these systems are interesting for comparison in our “bottom-up” observations as they may give valuable insight to different categories and strategies for Engineering Systems. In addition, a number of our specific Engineering Systems included in the list incorporate natural “components or subsystems”.

The second and third aspects of the decision to include a specific instance as an Engineering System of interest to ESD are the technical complexity and human complexity (management or social dimension) of the system. For each instance to be specific enough to examine these points we need to know what “components” are included within the system—i.e., define the boundaries of the system. In general, we include all software, artifacts (natural and man-made), processes and personnel involved in delivering the product, purpose or service of the system. We have labeled some entries (e.g., the Boeing 777 example) “as a system,” and in these few cases the named systems only include the software, hardware, and procedures used in the actual product. For many of these same items, if we considered the development teams that design the product and/or the manufacturing systems that make it, the entries would move from the right hand column to left hand one in Table I. We have demonstrated this by the two different entries for the Intel Pentium V. The “Intel Pentium V System” includes the development Organizations and Manufacturing Plants, personnel, and processes as “components” whereas the “Intel Pentium V as a system” does not.

Many systems can be unambiguously separated into Engineering Systems or “other interesting Systems” when we study them using this framework. The entries in our ES list typically contain many thousands of non-repeating artifact, process or algorithm components as well as several multi-level human organizations as “components”. Many of the entries in the Other Interesting Systems list are not human designed and the remainder typically have either very low technical or organizational/social complexity.

It is also now possible to recognize some systems where differentiation is not so clear. A single airplane with a pilot is not an engineering system by our definition because of the lack of the organizational or social component/complexity. However, with a very complex airplane some may disagree. Similarly, we assume that use of a complex system (such as information systems, weapon systems etc.) is not of sufficient technical complexity to consider items such as an Air Force Command System or the Boston Public Library to be engineering systems. Thus, we could make a third list in addition to the binary pair we show in Table 1 with the third category containing the controversial systems. However, since the rest of the paper relies on having a “testbed” we have separated it as shown and items labeled (P) in Table 1 are those we consider provisionally categorized. Our plan is to stimulate further discussion as part of the symposium and perhaps beyond to attempt to reach ESD consensus (which may involve three categories).

V. Classification Frameworks

In this section, we use the “testbed”—the ES systems list presented in Section IV—to assess various classification frameworks. We make the assessment using the criteria outlined in Section III. The frameworks of potential interest come largely from past work generally starting with the General Systems Theory ideas of the 1950’s [2,3,4,5,6,10]. Thus, we are looking at multiple aspects of engineering systems that may yield a useful basis for classification. Our assessments of these prior frameworks have suggested a few logical additions to these ideas and we also assess these.

The first system classification scheme is due to Bertalanffy [3] who extended Boulding's work [4,5,6]. These frameworks were suggested as part of their efforts on "General System Theories" in the 1950's. The list as presented by Bertalanffy had a strong orientation towards his discipline of biology, and is summarized in Table 2 below.

Table 2. Bertalanffy's Classification of Systems

Static Structures
Clock Works
Control Mechanisms
Open Systems
Lower Organisms
Animals
Man
Socio-cultural Systems
Symbolic Systems

In this list, each successive item increases in complexity, and to some degree incorporates the preceding entries. In addition, Bertalanffy suggests the "theories and models" useful in each level of the hierarchy. Although this is the kind of utility we would like, this framework fails our first criterion as it does not apparently differentiate among our systems of interest. All of the "testbed systems" are similar combinations of the last three levels in this hierarchy.

A second early framework was proposed by Paynter in his MIT course [13] where he considered four system types:

1. Services and utilities—water supply, electric power generation, communication
2. Structures—buildings, houses, bridges
3. Instruments—clocks, computers
4. Vehicles—submarines, aircraft, spacecraft, ships, automobiles

It is clear from this that Paynter was interested in a very broad range of systems. However, applying his framework to our ES list from Table 1 makes it apparent that he was not primarily concerned with Engineering Systems as ESD has defined them. Although some of our listed systems can be fit into his scheme, most are poorly described by the categories and many are simultaneously in two or more of the categories. Our inclusion of manufacturing systems, product development systems and markets (sometimes as "components") indicates—not surprisingly—that Paynter was not considering Engineering Systems as we have defined them within ESD.

A third more fully developed approach from within the European Systems Engineering tradition is due to V. Hubka [10]. Hubka considers a variety of possible bases for classification including function, branch of the economy, type of operand, physical principles of importance, product use, production method, materials, etc. Figure 2 shows Hubka's overall depiction of Technical Processes, the environment and the human along with the "Technical System". All of his classification discussion focuses on the Technical System. This framework therefore also fails our first criterion as it does not differentiate among or really address our systems of interest—all have significant interwoven technical and human complexity.

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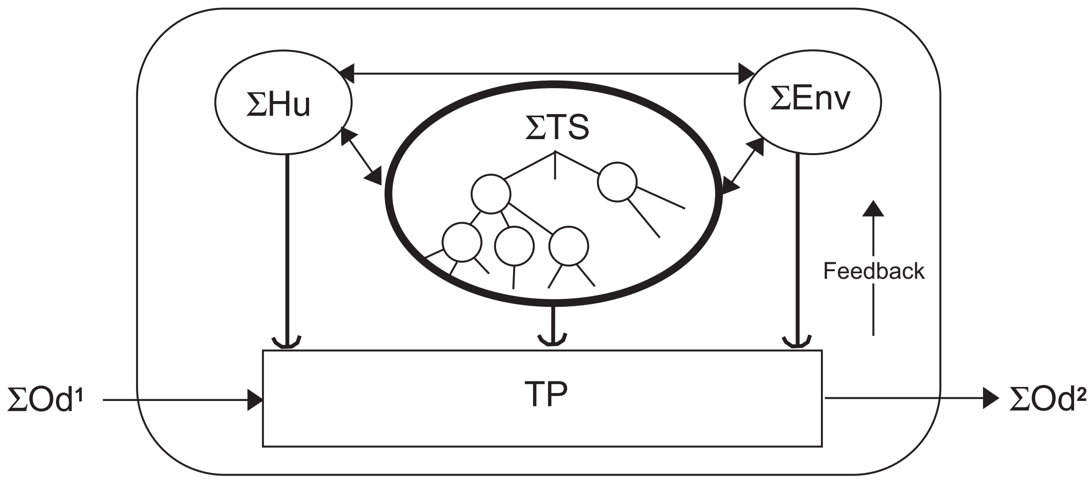


Figure 2. Hubka's depiction of a complex Technical System (∑TS) as interacting with a technical process (TP) which turns inputs (∑Od1) into outputs (∑Od2). The environment (∑Env) and humans (∑Hu) are separate from the Technical System and the Technical Process [10].

We have thus found that prior classification schemes did not consider ES by the ESD definition and thus fail to usefully separate them from one another. Nonetheless, Hubka and others [10,11,12,15,16,17] have considered attributes of systems which we want to examine (bottom-up) to determine if they can be a basis for useful characterization and classification. Therefore we now turn to study of potentially interesting attributes of the systems on our testbed list.

The attributes we consider are shown in Table 3, along with the literature sources suggesting the importance of the attribute. The third column in the table gives the basis for the qualitative assessment used in characterizing the testbed list. These are further defined in Tables 4–8, and in the legend below Table 3.

Table 3. System Attributes of Potential Use in Qualitative Assessment of the ES Testbed List

Attributes	Reference(s)	Specific Qualitative Scale
Degree of Complexity	[10,11,12]	See Table 4
Branch of Economy	[10]	See Table 5
Realm of Existence	[11]	Real vs. virtual
Boundary	[11,3,4]	Open vs. Closed
Origin	[11,3,4]	Natural vs. Artificial
Time Dependence	[11,3,4]	Static vs. Dynamic
System States	[11]	Continuous, discrete and hybrid
Human/Control	[2]	Autonomous/human in the loop/mixed
Human Wants	This study	See Table 6
Ownership	This study	See Table 7
Functional Type	[10,12,15,16,17]	See Table 8

Legend for Table 3:

Degree of Complexity: complexity is related to the amount of information needed to describe the system. System complexity is a function of the number of (unique) elements in the system as well as the number and nature of their interconnections. Table 4 shows the specific reference adopted here. By this measuring scale all ES in the testbed list turn out to be at the highest complexity (level IV) which confirms that our list and definition are in agreement.

Branch of Economy: what part of the economic system does the ES belong to? Table 5 shows the breakdown adopted here.

Realm of Existence: is the system only present in "thought" or does it manifest itself in the physical world, i.e. in some way connected to matter or energy? (All of the testbed list of ES are real, i.e., have physical aspects.)

Origin: is the system naturally occurring without human intervention or is its existence the result of a deliberate or accidental process involving human design and implementation? (All ES are artificial.)

Boundary: is there any exchange of matter, energy, or information across the system boundary? (All ES are open.)

Time Dependence: is the system time invariant, i.e. do any of the system's states change with time or do any of the system's properties change with time? The system is time varying if some system properties or system elements or interrelationships change over time[3]. (All ES are dynamic.)

System States: are the system states continuous (e.g. temperature) or are they discrete (e.g. "on" or "off") or a mix of both (hybrid). Few system modeling

[3] For example in a mathematical linear state space system the system dynamics are represented as $\dot{q} = Aq + Bu$ and $y = Cq + Du$, where q is the state vector. The system is considered time-invariant as long as the entries in the matrices A, B, C, D are constant.

techniques are good for hybrid systems, usually one finds techniques for dealing with continuous systems or finite state machines ("automata"). (All ES are hybrid.)

Human Involvement/System Control: some systems require constant involvement of a human operator, autonomous systems do not need human operators or guidance during operations, mixed systems have elements at least partially controlled by humans and autonomous elements. (All ES are mixed.)

Human Wants: a further attribute we consider potentially important to use in this study is the overall purpose of the system. From a highest level, the purpose of all engineering is to fulfill human wants so all engineering systems have been designed (over a complex series of designs and redesign that resemble evolution) to fulfill human wants. The system attribute associated with this are the Human Wants categories shown in Table 6.

Ownership: a further attribute of the Engineering Systems in Table 1 is the ownership or control of the specific system in question. This attribute is given in Table 7, where six classes of ownership/control are defined.

Functional Type: a potentially important classification scheme is due to Pahl and Beitz [12], Hubka [10] and Van Wyk [15,16,17]. Van Wyk's classification of functional types is shown below in Table 8. It is a three-by-three matrix consisting of 3 outputs (or operands) and three "types" of manipulators. We adopt in this study the 9 possible categories defined by this approach as our functional types.

Table 4. Technical Systems Classified by Degree of Complexity (from *Theory of Technical Systems* [10]):

Level of Complexity	Technical System	Characteristic	Examples
I (simplest)	Part, Component	Elementary system produced without assembly operations	Bolt, bearing sleeve, spring, washer
II	Group, Mechanism, Sub-assembly	Simple system that can fulfill some higher functions	Gear box, hydraulic drive, spindle head, brake unit, shaft coupling
III	Machine, Apparatus, Device	System that consists of sub-assemblies and parts that perform a closed function	Lathe, motor vehicle, electric motor
IV	Plant, Equipment, Complex machine unit	Complicated system that fulfills a number of functions and that consists of machines, groups and parts that constitute a functional and spatial unity	Hardening plant, machining transfer line, factory equipment

Table 5. Branch of Economy attribute defined by Examples of Technical Systems (from *Theory of Technical Systems* [10]):

Branch of Economy	Technical System TS	
	Equipment for	Typical Machine
Mining	Accessing Delivering Preparing	Cutting machine Conveyor Screening machine
Energy generation	Steam raising Electric generating	Steam boiler Water conditioner Steam turbine Gas turbine Water turbine Generator
Smelting	Pig iron smelting Steel smelting	Blast furnace Bessemer converter LD oxygen processor Rolling mill
Chemical industry	Coal scrubbing Color producing Explosives producing	Pressure vessel Piping Destillation column
Metalworking industry	Chipless forming Chip–forming Heat treatment Foundry Assembly	Press Forging hammer Machine tool Furnace Forming machine Jigs and fixtures
Constructional industry	Oil exploration Building Roadworks Hydro–construction Materials manufacture	Drill rig Personell lift Scraper Concrete mixer Block press
Transportation	Railway Shipping Space travel	Locomotive Wagon Passenger liner Rocket
Textile industry	Textile manufacture Dressmaking	Spinning machine Weaving loom Sewing machine
Food industry	Sugar refining Cheese production Milk processing	Concentrator Press Centrifuge
Medicine	Diagnosis Therapy	X–ray apparatus Artificial heart Prosthesis
Printing, offices	Printing Office work	Printing machine Typewriter Calculator
Agriculture	Transporting Harvesting Lumbering	Tractor Combine Chain saw
Distribution, trade	Self–service Packing	Check–out Wrapping machine

Table 6. Categories of Human Wants

Shelter
Food
Transportation
Communication
Security
Longevity and health
Entertainment
Aesthetic pleasure
Education
Social, Emotional, Spiritual & Curiosity

Table 7. Ownership/Control Attribute of Engineering Systems

SFP: Single, private, for-profit ownership and control of the system
MFP: Multiple, private, for-profit entities in control
SNFP: Single, not-for-profit controller
MNFP Multiple not-for-profit control
GOV: Governmental control
COMB: Complex combinations of 1 through 5

Table 8. Van Wyk's Table of Functional Types

Output	**Type of Manipulator**		
	Processor (1)	**Transporter (2)**	**Store (3)**
Matter (M)	Cement kiln	Truck	Silo
Energy (E)	Power plant	Copper cable	Battery
Information (I)	Computer	Optic fiber	Compact disk

Seven of the eleven attributes in Table 3 are useful in the *characterization* of ES (differentiation from other systems) but not in *classification* (differentiation among ES). All ES are complex, real, open, artificial, dynamic, hybrid (system states are both continuous and discrete) and have mixed control (have both autonomous and human-in-the-loop elements or subsystems). It can be suggested that these characteristics –if confirmed over a wider range of ES- can serve to strengthen our definition and understanding of Engineering Systems.

Appendix A shows the Engineering Systems of Interest to ESD listed according to the four attributes that give some differentiation-Human Wants, Functional Type, Economy Branch (after Hubka) and ownership. In Appendix A, the ES are shown separated according to Human Wants (given in Table 6) as it comes closest to being able to pass our first criteria—we can largely differentiate among our ES. Hubka's somewhat similar grouping (Table 5) is not as effective partly because it does not really consider service as opposed to manufacturing industries and does not consider all human wants. The ownership differentiation is also fairly strong but we choose to show that as an additional attribute.

The separation by Human Wants still leaves a significant number of systems simply unclassified or as for multiple human Wants. Among those classified, the largest groupings are for Transportation, Communication, Security and Health. In the multiple use category, many of the systems are markets, software, and other IT tools, all of which support meeting multiple human needs.

Appendix A shows Van Wyk's nine categories for each system in the second column. We should note that almost all of our systems transform, transport and store energy to some extent (All information is accompanied by at least a minimum amount of energy). In addition, almost all also process (transform), and store information. Thus, in Appendix A-column 2, we have tried to identify the essential functional categories and only list these. We imagined taking various functions away and asked whether the ES could still serve the Basic Human need(s). For a fair number of systems, a single "most important" function can be identified. However, for an equally large number there seem to be at least two major types that the Engineering System fits into. For some systems (the CVS computerized drugstore, and very complex systems such as Tokyo Metropolitan Area and the U.S. Aerospace Industry), at least three categories are well-described for the system basic functions.

Despite these difficulties, Functional Type as originally expounded by Hubka, Pahl and Beitz, and Van Wyk appears to be the technical attribute best able to differentiate among ES (Systems of interest to ESD). Indeed, no other technical attribute has been described or proposed which makes a start in differentiating among our ES. However, as shown in Appendix A, the systems are not simply separated by this attribute. Moreover, only our first classification criteria in Section III has been met but utility-particularly in ES design-is problematical. Thus, in the next two sections we explore (in preliminary fashion) approaches to further expand the concept of Functional Type.

VI. Preliminary Quantitative Studies

In complex differentiation problems, qualitative attribute classification is often insufficient to allow for classification. In one such well-known case, the practical classification of engineering properties of materials, quantitative studies proved very useful. Ashby [1] has studied a wide variety of materials and made plots of various "properties" of materials of interest in application. Interesting differentiation among different classes of materials occurs in such plots (now referred to as Ashby diagrams). Thus, Ashby's diagrams give useful insight into which materials may best be applied in various design problems. Figures 3 and 4 below show two such diagrams. Although there is some overlap in many of the diagrams-see Figure 3, the different known material classes often (for theoretically understandable reasons) cluster together in these kinds of plots.

The hypothesis we want to pursue by quantitative study is whether such differentiation may occur with engineering systems with “appropriate” attributes and plots. Unfortunately this hypothesis is difficult to test because Engineering System Attributes in contrast to material properties are not generally available. Indeed, such attributes are not yet agreed upon or defined quantitatively. This section begins this task.

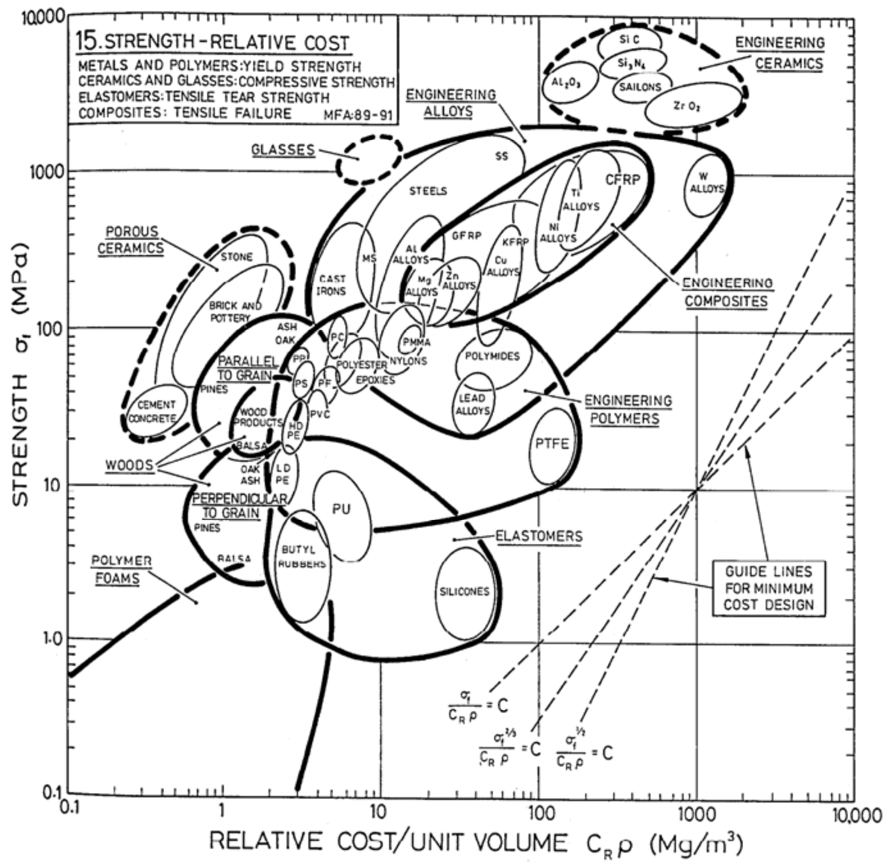


Figure 3. Ashby Diagram of strength versus relative cost/unit volume

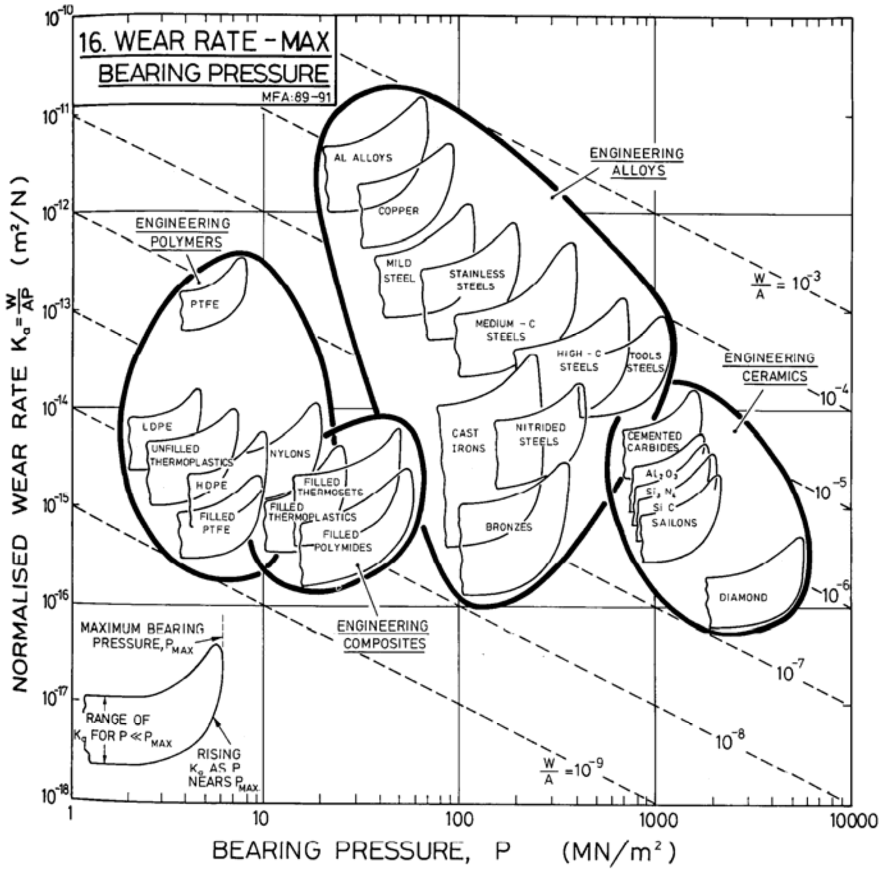


Figure 4. Ashby Diagram of wear rate vs. maximum bearing pressure

The results in Section V indicate that quantitative definition of parameters should begin with measures of information, energy, and matter. In addition, several specific examples from the testbed list and general logical analysis leads to measures of value, human effort and scale/shape as further basic parameters.

Table 9 below shows Preliminary Quantitative Data for 17 attributes and for 7 Engineering Systems from the Testbed list. The seven ES include two pairs of closely related examples- the pair of oil (and automotive) examples differ by scale and scope but might be expected to be fundamentally similar. The preliminary quantitative definition for each attribute is given in the Table legend. We note that many of the entries are not filled because of the paucity of existing data. In addition, we want to note that the quantities shown—while not carelessly listed are at an early stage of verification. The data was obtained by search of company public reports (3-5 year averages were used from annual reports of profits and most recent employment figures for personnel) and by discussion with experts.

Table 9. Preliminary Quantitative Data for Selected Attributes of Engineering Systems

			Engineering Systems						
	System Attributes	**Units**	**eBay Trading System**	**Federal Express North American Package Delivery System**	**Iridium Communication Satellites**	**Wixom (Ford Automotive Assembly Plant)**	**Baytown (Exxon-Mobil Refinery)**	**Toyota Automotive Products System**	**Exxon-Mobil Fossil Fuel Extraction, Refining, & Distribution System**
Dynamic Attributes	Mass Flow	kg/day	~0	$4x10^6$	~0	$2x10^6$	$7x10^7$	$2x10^7$	$1.5x10^9$
	Mass Displacement	kg·meters/ day	~0	TBD	~0	$2x10^4$	$7x10^{10}$	$2x10^{10}$	$1.5x10^{12}$
	Energy Flow	btu/day	~0	~0	~0	$5x10^3$	$2x10^7$	$3x10^5$	$5x10^8$
	Information Flow	bits/day	10^7	$2x10^9$	$7x10^{13}$	~0	~0	$2x10^{11}$	~0
	Information Transmitted		10^{12}						
	Information Used	bits/day	TBD	TBD	TBD	TBD	TBD	TBD	TBD
	Value Added	$/day	$1.6x10^5$	$3x10^6$		$2x10^6$	$2x10^6$	$1.4x10^7$	$4.5x10^7$

	System Attributes	**Units**	**eBay Trading System**	**Federal Express North American Package Delivery System**	**Iridium Communication Satellites**	**Wixom (Ford Automotive Assembly Plant)**	**Baytown (Exxon-Mobil Refinery)**	**Toyota Automotive Products System**	**Exxon-Mobil Fossil Fuel Extraction, Refining, & Distribution System**
	Human Effort	person-hours/day	1.3x10^{4}	2x10^{5}	3x10^{4}	4x10^{4}	2x10^{4}	10^{6}	8x10^{5}
	Idea Creation	R&D$/day	1x10^{5}/day	10^{3}	10^{4}	10^{2}	10^{2}	10^{7}	3x10^{6}
Static Attributes	Cost to Build	$	7.5x10^{7}	10^{9}	5.5x10^{9}	10^{9}	10^{9}	3x10^{10}	5x10^{10}
	Engineering Cost	$	6x10^{7}		10^{9}	2x10^{7}	10^{8}	10^{10}	7x10^{9}
	System Scale	meters	2x10^{7}	5.10^{6}	2x10^{7}	10^{3}	10^{3}	2x10^{7}	2x10^{7}
	Boundary Length	meters	3x10^{2}			3x10^{3}	4x10^{3}	2x10^{5}	3x10^{5}
	Boundary Area	meters^{2}	7x10^{4}			10^{5}	10^{5}	10^{7}	8x10^{6}
	Enclosed Volume	meters^{3}	5.10^{5}			10^{6}	2x10^{6}	10^{8}	2x10^{8}
	Technical Complexity		10^{8}/1	10^{7}/3	TBD	10^{5}/1	10^{6}/3	10^{13}/2	10^{12}/5
	Human Complexity		10^{4}/10	5x10^{4} /1	TBD	2x10^{3}/1	10^{3}/1	10^{4}/3	10^{3}/10

Table 9 (Continued)

Legend for Table 9:

Mass Flow. Weight of system output per day.

Mass Displacement. Pounds moved by system times average distance moved.

Energy Flow. Energy available for further use embodied in output.

Information Flow. Information content of output.

Information Transmitted. Information transmission for or by the system.

Information Used. Information transmitted and used in internal system decisions; i.e., by people “paid” by system elements—no customers or users. .

Value Added. Revenue from output minus cost of operating the system.

Human Effort. All human work done by the system (not customers/users).

Idea Creation. Surrogate is 10K R&D spending per day.

Cost to Build. Approximate replacement cost for system if built new.

Engineering Cost. Approximate engineering cost to design replacement.

System Scale. Maximum distance between any two system elements.

Boundary Length. Minimum physical distance needed to enclose all system elements.

Boundary Area. Minimum physical area needed to enclose all system elements.

Enclosed Volume. Minimum physical volume needed to enclose all system elements.

Technical Complexity. Surrogate is A/B, where A is the number of artifacts, processes or algorithm elements in the largest system and B is the number of systems within 3 O(M) of largest system.

Human Complexity. Surrogate is A/B, where A is the number of personnel in the largest organization in the system, and B is the number of organizations within three O(M) of the largest organizations

At this early stage of development, it is noted that the attributes differ by many orders of magnitude between the various entries. This is similar to the case for the properties of materials studied by Ashby. We thus will also use log-log plots. In order to do this, we arbitrarily set the small (shown in Table 9 as ~0) values to 1 for all dimensions since these small quantities are the least available and most subject to error.

Figures 5 and 6 show two of our "pilot-plots". Figure 5 simply shows the value added (~profit) plotted against the information flow. We see that the data does fall into three groupings which we have labeled A, B, and C. This simply differentiates the profitable-low information oil ES (grouping A) from the low profit, information flow intense Iridium (grouping C) and both from all of the intermediate-information intense ES (grouping B). It is clear that more entries would (probably) destroy the profit-information flow correlation but there might still be interesting differences among ES of different "information intensities".

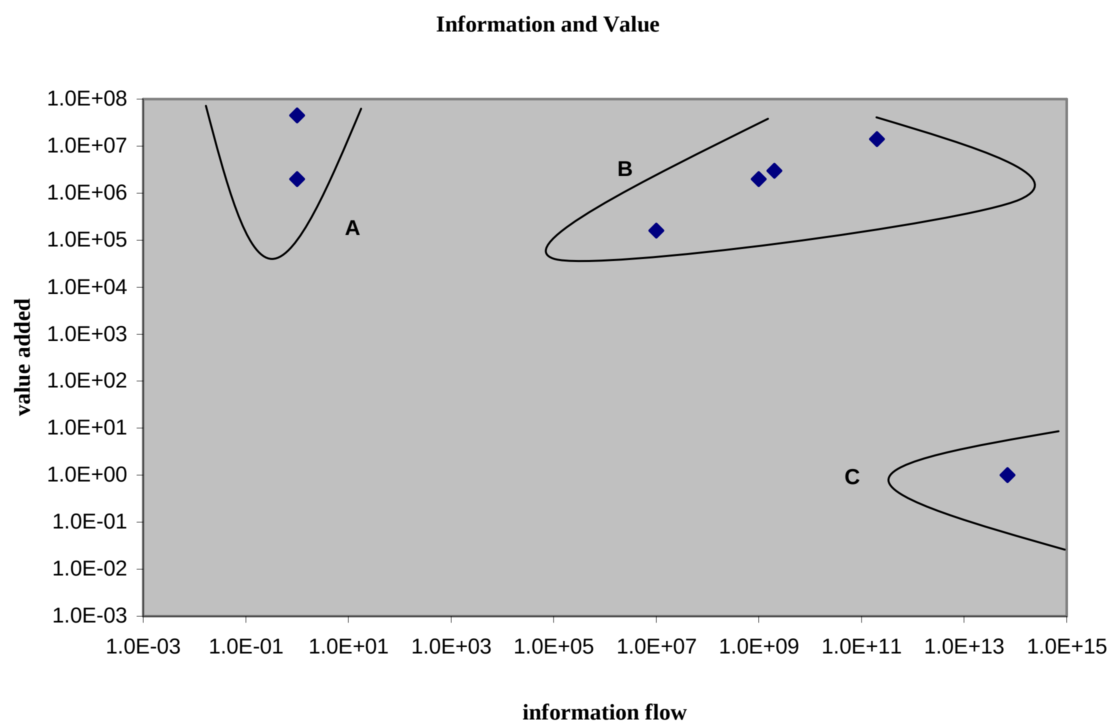


Figure 5. Plot of value added versus information flow

The concept of mass, energy, information, and value intensity can also be examined by plotting ratios of parameters from Table 9. Figure 6 is one such diagram and

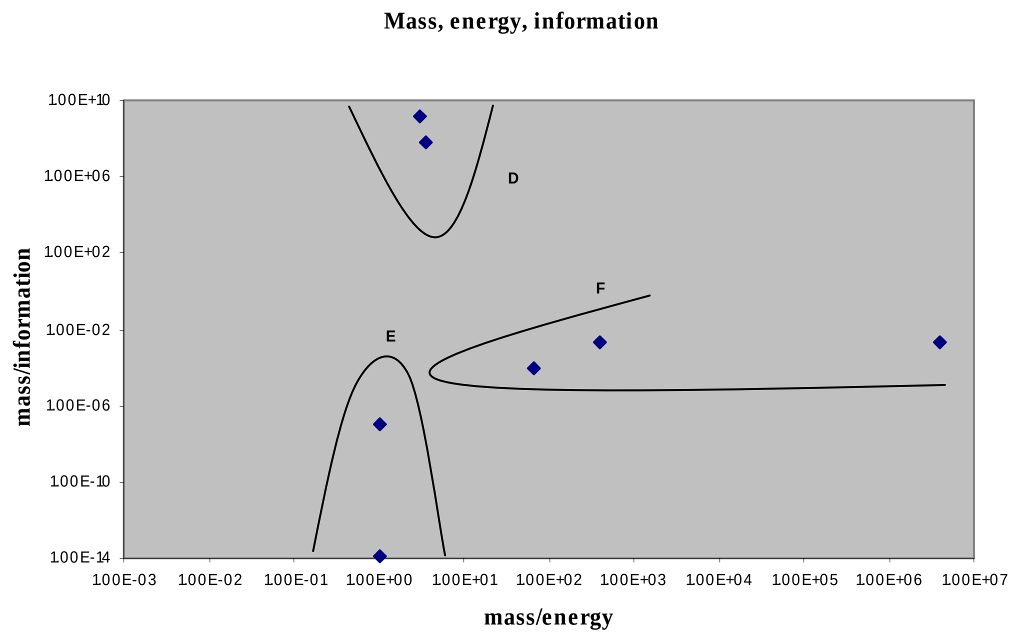


Figure 6. Plot of mass flow/information flow versus mass flow/energy flow

shows a plot of the ratio of mass flow divided by information flow against the ratio of mass flow divided by energy flow. This diagram is also "analyzed" to show three different ES groupings which we have labeled D, E and F. It shows differentiation of the energy and mass intensive oil ES (Grouping D) from the information-intense eBay and Iridium ES (Grouping E) and from both the intermediate mass and information-intense ES (Grouping F where Federal Express is the very high mass flow to energy flow point).

Many other direct plots such as Figure 5 also show groupings of the ES. However, relatively simple explanations exist and it would be premature to conclude that this even indicates that our hypothesis is promising. For ratio diagrams such as Figure 6, we remain optimistic that the diagrams will be useful in differentiating and possibly in a meaningful way. For example Whitney [14] has pointed out potentially fundamental reasons that energy and information intense systems might have different architectures (more modular for information-intensive and more integral for energy-intensive). Moreover, high mass displacement correlates to transportation systems, which tend to have large enclosed volume to boundary area (high asperity). Thus, it seems possible that quantitative studies may help identify important characteristics of our systems with multiple functional types and even help guide design and protocol design efforts. With the small number of ES and the low data quality in our present set there is not really objective evidence to support the optimism, however, we recommend further research in this area.

VII. A Meta-Model and Classification of Engineering Systems

Section VI is nonetheless suggestive that the relative intensity of information flow, value flow, energy flow and mass flow can possibly differentiate among ES in a meaningful way. Section V established that functional type was the most effective technical attribute

and basic human wants the most effective context attribute (among those tested in this paper) for differentiation among the testbed ES. In this section we briefly consider a model that integrates these attributes and extends the functional type attribute.
The model starts by viewing the human needs listed in Table 6 as potentials, similar to electrical or gravitational potentials. These human needs can be an expression of individuals, groups of individuals or more generally organizations. Unsatisfied needs create potential differences that drive the flow of goods and services in our world. A more pragmatic view is that the operands are matter, energy, information and monetary value as a surrogate for "value". In this way one may envision the existence of a multi-layered meta-network that comprises the entire engineered world, see Figure 7. The systems in this meta-network interact with natural systems in different ways (e.g. observation, obtaining natural resources, embedding natural systems as subsystems…)

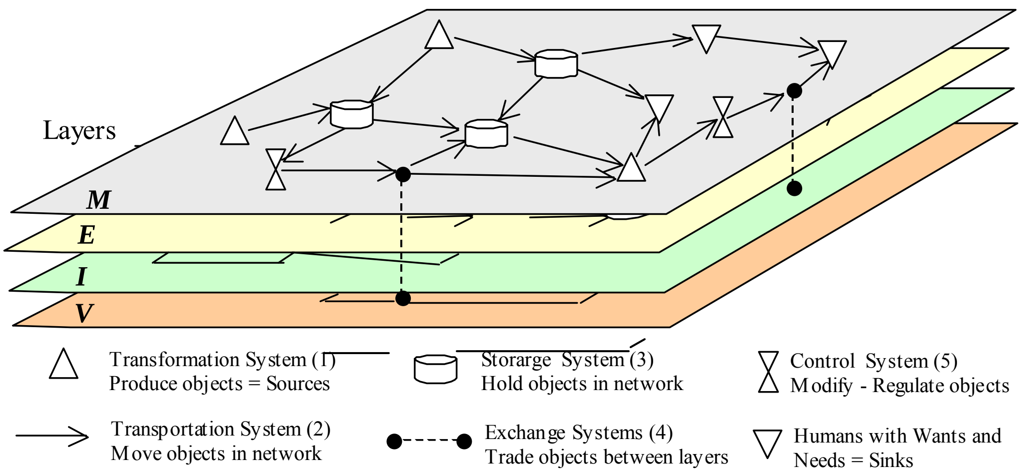


Figure 7: Meta-Model for Engineering Systems Classification

In the figure above, the layers are labeled according to the type of operand that exists within the layer. M-Matter, E-Energy, I-Information, V-Value. This notion appears quite general, but it does provide a potential framework for description of a "System of Engineering Systems". Within each layer there are a finite number of types of systems, distinguished by the function they perform in the pursuit of the fulfillment of human wants and needs. The ultimate ambition is to find a complete set of functions, i.e. an essential set that is sufficient to describe any Engineering System. An initial attempt is made here.

- **Transformation Systems (*1*):** <u>transform</u> objects into new objects
- **Distribution Systems (*2*):** provide <u>transport</u>ation, i.e. change the location of objects
- **Storage Systems (*3*):** act as buffers in the network and <u>hold/house</u> objects over time
- **Market Systems (4):** allow for the <u>exchange</u> of objects mainly via the Value layer
- **Control Systems (*5*):** seek to <u>drive objects</u> from some actual state <u>to a desired state</u>

Thus, a second dimension of classification is according to the type of operand that the Engineering System operates on (the layers in Figure 7). We refer to Dori's work [7,8] on

Object Process Methodology for exact definitions of object, process, state and operand. Only the same type of operand can flow within one layer. We distinguish the following:

- **Matter (M)** physical objects, including organisms that exist unconditionally
- **Energy (E):** Stored work that can be used to power a process in the future
- **Information (I):** Anything that can be considered an informational object
- **Value (Monetary) (V):** Monetary and intrinsic value object used for exchange

This meta-model thus also effectively expands the classification scheme discussed above due to van Wyk, see Table 10. One may form an expanded 5 x 4 classification matrix. Below we attempt to classify selected systems from the testbed list (Table 1) by assigning them to a particular cell of this Engineering Systems Classification Matrix. The functions are described by dual verbs to avoid a very narrow interpretation based on natural language semantics.

Table 10: Complex Systems Classification Matrix – **The gray shaded area corresponds to original matrix according to van Wyk (Table 8).**

Process/Operand	**Matter (M)**	**Energy (E)**	**Information (I)**	**Value (V)**
Transform or Process (1)	Ford Automotive Plant	Pilgrim Nuclear Power Plant	Cray 1 Computer System	N/A
Transport or Distribute (2)	FedEx Package Delivery	US Power Grid System	Iridium Satellite Constellation	Intl Banking System
Store or House (3)	Three Gorge Dam	Three Gorge Dam	Boston Public Library (P)	Fleet Bank Account System
Exchange or Trade (4)	eBay Trading System	California Energy Market	Reuters News Agency	NASDAQ Trading System
Control or Regulate (5)	MGH Health Care System	Atomic Energy Commission	International Standards Organization	US Federal Reserve

The entries in the columns of the first row of Table 10 correspond to the primary operand classes that an Engineering System can operate on. An operand is the object that is being affected or that results from the primary process that is enabled by the Engineering System. Examples of operands for the four classes are:

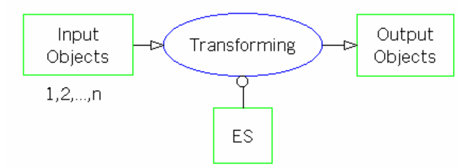
Matter: packages, vehicles, crude oil, animals, plants, water, memorabilia
Energy: potential, electrical, kinetic, thermal, nuclear
Information: news reports, email, TV shows, voice conversations, books (content), bits
Value: stocks, bonds, cash, inventory, loans, credit, currencies, options

Use of this expanded matrix introduces tighter definitions but more categories (20 vs. 9) than by following Table 8. Appendix A has 41 ES that are associated with a single functional type, 39 ES with two and 7 with three or more. As a test of the effect of introducing the new categories we categorized the ES in Appendix A by functional type using the classes shown in Table 10 (not shown in Appendix A). The result after this is 50 ES with a single technical type, 34 with two and only 3 with three or more. This occurs because some systems are more precisely defined by the expanded version (compare the GM accounting system in Appendix A with the single entry in Table 10). Of course, Table 10 shows that systems such as China's Three Gorge Dam are probably basically multi-functional.

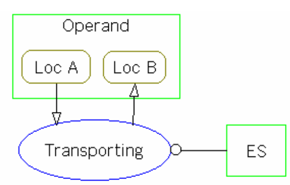
A more focused discussion of the functions (processes) associated with Engineering Systems is appropriate at this point. The process is always the link between the Engineering System (ES) and the operand or resultee [8]. The fundamental processes for Engineering Systems are as follows:

Table 11: Fundamental Processes (functions) of Engineering Systems

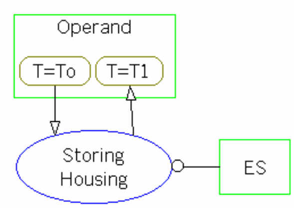
Transform or Process: New object(s) (resultee) results from the transformation process, which is enabled by the ES. A number *n* of input objects are completely consumed by the transformation.



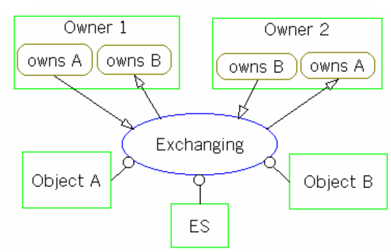
Transport or Distribute: ES only changes the spatial state "location" of the existing operand without intentionally changing it in other ways.



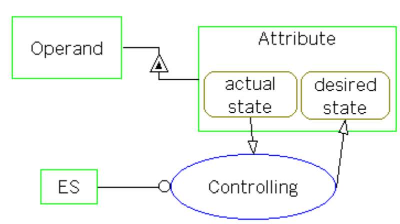
Store or House: ES changes the temporal state "time" of the operand without intentionally changing it in other ways. Storing or housing ensures that the operand is available for future processes.



Exchange or Trade: ES inverts the structural links or ownership rights between two owners 1 and 2 and two (or more) objects A and B if the value of both objects is perceived as being equal.



Control or Regulate: The ES attempts to drive the actual state of an attribute of the operand towards a desired state by sensing the actual state of the operand.



This object-process view of Engineering Systems immediately raises a number of questions. One is whether the set of proposed fundamental function is complete and unique. The examples in Table 10 seem to indicate the usefulness of the set, but cannot prove its exhaustiveness. This should be the subject of future research within ESD. Another valid question is how this rather theoretical view ties back to the fulfillment of human wants and needs? Each of the Engineering Systems has a particular purpose in the multi-layer network of Figure 7 and helps meet human wants and needs in concert with other Engineering Systems. Appendix B contains specific examples for some selected Engineering Systems.

Fundamentally this corresponds to a **functional classification** of Engineering Systems by specifying the layer in which they primarily operate as well as their function within that layer.

VIII. Challenges and Future Work

This paper has reviewed a number of proposed classification schemes from the literature and has attempted to assess their applicability to a testbed list of Engineering Systems. We have augmented the proposed classification schemes where this seemed to add value. In order to move forward there appear to be a number of challenges that have to be addressed by the ESD community as a whole, which naturally lead to future work:

Challenge 1: *What subset of systems are Engineering Systems? Should we in ESD simply designate Engineering Systems to be equivalent to Engineering Systems of Interest to ESD?*

While a definition of Engineering Systems has been proposed by an internal committee with faculty input, it is not clear whether there is clear consensus. The three attributes that make systems "Engineering Systems" are: human designed for a purpose, large scale, high degree of human and technical complexity. All of these criteria are in agreement with most of the ESD faculty input but the comments were not unanimous. These attributes can be used as a filter to find the subset that we call "Engineering Systems". This filter does not have to be rigid, but only once such a subset of systems emerges can we think about consensus on classification schemes and ultimately the formation of a new discipline.

Challenge 2: *What are significant system attributes?*

This paper has shown that classification of Engineering Systems only makes sense if we consider specific system attributes. There are many more attributes of systems than were discussed in this paper. Work will have to be done to see if any other attributes of Engineering Systems are considered to be important. A logical area for fruitful interaction would be economic classification schemes such as standard industrial classification (SIC).

Challenge 3: *Quantitative Systems Analysis*

In order to see whether the postulated classifications of Engineering Systems according to Sections V and VII are valid, they have to be corroborated by a quantitative study of systems attributes. This validation has occurred for all successful classification schemes. Mendeleyev measured atomic masses and counted valence electrons, Linnaeus measured animal sizes, catalogued their anatomical features and assembled them into species, Ashby tabulated material properties such as density, elastic modulus etc… based on extensive tests. Although we began this task in Section VI, it is obvious that further quantitative work is needed on Engineering Systems attributes as well as the attributes of their operands related to the fulfillment of human wants and needs. Only such rigorous work will prove or disprove the value of proposed classification schemes.

Challenge 4: *Meta-Model Refinement*

The meta-model idea of multiple matter, energy, information, and value networks intertwined appears promising, but is only weakly defined at this point. In a typical network potential differences (supply and demand in economics) drive the flow quantities from sources to sinks via nodes and arcs. A holistic and quantitative description of these networks, embedding information from the quantitative systems analysis, would be desirable. Particular emphasis should be on understanding phenomena such as equilibrium, aggregation and instability in such a meta-network. While it is clear how the flow of goods can be modeled in such networks, it is much more difficult to conceptualize a "flow of services".

Acknowledgments

The authors would like to acknowledge the help of all colleagues within ESD that have contributed to this paper with their comments and inputs to the testbed list. Sameera Ponda, an undergraduate student in Aeronautics and Astronautics, assisted in obtaining some of the quantitative data in Section VI.

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Appendix A

Engineering Systems Grouped According to Basic Human Wants (assessed according to the qualitative Attributes in Table 3).

Attributes	**Functional Types**	**Owner**	**Economy branch**
Shelter			
Tokyo Metropolitan Area	ALL	COMB	All
Plymouth Nuclear Power Plant	E1	SFP	Energy generation
U.S. Power Grid System	E2	COMB	Energy
Food			
Hudson River Watershed Water Supply System	M3,M2	COMB	Food, energy
U.S. Agricultural Food Production and Distribution System	M1	COMB	Food
Transportation			
Airbus 318-321 Airplane Family System	M1,I1	SFP	Transportation
Boeing Supply Chain System	M1,I1	MFP	Transportation
Automotive Products and Plants of Toyota Motor Company System	M1,I1	SFP	Transportation
Big Dig (central Artery Project, Boston)	M2,M1	GOV	Transportation
Chinese "People" Air Transport System (PRC)	M2	GOV	Transportation
General Motors Cost and Accounting System	I1,I2,I3	SFP	Transportation
European Union Roadway System	M2	COMB	Transportation
FAA/IATA Certification System	I1	GOV	Transportation
Ford XY Platform Products and Plants System	M1	SFP	Transportation
Exxon Mobil Fossil Fuel Drilling, Refining and Distribution System	E1,E2	SFP	Transportation
General Motors (GM) Supply Chain	M1,I1	SFP	Transportation
Global Air Traffic Control System	I1,I2,	GOV	Transportation
Global Air Transportation System	M2	COMB	Transportation

Attributes	**Functional Types**	**Owner**	**Economy branch**
Global Positioning System (GPS)	I1,I2	GOV	Transportation
Gotthard Transalpine Tunnel (Switzerland) (P)	M2	GOV	Transportation
Mexico City Transportation System	M2	COMB	Transportation
New York City Subway System	M2	GOV	Transportation
Newark Airport	M2,M3	GOV	Transportation
Pratt and Whitney XYZ Gas Turbine Family System	E1	SFP	Transportation
U.S. Aerospace Industry (as a system)	M1,I1	COMB	Transportation
Star Alliance (United, Lufthansa, Singapore Airlines…)	M2	MFP	Transportation
U.S. Air Traffic Control System	I1,I2	GOV	Transportation
Wixom (Ford) Automotive Assembly Plant System	M1	SFP	Transportation
ZF XYZ Continuous Variable Transmission System	E1	SFP	Transportation
Boeing-777 Aircraft System	M1,I1	SFP	Transportation
Baltimore Harbor (P)	M2,M3	MNFP	Transportation
Communication			
AOL instant messaging community/communication system	I2,I1,	SFP	none
AT&T Telecommunication Network	I2,	SFP	none
Boston Globe Print Media System (Newspapers, Magazines)	I1,I2	SFP	none
Geosynchronous Orbital (GEO) Belt Satellite Systems	I2	GOV	none
Global Satellite Launching System	M2	COMB	none
Global Wireless Communication System	I2	COMB	none
International Space Station (ISS)	I1,M3	GOV	none
Global Internet	I2	COMB	none
Iridium Low Earth Orbit Communication Constellations	I2	MFP	none
Space Satellite Guidance and Navigation System	I2,I1,	GOV	none
Reuters Global News Distribution Service	I2,I1	SFP	none
Security			
BOSTON Fire Alerting Prevention and	I2	GOV	none

Attributes	**Functional Types**	**Owner**	**Economy branch**
Fighting System			
Department of Defense Acquisition System (USA)	I1,I3	GOV	none
JSF System (Joint Strike Fighter)	I1,M1	COMB	none
Military Air Transport System	M2,	GOV	none
National Defense System (Strategy, Personnel, Hardware…)	I1,M1	GOV	none
NYPD security system (P)	I2,I1	GOV	none
U.S. Aerospace Industry (as a system)	I1,M1	COMB	none
U.S. Navy XYZ Aircraft Carrier Battle Group	M2	GOV	none
XY Rocket Engine Product Verification (Test) Systems	I1	GOV	none
Health and Longevity			
CVS Computerized Drug Store Chain (T,P)	M2,M1,I2,I3,	SFP	medicine
Health Care System of France	I2,I1,M1,	GOV	medicine
Human genome project	I1	COMB	medicine
MGH health care system	I2,I1,M1	SNFP	medicine
U.S. Social Security System	I3,I1,I2	GOV	medicine
Synthes-Norian Bone Surgery System (P)	I1,M1	SFP	medicine
U.S. Government OSHA Systems	I1,I2	GOV	medicine
U.S. Government Environmental Regulatory System	I1,I2	GOV	medicine
Education			
MIT Facilities System	E1,E2,I2	SNFP	none
MIT Information Technology System (incl. Athena)	I2,I1	SNFP	none
Social, etc.			
South Pole International Research Station	I1,M3	GOV	none
Synchrotron (Quantum Physics Experimental System)	I1	GOV	none
Multiple Human Wants			
China's Three-Gorge Dam	M3,E3	GOV	Energy
CNN Global News Gathering and Distribution System	I1,I2	SFP	Communication
Exxon Mobil Enterprise Resource	I1	SFP	Energy

Attributes	**Functional Types**	**Owner**	**Economy branch**
Planning (ERP) System			
Microsoft Corporation Knowledge Management System	I3	SFP	Software
Xerox Corp. Preventative Maintenance System (P)	M1,I3	SFP	Office equipment
General Electric Quality Control & Operating System	I1	SFP	All
eBay trading system	I2	SFP	Market
Amazon.com System	I2,M2	SFP	Distribution
Federal Express (or UPS) North American Package Delivery System	M2	SFP	Distribution
Federal Reserve System (T,P)	I1,I3	GOV	All
GE Polycarbonate Manufacturing and Distribution System	M1,M2	SFP	Chemical
Global Freight Transportation System	M2	COMB	Transportation
International Banking and Monetary Transfer System	I2,I3	COMB	All
Java Software System	I1	SFP	Software
Linux/UNIX Operating System	I1	MNFP	Software
Company XYZ Marine freight transportation	M2	SFP	Transportation
NASDAQ Trading System	I2	SFP	Market
Rohm and Haas IC "Blocker" Manufacturing System	M1	SFP	All
Shanghai Freight Transport System	M2	COMB	Transportation
Sun XYZ Server Family System	I1,M1,	SFP	All
U.S. Aluminum production and recycling system	M1	COMB	Smelting
Windows NT Operating System	I1	SFP	Software
Xerox Family of Photocopiers System	I1,M1	SFP	Office equipment
Cray-1 Computer System	I1,I3	SFP	all

Appendix B

Functional Classification of Selected Engineering Systems

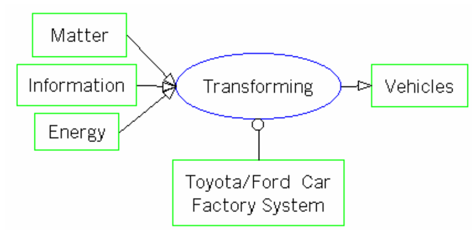
Let us consider some specific examples of Engineering Systems from the testbed list, Table 1, along with their corresponding high-level Object-Process Diagrams (OPD). Note that in all cases the Engineering System is connected to the process via an instrument link. In the table each cell has the functional classification, name and a short description of the Engineering System on the left and the corresponding OPD on the right.

Table B-1 Examples of Engineering Systems Classification

M1: Matter Transformation System

"Toyota/Ford Car Factory System"

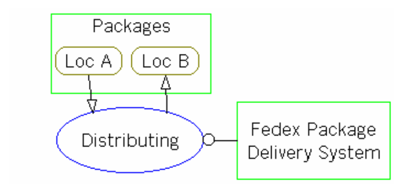
Matter objects "vehicle" result from a transformation process, where matter, information and energy are consumed.



M2: Matter Transportation System

"FedEx Package Delivery System"

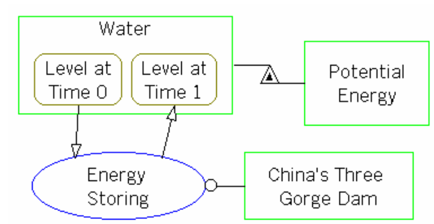
The distribution process changes the state "location" belonging to the operand "package" from A to B.



E3: Energy Storage System

"China's Three Gorge Dam"

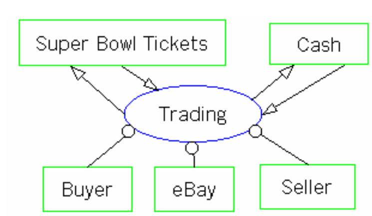
The dam's function is to store energy by transforming the water level at time T0 to the level at time T1, whereby the water is characterized by its "potential energy"



M4: Matter Trading System

"eBay Trading System"

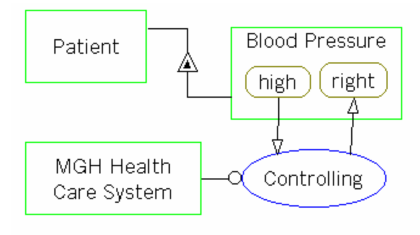
The matter trading switches the ownership of object A (tickets) and object B (cash). Trading systems represent a market place and usually involve one object in the value layer (e.g. "cash").



M5: Matter (Human) Control System

" MGH Health Care System"

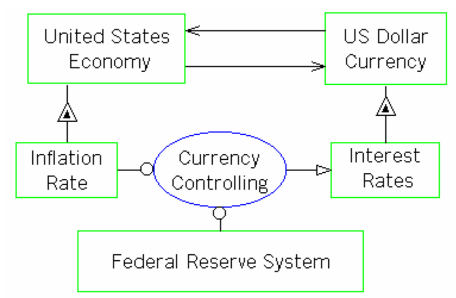
The MGH health care system attempts to control the blood pressure state (really the health state in general) of a patient from a high value to a nominal value



V5: Value Control System

Federal Reserve System

The Federal Reserve acts as a control system by setting interest rates based on changes in economic indicators



I2: Information Distribution System

"Iridium LEO Satellite Constellation"

Voice bit stream is transported from Caller A to Caller B via wireless satellite link and/or the Public Switched Telephone Network (PSTN)