

Sustainability Network Theory and Industrial Systems

Junbeum Kim, Braden Allenby, and Ming Xu

May 15, 2007

A Center for Sustainable Engineering Education Module



Center for Sustainable Engineering

SUMMARY

The integrated human/natural/built systems that characterize the anthropogenic earth are highly complex, interconnected, and overlapping. One way to understand and visualize these complex systems is through conceptualizing them as networks. The theory of networks, and network analysis, have been applied widely, providing a unifying language to describe disparate systems ranging from social interactions to power-grids. Thus, the science of networks is a promising vehicle by which to study, and advance our understanding of, the complicated systems that are at the heart of sustainability and sustainable engineering.

A major challenge of sustainability is to visualize all the relevant information on various issues and demonstrate the connections between seemingly disparate factors. Network theory and analysis can support identification of causal loops, help with prioritization of conflicting factors, and facilitate intervention at the right levels.

This module is about a set of models and tools collectively based on, and illustrating, a new competency we call “sustainability network theory” or “SNT”. The first part of the module introduces network concepts and examples of their application. The second part develops SNT as a means to reflect and model complex aspects of industrial networks, including interconnections between environmental, economic and social aspects. As this is a cutting edge integration of theory and practice in sustainable engineering, students and practitioners should be encouraged to develop their own applications.

The target audiences of this module are advanced undergraduate engineering classes, and graduate classes in sustainable engineering and industrial ecology. This module is part of a series designed for the Center for Sustainable Engineering (CSE). Instructor’s guides and further information are available at the Center’s website (www.csengin.org).

Keywords: Industrial ecology, network theory, complexity, industrial ecology theory, sustainability

Sustainability Network Theory and Industrial Systems

Junbeum Kim, Braden Allenby, and Ming Xu

1. Introduction

The classic definition of “sustainable development” as provided by the Brundtland Commission is “development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” (WCED, 1987, at 43) While there are many elaborations on this theme, most recognize that “sustainability” comprises three domains: the environmental/ecological, the economic, and the socio-cultural. Thus, firms are encouraged to attend to their “triple bottom line,” or financial, environmental, and social performance (Allenby, 2005). While conceptually simple, the idea of sustainability is quite difficult to quantify for many reasons, ranging from data inadequacy to hidden value systems and problematic assumptions. In response, the scientific and engineering communities developed the field of industrial ecology, the first, and perhaps most mature, effort to understand the systemic relationships among industrial, economic, and social systems (Frosh and Gallopoulos, 1989; Allenby and Richards, 1994; Graedel and Allenby, 1998, 2003). Industrial ecology has since become institutionalized, with the establishment of an International Society for Industrial Ecology, a Gordon Research Conference on Industrial Ecology, and the Journal of Industrial Ecology. It has become the basis of government policies in countries such as China, where it is the foundation of the “circular economy” policy, and has developed a growing toolbox of methods such as Design for Environment and Life Cycle Assessment.

But both industrial ecology theory and methodologies are incomplete in that they have difficulty addressing complex integrated human/natural/built systems, which are highly non-linear, transdisciplinary, and unpredictable, and scale across systems from the local to the global. Modern industrial systems integrate everything from local relationships based on mutual trust to regional and global trading systems based on contract and international legal regimes, are characterized by complex networks and sophisticated systems of supply and utilization at all scales, and are not susceptible to centralized control (Wallner, 1999). It is therefore critical that industrial ecology take the next step and begin developing tools and methodologies that are appropriate for such complex adaptive systems. This is not a trivial problem, as there are numerous challenges facing such an effort. To begin with, without supportive tools humans are not able to grasp the interdependencies among the many variables and dynamic processes that characterize such large, multiscalar systems. Such systems have a number of challenging characteristics (Brown, 1995, 1999):

- They are composed of numerous components of many different kinds.
- Their components interact both linearly and nonlinearly and on different temporal and spatial scale.
- The systems organize themselves to produce complex structures and behaviors.
- The systems maintain thermodynamically unlikely states because of their open nature.
- Some form of heritable information allows the systems to respond adaptively to environmental changes.
- The structure and dynamics of these systems are effectively irreversible (potential future paths are dependent on the past paths of the system).
- They are hierarchically organized.

Moreover, industrial systems in particular are reflexive; that is, the learning that a human system does about itself is endogenous to the system, and thus changes the system even as it is observed. Accordingly, the industrial ecologist is an integral part of the industrial system that she or he is observing,

which means that methodologies intended to capture this complexity must be as flexible as the system itself is in its responses to internal and external changes.

While the tools such as LCA (Life Cycle Assessment) and MFA (Material Flow Analysis) that industrial ecology has developed are powerful when dealing with bounded systems, such as a particular material in a particular application, or the material flows of a particular substance in a region or country, they are not adequate to model or enable understanding of complex adaptive systems. Yet these are precisely the systems we are now presented with. Moreover, our interaction with and dependence upon such systems is increasing at a rapid rate, so that our continuing inability to understand their behavior creates the potential for major problems and even disasters. This complexity created the need to explore sustainability network theory (SNT).

Sustainability networks concern properties that arise in systems of many objects linked together and displaying both static and dynamic complexity. From a static perspective, networks are characterized by a number of key concepts such as connectivity (nodes, links, and flows), criticality, loops and cycles, dynamics, modularity, trees and hierarchies. But it is the dynamics of industrial systems that are particularly challenging, and it is here that the need for Sustainability Network Theory (SNT) (Kim, J. and Allenby B R., 2007) becomes apparent, because many of the behaviors of such systems arise not from the substantive factors that are the usual focus of analysis, but from their underlying network structure and dynamics. Thus, for example, tightly coupled networks are more resistant to change than loosely coupled networks, a characteristic of complex systems that explains why changes to pollution control equipment regulations are more easily accomplished than changes to product design or manufacturing process regulations. In the former case, the technology is only loosely coupled to underlying product and manufacturing networks, and thus can be changed with only minimal implications for other aspects of the product and manufacturing networks. In the latter case, however, the intervention is to tightly coupled networks (product design and manufacturing processes are complex, tightly coupled, interdependent networks), which means that changes and shifts in state propagate throughout the system.

The ability to harness the power of the sustainability network formalism is an important advance over existing methodologies for many reasons:

- many present-day problems are concerned with flows of energy, materials, information, or capital, and interacting flows are an ideal application domain for SNT;
- network models lend themselves to graphical or visual depiction of complex systems, an important consideration in informing decision-makers to enable them to act more rationally;
- one may identify similarities and differences in distinct problems through their underlying network structures; and
- network models make it easier to identify behaviors arising not from decision or policy, but from system structure and dynamics.

Every network is a model, and accordingly represents a specific query or point of view regarding a complex system. Thus, the purpose for which SNT is applied will in each specific case determine a different network structure. To illustrate this, consider a hypothetical product life cycle case where the focus of the network analysis is from the perspective of the manufacturer. In such a life cycle view (illustrated in figure 1), the further upstream or downstream the activities are located, the weaker the influence of the manufacturer and the less detailed the network model will usually be. So, for example, the product manufacture has significant influence on immediate suppliers as a customer, but less on secondary suppliers. Similarly, the product manufacturer exerts direct influence in the distribution stage whether performed in house or outsourced, but in most cases much less on end-of-life management of the

product. This would change, of course, if regulations made the manufacturer responsible for the product at its end of life, as with European product takeback requirements for electronic consumer goods. In such a case, the change in regulation would change the structure of the network within which the firm was making its decisions by changing the weighting of different life cycle stages from the perspective of the manufacturer.

A standard industrial ecology stock and flow model would include the material, and perhaps the energy flows, associated with this case. It is possible that a modified life cycle assessment analysis (LCA) could capture some of the environmental effects directly related to the product, although product LCAs are difficult to do systematically. An SNT model, however, would differ by including network components representing social, economic, and environmental dimensions. Moreover, the SNT network would identify the major linkages among these three dimensions, identifying, for example, material flows that might be problematic for environmental or business reasons (e.g., use of toxics, or major supply from an unstable state).

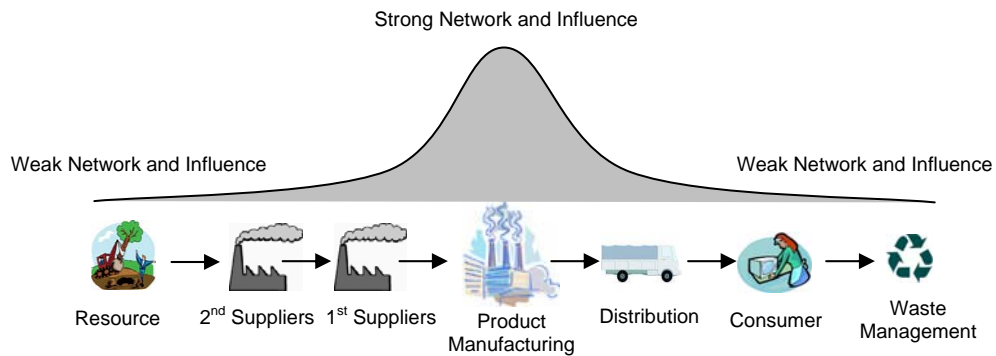


Figure 1. A Product Life Cycle and Intensity of Networks from the Perspective of the Manufacturer

How networking and interaction among networks previously studied independently (such as social, environmental and economic networks) will affect the system in its entirety is not at this point well defined and will undoubtedly be the subject of future research

2. What is Network Theory?

Network theory has developed considerably since beginning in the 1950's. It has been used widely in electrical engineering, computer science, engineering economics, social science, business applications (for example, modeling increasingly complex inventory and logistics systems) and biology, where it has increasingly proven to be a powerful tool in systems ecology and in enabling understanding of complex metabolic pathways and processes (Chen, 1990; Song, 2005; Heyman, 2006). Especially as fields struggle with increasing complexity – which is precisely the case with industrial ecology at this point - the network representation is a valuable visual and conceptual aid to the understanding of the relationships between events and objects that are otherwise unintelligible because of their complexity. Thus, for applications involving industrial systems, networks and network analysis are playing an increasingly important role in the description and improvement of operational systems primarily because of the elegance with which such systems can be modeled as networks.

Network theory and modeling is not, however, confined to only one branch of academia or industry. Indeed, the real strength of the network approach lies in the fact that it can be successfully applied to almost any problem when the modeler has enough knowledge and insight to construct the proper network representation. Benefits and advantages include:

- 1) The ability to model complex systems by compounding simple systems.
- 2) The mechanistic procedure for obtaining system figure-of-merits from networks.
- 3) The need for an intuitive and comprehensible communication mechanism to discuss the operational system in terms of its significant features.
- 4) Network models accurately represent many real-world systems for purposes of useful types of analysis.
- 5) Network models are more readily accepted by nonanalysts than other methods of data illustration, perhaps because they include both relationships and weighting factors. In particular, managers seem to accept a network diagram more easily than they do abstract symbols.
- 6) Network theory facilitates extremely efficient solutions to some large-scale models.

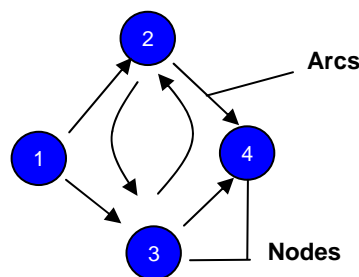


Figure 1. An Example of Network Flow Model

As illustrated in figure 1, a network consists of a set of nodes and a set of arcs connecting the nodes. The nodes are also referred to as vertices or points. The arcs are also called edges, links, lines, or branches. A network can be represented by the notation $G = (N, A)$, where N is the set of nodes and A is the set of arcs of the network G (Don, 1981).

The nodes of an industrial network can represent resource extracting facilities, suppliers at different tiers, product manufacturing companies, consumers, and waste treatment facilities and operations (recycling and landfill). In general, a node can represent a point where some kind of flow is originated, relayed, modified, or terminated. For this reason, a node can be viewed as a branching point in a SNT model.

The arcs of an industrial network can represent physical (e.g., roads, water mains, power lines, inventory supply routes) or non-physical (e.g., informational, legal or financial couplings) relationships. In some instance, the arcs have no physical meaning but serve to direct flow in a logical sequence, or to maintain a specified precedence relationship. The flow is associated with the network, entering and leaving at the nodes and passing through the arcs. Flows entering or leaving a node from external sources are called *external flows* and are shown adjacent to the nodes in the square brackets. A positive external flow is a supply, flow that enters the network, and a negative external flow is a demand, flow that leaves the network. The flow is conserved at each node, implying that the total flow entering a node, either from arcs or external supplies must equal the total flow leaving the node, either to arcs or to external demands. The arc flows are the decision variables for the network flow programming model. Table 1 shows examples of nodes, arcs and flows in a classical network.

Table 1. Examples of Classical Networks

Network System	Nodes	Arcs	Flows
Transportation Urban	Intersections Homes Places of Work	Roads Virtual communication Links	Autos Information
Air Rail	Airports Railyards	Airline Routes Railroad Track	Planes Trains
Manufacturing and Logistics	Distribution Points, Processing Points	Routes Assembly Lines	Parts, Products
Communication	Computers Satellites Phone Exchanges	Cables Radio Microwaves Virtual Networks	Messages Voice Data
Energy	Plumping Stations Plants	Pipelines Grides	Water Gas, Oil, Electricity

Source: Supernetworks, Anna Nagurney, 2002.

2.1 Networks in the real world

1) Social Networks

Social Networks are made by mapping and measuring relationships and flows between people, groups, organizations, animals, computers or other information/knowledge processing entities. Social network analysis has gained prominence in business and intelligence circles under the belief that it can yield extraordinary insights, such as the fact that people in disparate organizations have common acquaintances.

Social network analysis is based on an assumption of the importance of relationships among interacting units. The social network perspective encompasses theories, models, and applications that are expressed in terms of relational concepts or processes. Along with growing interest and increased use of network analysis has come a consensus about the central principles underlying the network perspective

(Hanneman, Robert A. and Mark Riddle, 2005). In addition to the use of relational concepts, the followings are important:

- Actors and their actions are viewed as interdependent rather than independent, autonomous units
- Relational ties (linkages) between actors are channels for transfer or "flow" of resources (either material or nonmaterial)
- Network models focusing on individuals view the network structural environment as providing opportunities for or constraints on individual action
- Network models conceptualize structure (social, economic, political, and so forth) as lasting patterns of relations among actors

The unit of analysis in network analysis is not the individual, but an entity consisting of a collection of individuals and the linkages among them. Network methods focus on dyads (two actors and their ties), triads (three actors and their ties), or larger systems (subgroups of individuals, or entire networks). (Wasserman, S. and Faust K., 1994)

Figure 2 shows an example of Social Network Visualization. This example is about a contagion passed by human contact, such as SARS or TB, spreads through human networks based on how infectious and susceptible each party is. Multiple contacts with infectious others play a role in the probability of infection.

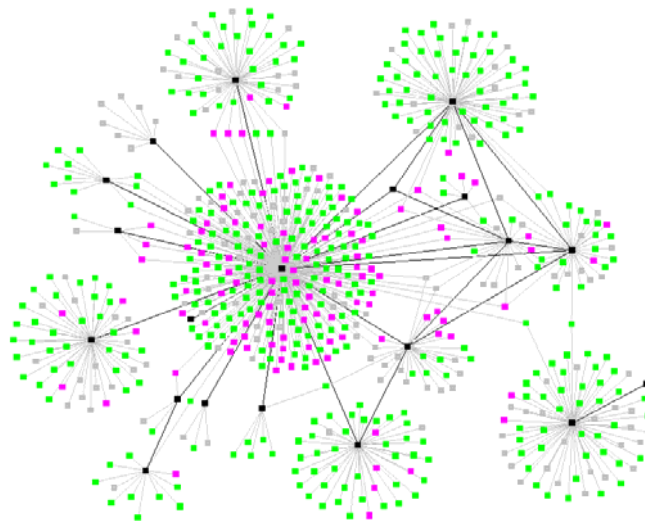


Figure 2. Example of a Social Network Visualization
(Mapping the Spread of Contagions via Contact Tracing)
Source: www.orgnet.com

2) Transportation Networks

Transportation systems are composed of a complex set of relationships between the demand, the locations they service and the networks that support movements. They are mainly dependent on the commercial environment from which are derived operational attributes such as transportation costs,

capacity, efficiency, reliability and speed. Such conditions are closely related to the development of transportation networks, both in capacity and in spatial extent. As Anna Nagurney (2002) comments:

Transportation networks are complex network systems in which the decisions of the individual travelers affect the efficiency and productivity of the entire network system. Transportation networks come in many forms: notably, urban networks, freight networks, and airline networks. The “supply” in such a network system is represented by the network topology and the underlying cost characteristics, whereas the “demand” is represented by the users of the network system, that is, the travelers.

One of the big problems facing transportation engineers or planners is that of predicting the impact of given transportation situation. This situation is specified mathematically as a set of inputs that are used to predict the flow pattern resulting in from such a scenario. The first stage of the network analysis uses these inputs to calculate the flow through each component of the urban network. Flow is measured in terms of the number of travel units (vehicles, passengers, pedestrians) that traverse a given transportation facility in a unit time. This part of the analysis builds on functional relationships between flows and congestion as well as relationships between congestion and travel decisions (Sheffi, Y., 1984). Figure 3 shows the US national highway system by an example of transportation network system.

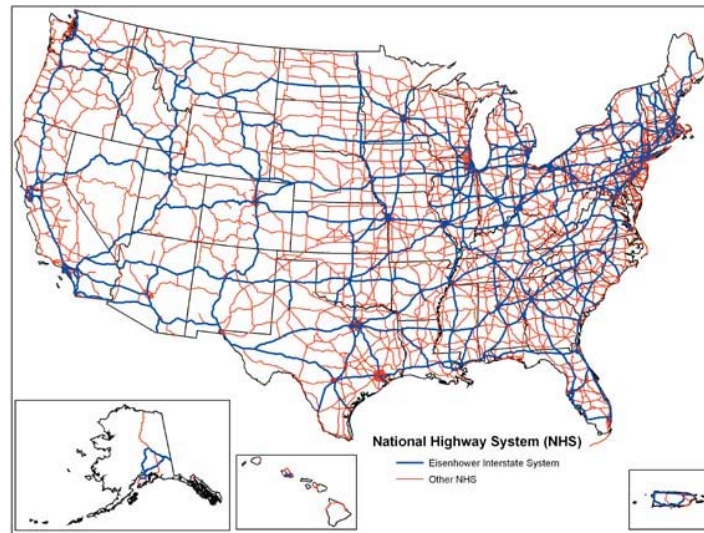


Figure 3. Example of a Transportation Network System (US National Highway System)
Source: www.fhwa.dot.gov

3) Industrial Symbiosis networks

Industrial Symbiosis networks aim to create resource efficiency by identifying and implementing synergies and linkages between different industrial facilities. Henning (1997) describes the industrial symbiosis network as follow:

It is a process whereby a waste product in one industry is turned into a resource for use in one or more other industries. It is the essence of a well-functioning ecosystem. It is the essence of a well-functioning ecosystem. The Kalundborg experience shows that

cooperation among different industries in the use of waste increases the viability of the industries. At the same time, the demands from society for resource conservation and environmental protection are met.

Figure 4 shows the Kalundborg symbiosis networks. Four industrial facilities (a power plant, an oil refinery, a plaster-board manufacturing plant, and a biotechnology production facility) and the local municipality participate in the network.

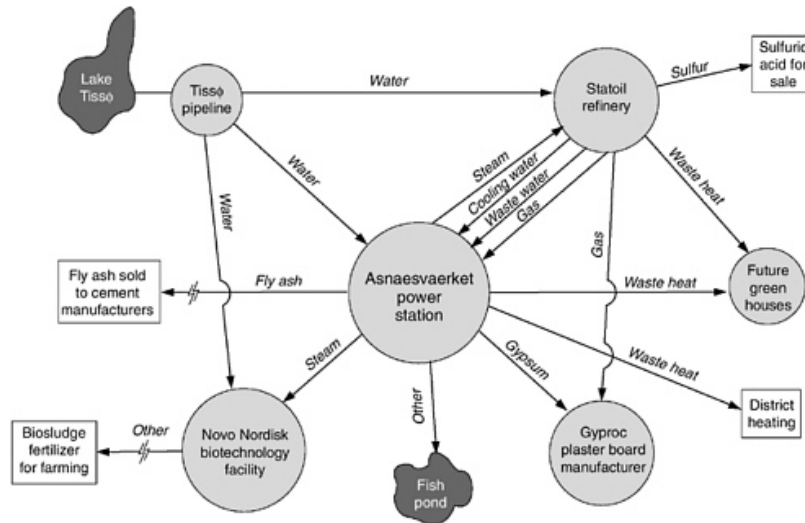


Figure 4. The Kalundborg symbiosis network (Adapted from Henning, 1997)

3. Sustainability Network Theory and Model

Sustainability Network Theory (SNT) is a rigorous theory applying network modeling and theory to industrial systems, with industrial systems understood in a holistic sense to include social and industrial dimensions, manufacturing and service components, and consumption and end-of-life activities. Because SNT accepts the complex nature of industrial systems, determining the appropriate boundary for an analysis will depend on the reason for the analysis. Accordingly, existing boundaries, such as those of a firm, sector, or political entity, are important in establishing the network structure, but do not predetermine what the boundary of the network itself should be. Thus, SNT from the beginning responds to the frequent complaint that industrial /environmental analyses do not take into account the situation 'beyond the gate' of the production plant, and an SNT analysis can be structured to reach whatever level of a complex industrial system is appropriate given the analysis desired. Figure 5 shows a conceptual SNT framework made up of a social, cultural and regulatory network (SCRN); an economic and financial network (EFN); and a material, energy and environmental network (MEEN).

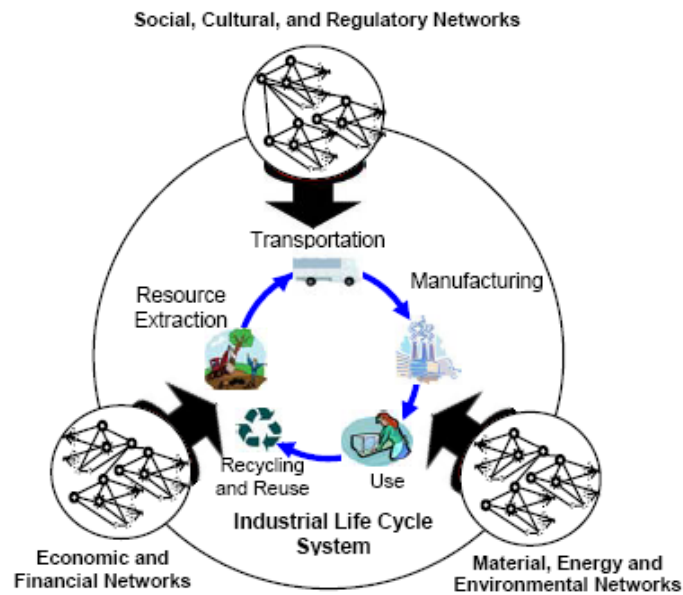


Figure 5. Conceptual Model of an SNT

3.1 Social, Cultural and Regulatory Network Model (SCRN)

In general terms, a social, cultural and regulatory network is broadly defined as an arrangement of differentiated elements (individuals, firms or organizations) linked to each other by a multitude of ties of a specified type. This model includes communities, social structures made of nodes and ties at the individual and organizational level; additionally, it focuses on the interrelationships with broader (political, cultural, and moral) social systems. Nodes are the organizational actors, which may themselves be networks, and ties are the relationships between the actors. There can be many kinds of ties between the nodes. In its most simple form, this network is a map of all of the relevant ties between the nodes being studied. New approaches to the study of industries are needed to understand better how different markets (e.g. capital markets, product markets, etc.) and market processes (e.g. competition, cooperation, speculation, and risk) are related to the changing strategies, structures and governance of business firms. Moreover, both markets and firms are themselves embedded within various institutional contexts at the sectoral, regional, national and international levels. Institutional diversity impacts the capacities of firms and patterns of cooperation and competition in markets; while markets and business interests themselves are important factors in the politics of institutional change. The models may include financial systems, corporate governance, inter-firm networks, strategy, regional and national business systems, regional integration, business interest associations, and processes of institutional change. Further studies and comparative analysis will provide more insights on social logistics of institutional and technological change.

3.2 Economic and Financial Network Model (EFN)

The goal of the economic and financial network model is to develop theoretical tools for the analysis of specific processes and their interaction into an appropriate representation of an economic and financial network. The role of the economic and financial network model is important for a variety of reasons:

- the emergence of industries that are clearly network-based, such as transportation and logistics, telecommunication, energy, and power companies, which increasingly provide the foundations for advanced economies, and inevitably introduce network dynamics and structure into industrial systems;
- the recognition of the interdependence among many networked systems (for example the relationship between telecommunications and finance, telecommunications and transport in the form of electronic commerce; and telecommunications with a variety of energy transmissions mechanisms);
- the recognition that new relationships between economic agents in terms of competition and cooperation are giving rise to new supply chains as well as new financial networks;
- the realization of the importance of networks in terms of infrastructure and the pricing of their usage as well as the management of risk and uncertainty surrounding networks; and - interest in the dynamics surrounding networks and their evolution over space and time.

The economy is a giant network of organizations linked by buying and selling relationships. Every company has suppliers who provide inputs and customers who receive outputs. Every company is dependent on both their suppliers and their customers for resources and money. Figure 6 presents an example of economic and financial flow network in the automotive industry. This shows not only the flow of materials through this system, but also incorporates some of the economic and financial flows which accompany this material flow. The economic and financial network model of linkages represented in Figure 6 amply demonstrates the complexity of the infrastructure for a myriad of interconnections and interrelationships between the actors. The financial network structure may not only cover the flows of transaction but also the flows of short term and long term debt and equity capital.

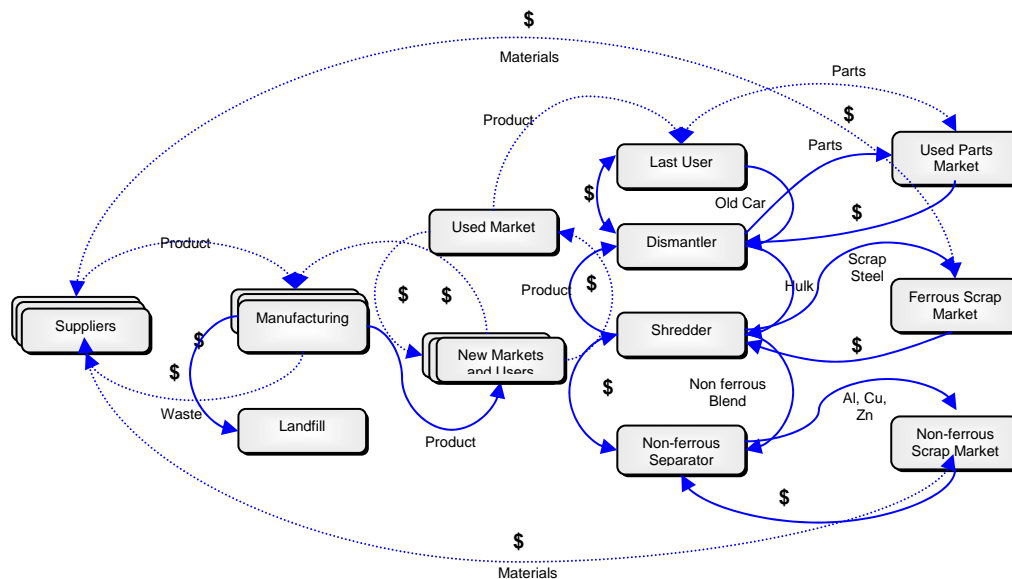


Figure 6. An Example of Economic and Financial Flow Network in Automotive Industry

3) Material, Energy, and Environmental Network model (MEEN)

In an industrial system, materials and energy movement extends from the extraction of resources for manufacturing, to consumption, to the discharge of wastes into the natural environment. The representation and interpretation of material and energy flows in an industrial system has become one of the most important tasks of industrial ecology and an important part of environmental management in

organizations (Schaltegger, S. and Burritt, R., 2000). The concept of material, energy, and environmental flow networks is a flexible and powerful approach to conceiving models of systems which are to be assessed. Materials and energy flow network models describe systems which take inputs from nature and return outputs to nature. The model consists of a system with a defined system boundary; processes describing the transport, transformation and change of value of materials and goods; and flows describing the transport of products, materials or energy between the processes. The system, as well as each individual process, has thus defined inputs and defined outputs. The flows, inputs and outputs can be measured in either goods (materials or material mixtures with economic value) or materials and substances (chemical elements and their compounds) (Pesonen, 1999). Material and energy flow networks can be used in industry to control and forecast material and energy flows in organizations as well as to describe the dynamic and behavior of the system in a simulation model. The concept of combining material and energy models, which are in use in industrial ecology today, with associated environmental networks, creates a new and powerful approach to creating models of many difficult relevant systems. Existing tools enable us to establish both material and energy flows, and environmental impacts, across the life cycle of products; integrating both types of analysis into a single network model approach not only reflects the close relationship among these factors, but facilitates integrating them with the SCRN and EFN networks discussed above.

In material and energy flow networks, both substances, (e.g. steel, aluminum, polyvinyl, or water) and energy (e.g. electricity from a power plant) are dealt with in the same manner. The distinction is only reflected in the different measures (basic units) for both categories: mass-bound substances are given in 'kg' (kilogram), while energy is measured in 'kJ' (kilojoule).

There are basically two components of material and energy flow networks to be distinguished transformation processes and storage of materials or energy. "Process", "transformation", and "storage", are used in the broadest sense. For instance, the transport of goods can be considered a transformation process, since the material has been transported to a different site and for this process energy has been transformed and consumed. The network is constructed by linking the transformation processes and storage entities. In addition to these links within the model, there are also interfaces to the system's environment (i.e. the "outside world"). Through these interfaces materials and energy enter and leave the model. Material and energy flow networks serve to draw up input/output balances or life cycle inventories. This is achieved by listing the materials and the respective quantities that traverse the system boundaries as items in a balance sheet. Environmental considerations are included in this network as they are integral parts of material and energy flows, and should be treated as such. Tools such as the Carnegie Mellon economic input-output model (www.eiolca.net) facilitate this approach. In practice, there may be cases where these phenomenons differ at the subsystem and component level.

References

- Allenby, B.R. (2005), *Reconstructing Earth* (Washington, DC: Island Press).
- Brown, James, (1995), *Macroecology*. Chicago: University of Chicago Press, An ecologist seeks an appropriate framework to reflect the multidimensional intricacy of natural habitats.
- Brown, James (1999), *Macroecology: Progress and Prospect*, *OIKOS*. 87/1, An update on the discovery of similar, repeatable networks and scales throughout flora and fauna.
- Chen, Wai-Kai (1990), *Theory of Nets: Flows in Networks*, John Wiley & Sons.
- Don T. Phillips and Alberto G.D., (1981), "Fundamentals of Network Analysis", Prentice-Hall, Inc.
- Frosch, R and Nicholas G., (1989). "Strategies for Manufacturing". *Scientific American*. September, 1989, pp. 144-152.
- Graedel, T.E. and Allenby, B.R. (2003), *Industrial Ecology*, Prentice Hall, Upper Saddle River, NJ,.
- Graedel, T.E. and Allenby, B.R. (1998), *Industrial Ecology and the Automobile*, Prentice Hall, Upper Saddle River, NJ.
- Hanneman, Robert A. and Mark Riddle, (2005). Introduction to social network methods. Riverside, CA: University of California, Riverside.
- Henning, G., (1997), 'The Industrial Symbiosis at Kalundborg, Denmark', in Deanna J. Richards (ed.), *The Industrial Green Game: Implications for Environmental Design and Management*, Washington, DC: National Academy Press
- Heyman K.(2006), "Making connections," *Science* 313:604-606.
- Kim, J. and Allenby, B R., Development of Sustainability Network Theory (SNT) and Model for Managing Electronics Industrial System, *Proceeding, IEEE International Symposium on Electronics and the Environment*" Orlando, FL., pp 336-339.
- Nagurney A. and Dong J., (2002), *Supernetworks: Decision-Making for the Information Age*, Edward Elgar Publishing Ltd
- Pesonen, H.-L. (1999), "Material Flow Models as a Tool for Ecological-Economic Decision Making." *Eco-Management and Auditing* 6: 34-41.
- Schaltegger, S., Burritt R.(2000), *Contemporary Environmental Accounting*, Sheffield, UK, 2000.
- Sheffi, Y., 1984, *Urban Transportation Networks Analysis*, PRENTICE-HALL, INC., *Englewood Cliffs, New Jersey 07632*
- Song C., Havlin S. and Makse H. (2005), "Self-similarity of complex networks," *Nature* 433:392-395.

Wallner, Heinz Peter, (1999), Towards sustainable development of industry: networking, complexity and eco-clusters, *Journal of Cleaner Production*, 7, pp 49-58.

Wasserman, S. and K. Faust, 1994, *Social Network Analysis*. Cambridge: Cambridge University Press.

WCED (World Commission on Environment and Development) (1987), *Our common future*. Oxford: Oxford University Press, 1987.

www.orgnet.com (accessed Feb 2007)

www.fhwa.dot.gov (accessed Feb 2007)

www.eiolca.net (accessed Feb 2007)