Reminders

• handouts
• Returns
• Homework 3 due next week
• Draft term paper due next week

Engineering Systems

• We are interested in systems with the following characteristics:
  - Technologically Enabled
  - Large Scale (large number of interconnections and components)
  - Complex
  - Dynamic, involving multiple time scales and uncertainty
  - Social and natural interactions with technology
  - May have Emergent Properties

ES Examples

• Military Aircraft Production & Maintenance Systems
• Commercial & Military Satellite Constellations
• Megacity Surface Transportation Systems
• The Worldwide Air Transportation & Air Traffic Control System
• The World Wide Web & the Underlying Internet
• Automobile Production & Recycling Systems
• Consumer Supply Logistics Networks
• Electricity Generation & Transmission Systems

ES Requires

• An Interdisciplinary Perspective—technology, management science and social science
• The incorporation of system properties, such as sustainability, safety and flexibility in the design process. (These are lifecycle properties rather than first use properties.)
• An Enterprise Perspective
• The incorporation of different stakeholder perspectives

Hierarchy of Knowledge

• 1. Observation
• 2. Classification
• 3. Abstraction
• 4. Quantification and Measurement
• 5. Symbolic Representation
• 6. Symbolic Manipulation
• 7. Prediction
**Disciplines with ES**

- Systems Engineering
- Operations Research
- Engineering Management
- Technology Policy

**Examples of Desirable and Undesirable Anticipated and Emergent System Properties Influenced by Architecture**

<table>
<thead>
<tr>
<th>Desirable</th>
<th>Anticipated</th>
<th>Emergent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric power networks share the same feeder.</td>
<td>Hub-and-spoke airline routes shorten the length of trips.</td>
<td>Blackouts are associated with increased deaths.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Undesirable</th>
<th>Anticipated</th>
<th>Emergent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power networks can propagate blackouts.</td>
<td>Hub-and-spoke causes huge savings in airport and resource utilization at airports.</td>
<td>Blackouts are associated with increased food costs.</td>
</tr>
</tbody>
</table>

**Why is System Architecture Important?**

- Architecture Is A Way To Understand Complex Systems
- Architecture Is A Way To Design Complex Systems
- Architecture Is A Way To Design Standards And Protocols To Guide The Evolution Of Long-lived Systems
- Architecture Is A Way To Manage Complex Systems

**Systems Architecture**

- An abstract description of the entities of a system and the relationships between those entities.
- System engineering theory works most smoothly when the product can be broken into modules that are relatively independent - Modular.
- When products cannot be decomposed simply, or when their behaviors interact, they are called integral.

**4 Types of Architectures**

- The functional architecture (a partially ordered list of activities or functions that are needed to accomplish the system’s requirements)
- The physical architecture (at minimum a node-arc representation of physical resources and their interconnections)
- The technical architecture (an elaboration of the physical architecture that comprises a minimal set of rules governing the arrangement, interconnections, and interdependence of the elements, such that the system will achieve the requirements)
- The dynamic operational architecture (a description of how the elements operate and interact over time while achieving the goals)

**Decomposition of Architecture**

Diagram showing the different types of architectures and their interconnections.
**Further Decomposition**

- [Diagram showing further decomposition of concepts]

**Properties**

- Delivery of Basic Function: Performance & Cost
- Illities: Flexibility, Robustness, Scalability, Safety, Durability, Sustainability, Reliability, Recyclability, Maintainability, Quality
- Characteristics: Complexity, Emergence, Systems, Architecture, Uncertainty

**Robustness**

- Robustness is defined as “the demonstrated or promised ability of a system to perform under a variety of circumstances, including the ability to deliver desired functions in spite of changes in the environment, uses, or internal variations that are either built-in or emergent” (ESD 2002).

**Adaptability**

- Adaptability is defined as “the ability of a system to change internally to fit changes in its environment,” usually by self-modification to the system itself (ESD 2002).

**Flexibility**

- Flexibility is defined as “the property of a system that is capable of undergoing classes of changes with relative ease. Such changes can occur in several ways: a system of roads is flexible if it permits a driver to go from one point to another using several paths. Flexibility may indicate the ease of changing the system complexity and rework” (ESD 2002).

**Safety**

- Safety is defined as “the property of being free from accidents or unacceptable losses.” Associated with this definition are several others: An accident is “an undesired and unplanned (but not necessarily unanticipated) event that results in a specified level of loss” (human, economic, etc). A hazard is “a state or sets of conditions that, together with worst-case external conditions, can lead to an accident.” Risk is “the level of hazard combined with the likelihood of the hazard leading to an accident, and the duration of exposure to the hazard” (Leveson 1995).
**Scalability**

- Scalability is defined as “the ability of a system to maintain its performance and function, and retain all its desired properties when its scale is increased greatly, without causing a corresponding increase in the system’s complexity” (ESD 2002).

**Complexity is Complex**

- **1. Behavioral complexity**—A system is deemed behaviorally complex if its external behavior is difficult to predict. Unfortunately, it does not take much to achieve this state of affairs. Chaotic and thus unpredictable behavior can be achieved with a relatively simple mechanical arm.

- **2. Interface complexity**—A system has a complex interface if it has numerous components, such as knobs and dials, in its interface to humans or to other technical systems. Systems with complex interfaces are usually difficult for humans to operate or successfully integrate with other systems. George Miller wrote a famous paper in psychology called The Magical Number 7±2 (1956). An interpretation of the paper is that humans are limited in their processing ability to dealing with no more than 7±2 different things at any one time.

- **3. Structural complexity**—A system is structurally complex if it has numerous components whose interconnection, interaction or interdependence is difficult to describe or understand. Our discussion below will emphasize structural complexity. It is hoped that systems whose structural complexity is reasonably limited will meet the traditional, and some non-traditional, properties and goals without too much difficulty.

---

**Sustainable Transportation**

- **Twin Cities Transit & Land Use**
  - Attached Case
  - Questions:
    - Consider Light Rail Transit in Minneapolis and the “Illities” ... Does the system exhibit properties that are desirable, undesirable? What are they?

**Supply Chains**

- **David Levinson**

**Network Analysis of Economy vs. Economic Analysis of Networks**

- The economic analysis is required to understand and speculate about the deployment of advanced technologies, such as road pricing, and how those technologies interact and depend on each other.

- The central idea of a network is connections between links which reinforce each other. These links can be physical (threads, wires, beams, highways, rails, pipes) or socio-economic (kinship, social, or exchange relationships).

- The market on the other hand is a place (real or virtual) where exchange takes place. An economic network may be comprised of multiple markets. A market may sell the right to use, or the ownership of, physical networks.
Network Model of the Economy

Comments

- While each of these elements is modeled as a link or node, it should be remembered that each can be expanded to form a subnetwork. This is part of the robustness of the framework, and extends the potential for scalability and the availability of the analysis.
- A production/consumption agent in an economic network has both suppliers and customers, and can be modeled as an "agent node" on a network. Because production and consumption are two sides of the same coin, they are referred to together, as a process consumes inputs to produce outputs. The "exchange nodes," are defined by the presence of "connection links," and are analogous to markets.
- The agent nodes are connected to exchange nodes by "connection links." The model includes several conditions that need to be satisfied to account for transportation or communication costs in the production system. The firm is a direction of grains that are input into the production process, transformed and output to a market or another node. The model also suggests that a direct preference for consuming substitution and quality improvements that lead to the good.
- In the model represented by Figure 1, an agent node is connected by production nodes in an input market (Stage 1) and may be supplied by one or all those alternative markets. The goods are handled by the "market," which is seen as a buffer transformed Stage 2, and sold to other nodes (Stage 3). The industries are defined as the market or to a company, while it is compatible with parallel and interconnected nodes.

Network Model of the Economy

Agent: stage s, market m, firm number n

Open or hatched circles indicate production/consumption agent nodes

Filled circles indicate market or exchange nodes

Lines indicate links connection markets and agents

There are three main elements:

- the site of production/consumption (material transformation),
- the site of exchange (ownership transformation),
- and the connection between the two (spatio-temporal transformation)

Payment

- In one sense, the link is selling the right to be traveled on and is paid by users or government for this right.
- If it is not paid, it deteriorates over time (depreciation comes from the link's own capital stock which is disinvested).
- The more generalized version of a graphed economy substitutes the transportation network as a special case. The use of the framework here is to incorporate, at least conceptually, financing in the standard highway network analysis, and thereby allows us to identify some pertinent issues.
- In particular if we identify links with firms, the issue of payment becomes clear. In order to operate, the link must be subsidised by government, be paid for directly by users, or allow in capital stock to deteriorate. This treatment from users capital to the marginal cost is clearly more efficient, is not until the social loss described in section 2 due to overuse and underuse, and does not impose deadweight losses inherent in certain economic structures. Imposing road pricing is a natural conclusion to these problems.

Linking Economy with Transportation

Clearly the situation is idealized. Some firms may have different degrees of vertical integration, that is they interact minimally what is represented here as an input market or the output market. However, this figure does reflect that a production process may have a combination of steps, so that a single firm produces for more than one output market, as in the case of stage 2, where the firm produces goods in both stages 1 and 2: for example, the firm produces goods which are transformed from inputs into output goods in stage 2. Stage 2 may be sold to stage 3 (for example, for sale to the final consumer), or it may be transformed into output goods in stage 2. Clearly this situation is idealized. Some firms may have different degrees of vertical integration, that is they interact minimally with each other. As part of a larger system, the link may be viewed as part of a larger transportation network, with input and output linkages to other nodes.

Figure 1 is a snapshot of the processes and relationships at a given point in time. Over a long period of time, links and nodes are added and deleted as the economy grows and contracts, markets change, and transportation systems in response to the economic system. This framework is intended to provide a tool to examine how networks and relationships in general develop. We might consider the social networking, the role of the link in a given process. The link (or "link") provides services to a number of nodes, and can be modeled as a link node acting on behalf of the link. An example of such a link node is a transportation authority, which acts on behalf of the link to operate its network, or to represent the link in negotiations with external bodies.

Nomenclature

- Agent: stage s, market m, firm number n
- Open or hatched circles indicate production/consumption agent nodes
- Filled circles indicate market or exchange nodes
- Lines indicate links connection markets and agents
- There are three main elements:
  - the site of production/consumption (material transformation),
  - the site of exchange (ownership transformation),
  - and the connection between the two (spatio-temporal transformation)

Snapshot

- Figure 1 is a snapshot of the processes and relationships at a given point in time. Over a long period of time, links and nodes are added and deleted as the economy grows and contracts, markets change, and transportation systems in response to the economic system. This framework is intended to provide a tool to examine how networks and relationships in general develop. We might consider the social networking, the role of the link in a given process. The link (or "link") provides services to a number of nodes, and can be modeled as a link node acting on behalf of the link. An example of such a link node is a transportation authority, which acts on behalf of the link to operate its network, or to represent the link in negotiations with external bodies.
Supply Chains

- A supply chain is a network of facilities and distribution options that performs the functions of procurement of materials, transformation of these materials into intermediate and finished products, and the distribution of these finished products to customers.
- Supply chains exist in both service and manufacturing organizations, although the complexity of the chain may vary greatly from industry to industry and firm to firm.
- Source: Ram Ganesan Terry P. Harrison

Supply Chain Decisions

- We classify the decisions for supply chain management into two broad categories – strategic and operational.
  - Location Decisions
  - Production Decisions
  - Inventory Decisions
  - Transportation Decisions

Freight Logistics

- Freight Logistics - the process of planning, implementing and controlling the efficient, effective flow and storage of raw materials, in-process inventory, finished goods, services and related information from point of origin to point of consumption for the purpose of conforming to customer requirements.
- This management is increasingly important as producers move from a inventory based system (push) to a just-in-time system (pull). This is enabled by (and demands) reliable transportation and information technology.
- The process is multimodal and inter-modal. Most products are loaded and unloaded multiple times at various stages within the logistics cycle.

Single-Product Chain

- To the right is an example of a very simple supply chain for a single product, where raw material is procured from vendors, transformed into finished goods in a single step, and then transported to distribution centers, and ultimately, customers.
- Realistic supply chains have multiple end products with shared components, facilities and capacities.
- The flow of materials is not always along an adversarial network, various modes of transportation may be considered, and the bill of materials for the end items may be both deep and large.

Modeling Approaches

- Network Design methods, for the most part, provide normative models for the more strategic decisions. Optimization of system.
- Inventory Control methods, on the other hand, give guiding policies for the operational decisions. These models typically assume a “single site” (i.e., ignore the network) and add supply chain characteristics to it, such as explicitly considering the site’s relation to the others in the network. These derive from Inventory Control optimization
- Simulation methods are used to evaluate the effectiveness of a pre-specified policy rather than develop new ones. It is the traditional question of “What If?” versus “What’s Best?”.

Statistics

<table>
<thead>
<tr>
<th></th>
<th>Value (%)</th>
<th>Volume (%)</th>
<th>$/lb</th>
<th>Avg Length (mi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipeline</td>
<td>3.9</td>
<td>5.0</td>
<td>$0.20</td>
<td>528</td>
</tr>
<tr>
<td>Maritime</td>
<td>10.4</td>
<td>17.9</td>
<td>$0.06</td>
<td>2300</td>
</tr>
<tr>
<td>Railroads</td>
<td>4.0</td>
<td>12.7</td>
<td>$0.08</td>
<td>794</td>
</tr>
<tr>
<td>Airplanes</td>
<td>2.4</td>
<td>0.02</td>
<td>$26.77</td>
<td>1325</td>
</tr>
<tr>
<td>Intermodal</td>
<td>10.4</td>
<td>1.7</td>
<td>$1.61</td>
<td></td>
</tr>
<tr>
<td>Pipelines</td>
<td>2.6</td>
<td>10.8</td>
<td>$0.35</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>3.9</td>
<td>5.0</td>
<td>$0.20</td>
<td></td>
</tr>
</tbody>
</table>
**Freight Stats**

- Freight tons per capita has been increasing slowly (about 0.1% per year), but freight ton-miles has been increasing at more than 1% per year. Things are being shipped farther.
- Railroads - move low value commodities long distances slowly (e.g. coals, chemicals, farm products), as well as large items that can’t be easily or efficiently moved by truck (e.g. cars and large machinery).

**Low Cost Envelope**

```
Cost

Distance
```

**Standard Control Loop**

```
Figure 1: Standard Control Loop
```

**Freight Stats**

- Class I - major railroads
  - Western (east west) Burlington Northern/Santa Fe, Union Pacific,
  - Eastern (east west) CSX, Norfolk Southern,
  - Central (north south) Chicago and Northwestern, Illinois Central, Kansas City Southern, Grand Trunk Western (Canadian National), and Soo Line (Canadian Pacific).
- Class II - regional and short line railroads
- Trucks - move higher value products short distances rapidly.
- Truckload - one shipment, one truck
- Less-than-Truckload (LTL) - multiple shippers use same truck.
- Some owned by manufacturers, some by private trucking firms, some by publicly held (stock market) trucking firms.
- Small trucks are often used as private vehicles, so truck statistics need to be considered with care. Almost 60,000,000 trucks in United States.