Assessment of Robustness, Redundancy and Efficiency of Process Networks for Reliable Process Operation and Mode Switching

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Any chemical process such as a petrochemical plant or its supervision and control system is a network. In case of major equipment malfunctions or process disturbances, modification of these networks may become necessary to continue the operation of the process. Process equipment, sensor, and actuator malfunctions can often be solved by switching to a redundant unit. But if redundant units do not exist or are out-of-commission, "network" modifications may be necessary. Similarly, malfunctions in data logging or control system computers may necessitate the reconfiguration of the computer network. There may be a number of alternatives for process modification, yielding different networks. A critical question is to select the configuration with the best characteristics. These characteristics would include stability, robustness, redundancy, low cost of switching and operation, and ability to operate the process profitably. In some cases there may be only one obvious alterative known to plant personnel. But in other cases, a new "network" needs to be established.

Graph theoretic methods have been proposed to study networks. Various metrics to evaluate network characteristics such as efficiency, robustness, redundancy, and cost have been defined. A comparative study of various networks network topologies such as star, circle, linear, triangular hub, pentagonal hub and perfect hub using genetic algorithm simulations (Venkatasubramanian et al., Spontaneous Emergence of Complex Optimal Networks Through Evolutionary Adaptation, Comp. Chem. Eng, 2004).

We have developed analytical expressions for these idealized network topologies. This enables rapid assessment of the metrics for a network with a specified number of nodes.

Many complex network systems are based on fundamental network topologies such as circle, linear, and star networks. The hub network is a complex network that combines circle and star networks; thus, it will have the properties of both circle and star networks. Properties of large fundamental networks can be predicted from the properties of small fundamental network systems by deriving mathematical sequences. Specific equations can be developed for normalized efficiency and average path length of networks with different number of nodes by using the mathematical series sequences. The efficiency is defined using the inverse of the average path length; thus, it indicates delays in data or material transfer rate because the delay time depends on the path length. Efficiency will indicate the degree of difficulty in controlling the system. The linear network has the highest average path length among different fundamental network structures; thus, its normalized efficiency is the lowest in the fundamental network. Specific equations can be developed for average-case and worst-case robustness, redundancy, average degree of vertex, power law, and average path length. Robustness is important for designing a network system that enables continued process operation in spite of some malfunctions in the system. The circle network has the highest robustness for both average case and worst cases while the star network has the highest normalized efficiency when the system is bigger than 5 connected nodes. Thus a hub

network will have a higher normalized efficiency than the circle network and higher robustness than the star network. But the number of hub arms affects the normalized efficiency and the robustness. When the number of hub arms increases, the average-case and worst-case robustness decreases and the normalized efficiency increases because increasing the number of arms increases the star properties in the hub network. The optimal hub network can be determined by using normalized efficiency and robustness.

The presentation will focus on the analytical expressions for idealized network topologies for a range of network node sizes, and the illustration of these metrics for an array of CSTR reactors with autocatalytic reactions with changing operation modes. The extension of these metrics to networks with other patterns of symmetry will also be discussed.