Embracing Complexity in System of Systems Analysis and Architecting

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Outline

- Systems of Systems Analysis and Architecting
  - Sos as a Complex System
  - Modeling Approach
  - Meta-Architecture Generation
  - Simulation Methodology
- Concluding Remarks

SoS as Complex Systems

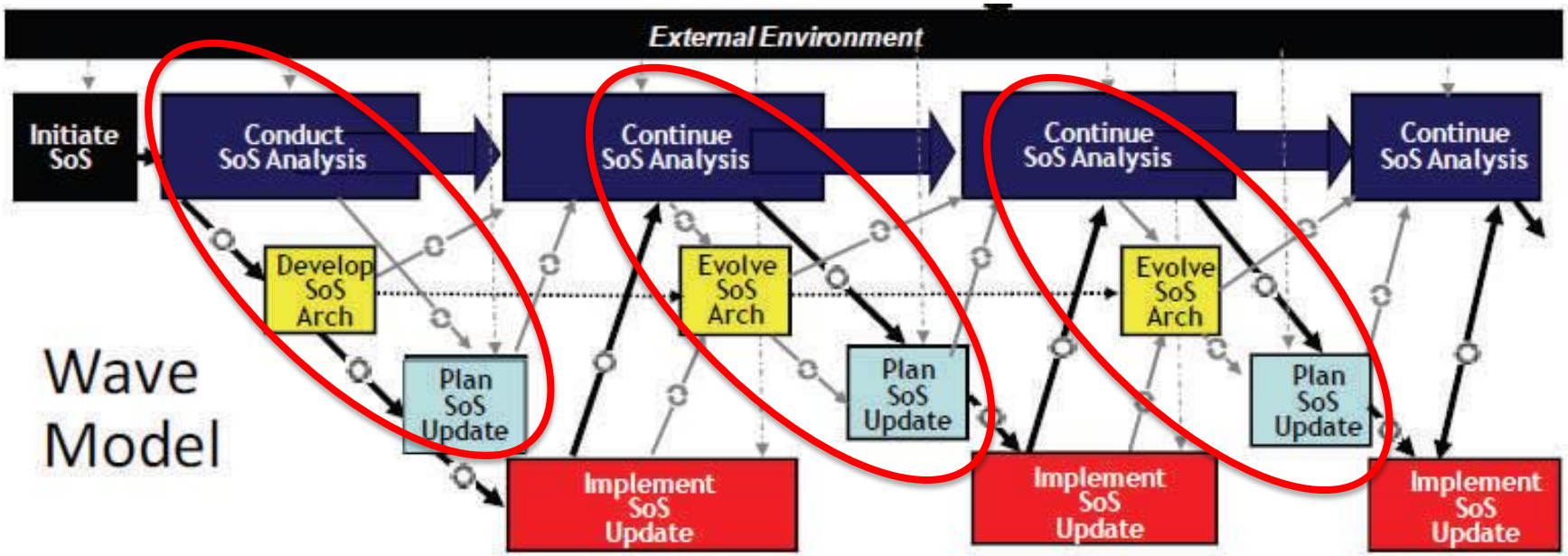
- Motivation for SoS as Complex System
  - Current lack of understanding of system participation choice on the overall SoS capability.
  - Simulation and Modeling techniques for Acknowledged SoS are still in their infancy.
  - Need for Domain Independent SoS Architecture assessment method.
- Objectives for SoS as Complex System
  - To develop a proof of concept ABM tools suite for SoS systems simulation for architecture selection and evolution.
  - To have a structured, repeatable approach for planning and modeling.
  - To study and evaluate the impact of individual system behavior on SoS capability and architecture evolution process.

Acknowledged SoS: Complex System

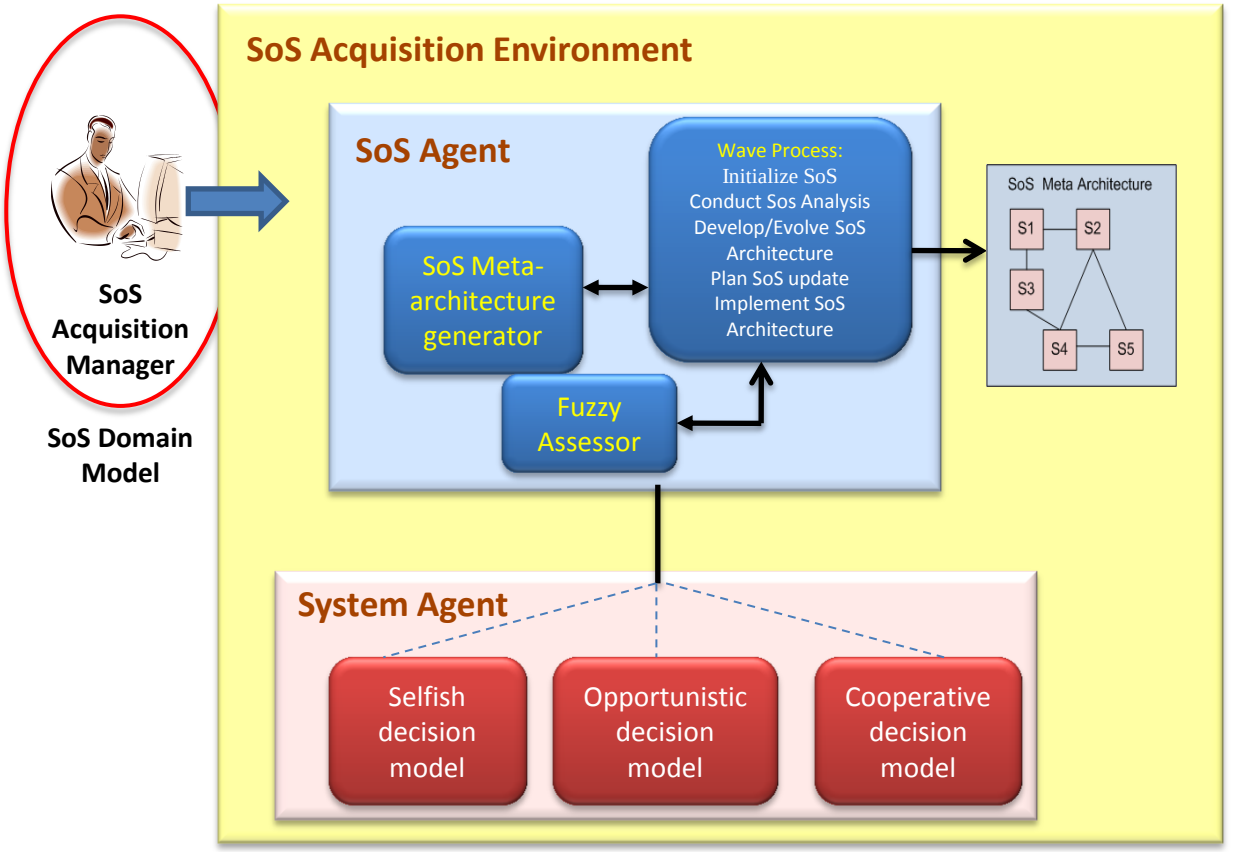
- Recognized objectives, a designated manager
  - Allocated resources for the SoS development
- Constituent systems
  - Independent ownership, objectives
  - May be different in any stage of their life cycle
  - Their own development and sustainment approaches
- Participation in the SoS may be desired, but infeasible
  - Changes in the systems are based on collaboration between the SoS and the system.
  - There are no guarantees that individual systems will be able to deliver any part of the capability they are asked to provide to the SoS.

SoS Acquisition Wave Model

- The evolution of the SoS proceeds in Waves of Analysis and Update



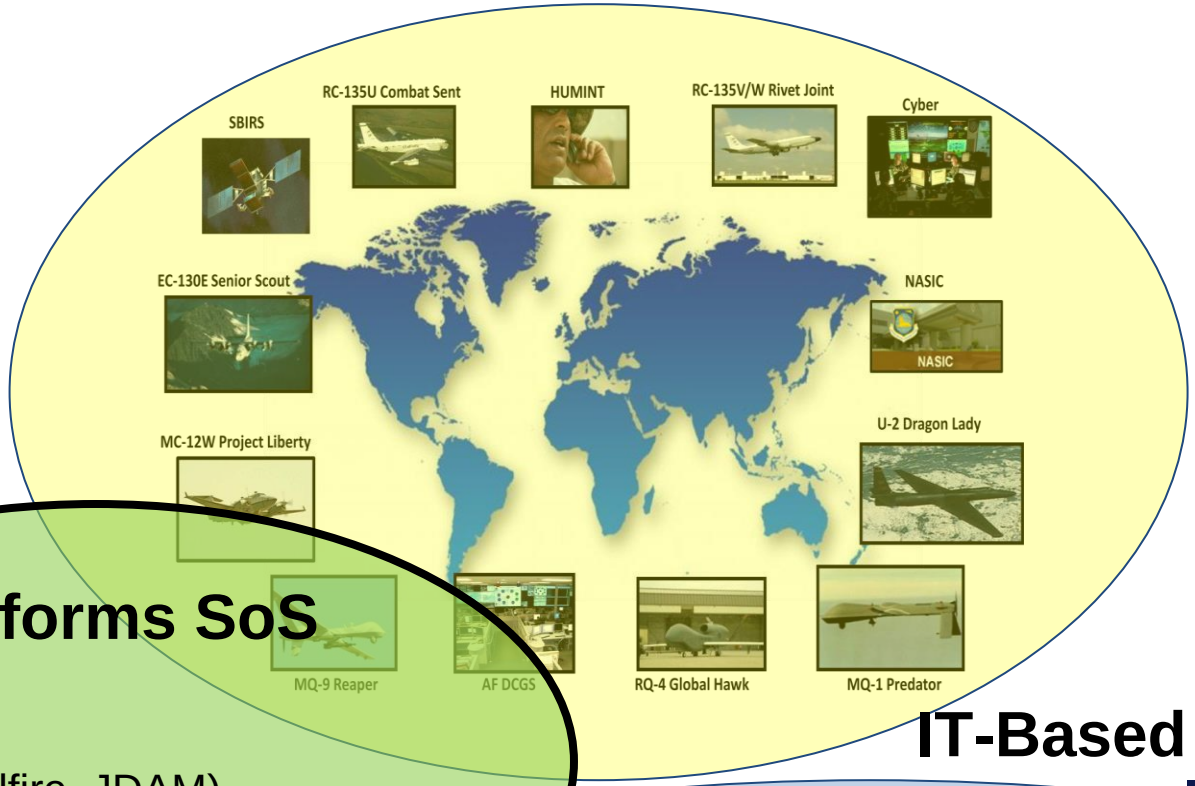
The Start of an Acknowledged SoS



Global ISR Mission SoS

- In the Gulf War, Iraqi forces used mobile missile launchers called Transporter Erector Launchers (TELS) to strike at Israel and Coalition forces with ballistic missiles.
- Existing intelligence, surveillance, and reconnaissance (ISR) assets were inadequate to find the TELs during their vulnerable setup and knock down time.
- This offers a prime example of existing systems being inadequate to address a mission, but some relatively low cost, quick changes, and joining together of existing systems might be used to create an SoS capability to achieve the mission.

Global ISR Mission SoS



RPA Platforms SoS

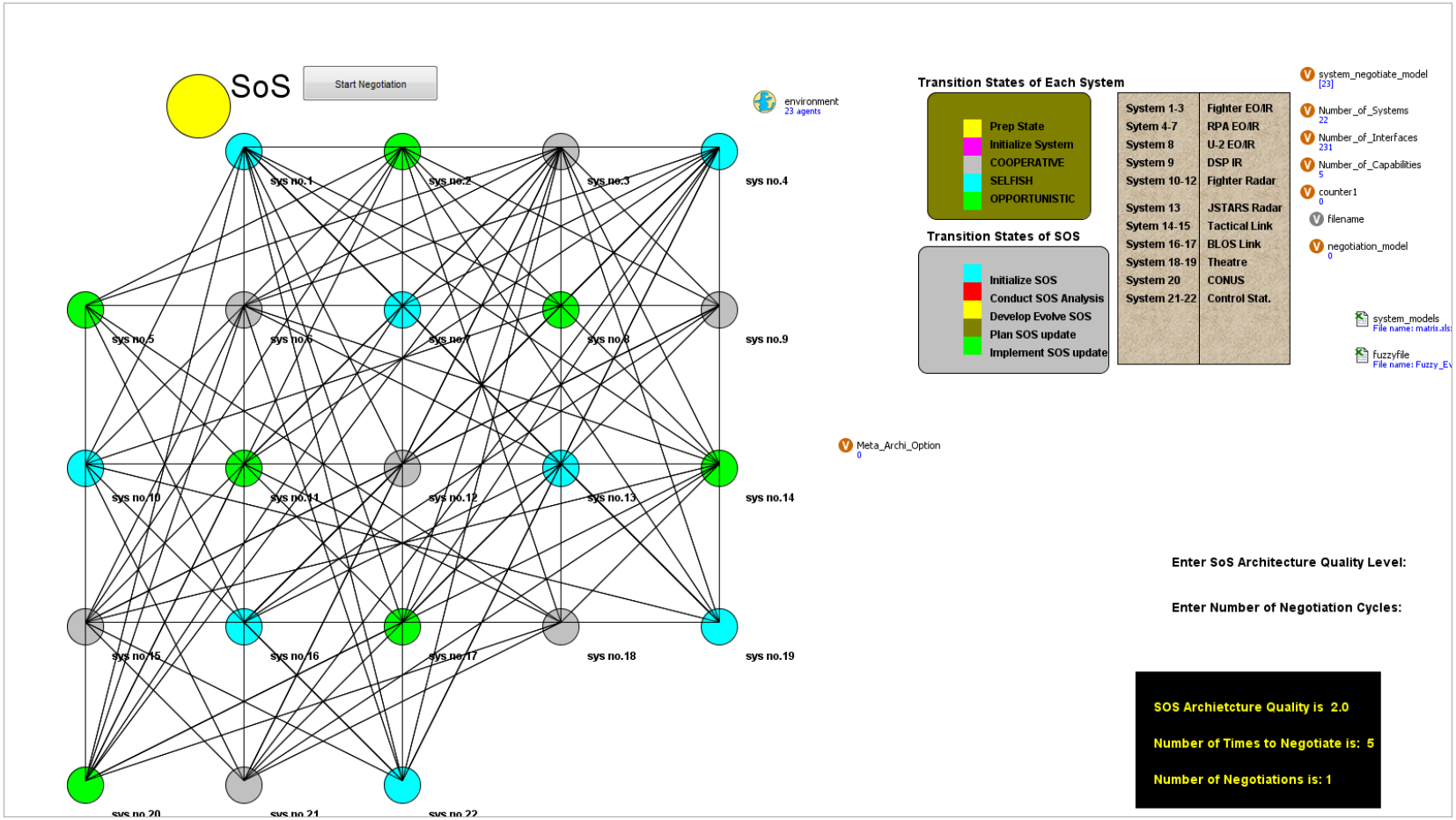
MQ-1, MQ-9

Weapons (Hellfire, JDAM)
Payloads (Sensor, Targeting)
Ground Control Station

IT-Based SoS

SATCOM
Tactical Datalink (Link16)

Network Representation of SoS



Modeling SoS as Complex Systems

- The framework is applicable to Acknowledged SoS.
- Each contributing system is a fully functioning, independently funded and managed system with predefined capabilities.
- Wave Model for SoS SE is used to abstract behavioral aspects of the acquisition process
- The SoS achieves its goals by combining existing system capabilities and adding minor new capabilities and interfaces.
- One cycle through the proposal – agreement – negotiation steps is an *epoch* in the wave model.

Modeling SoS as Complex Systems

The overall mathematical framework of the ABM is described based on 3 main elements of the model:

1. **SoS acquisition environment**: The SoS agent is influenced by the changes in the SoS acquisition environment. Thus the initial environment model E_0 can be represented as a function of these variables:

$$E_0 = f(National\ priorities, SoS\ funding, threats)$$

2. **SoS agent behavior**: SoS agent is responsible for the overall SoS engineering activity and coordinates with individual system agents to achieve the desired SoS mission capability.

3. **Individual system agent behavior**: Individual systems receive request for connectivity to SoS architecture. The system has the option to cooperate or negotiate with the SoS agent to request more funding, deadline or performance change.

Modeling SoS as Complex Systems

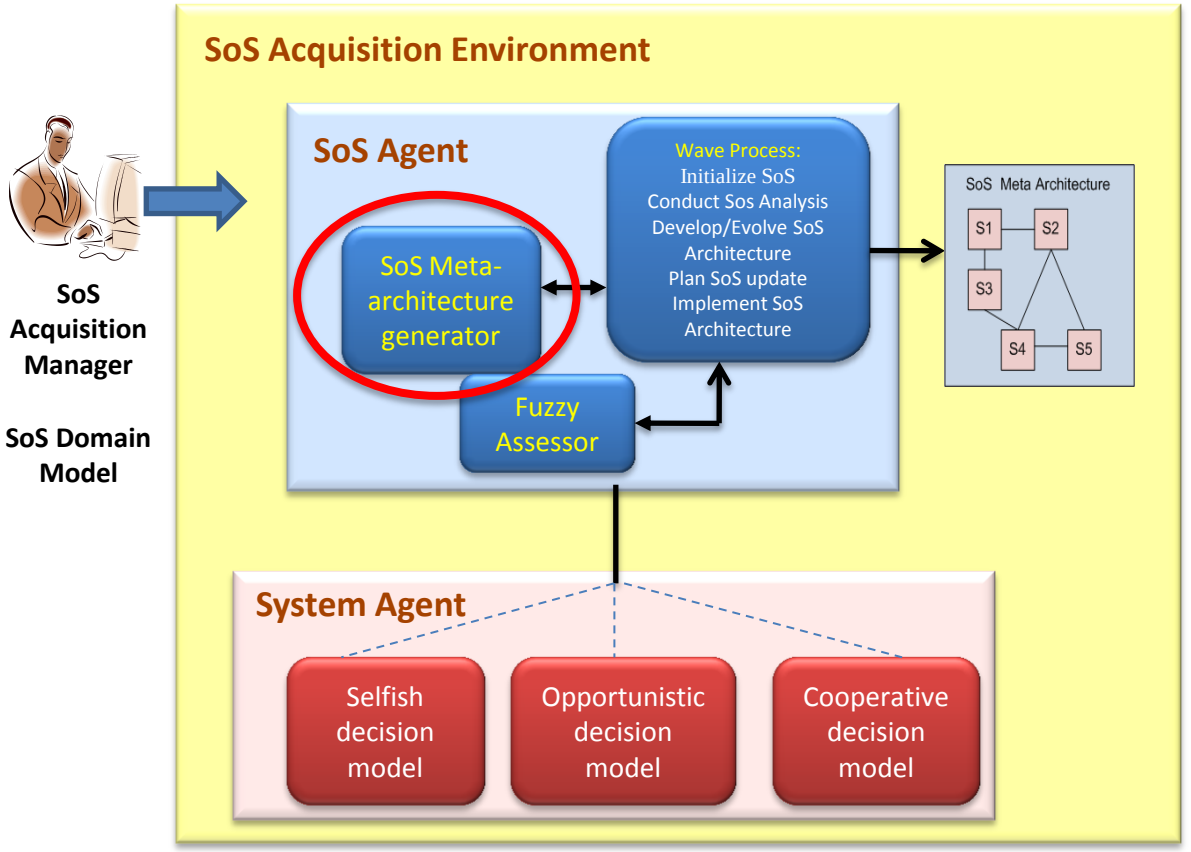
SoS Agent

- Starts with an initial SoS architecture.
- Follows the Wave Model for SoS SE.
- Makes request to each system for capabilities defined in the initial architecture.
- Gathers responses from all systems.
- Evaluates SoS architecture quality from agreed system contributions.
- Negotiates with systems to achieve better SoS.

Modeling SoS as Complex Systems

- **Create a domain specific model**
  - Key Performance Attribute algorithms for evaluating an SoS architecture using a fuzzy inference system (FIS).
  - Feasibility rules prohibit some architectures.
- **Search for SoS Meta-architecture**
  - Genetic Algorithm develops optimized architectures. using the domain specific model.
- **Negotiation with individual systems**
  - Agent Based Model manages individual system negotiation models to produce a “realizable” architecture chromosome through their cooperation.

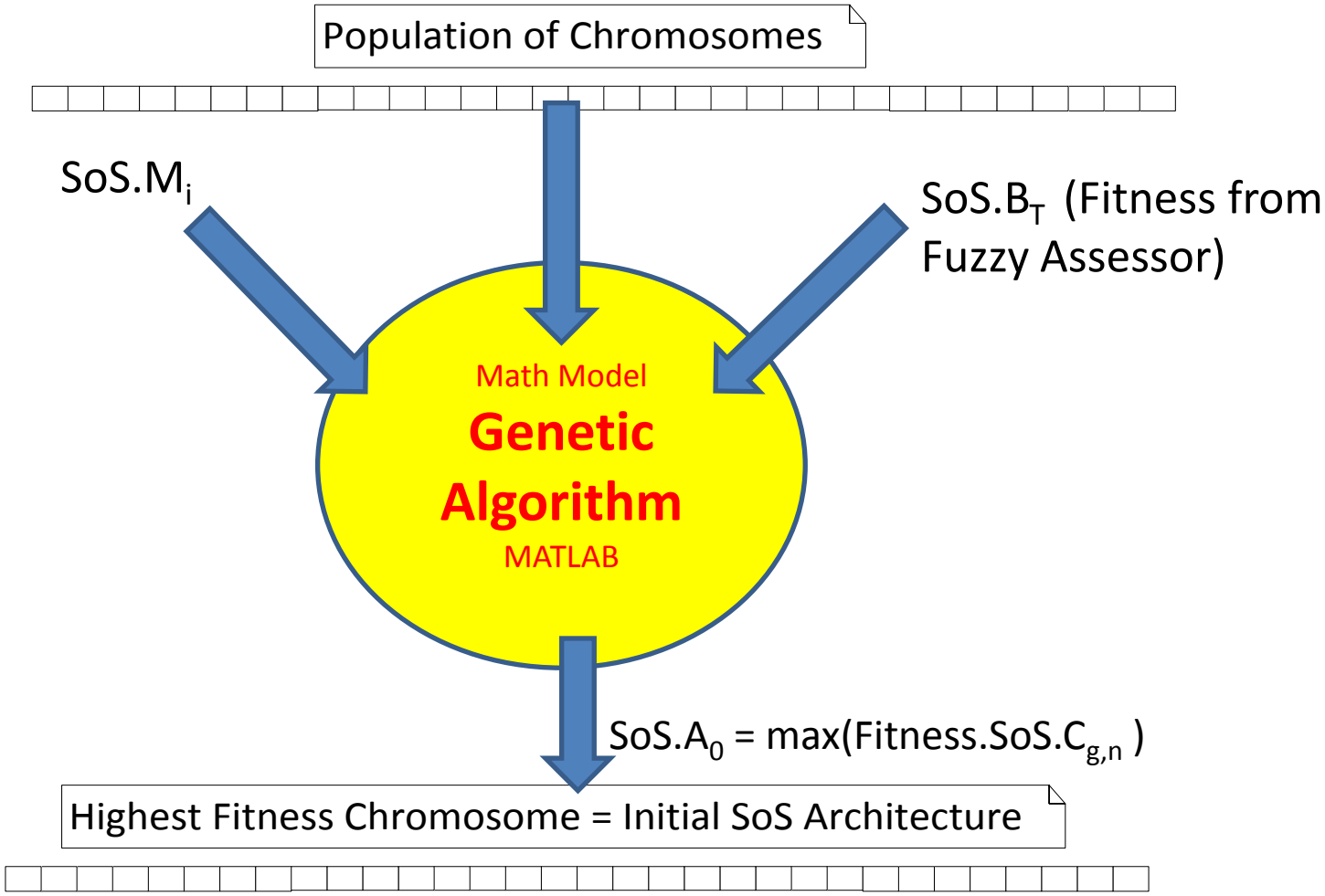
Searching for SoS Meta-Architecture



Evolutionary Methodologies For Solving Multi-Objective Functions

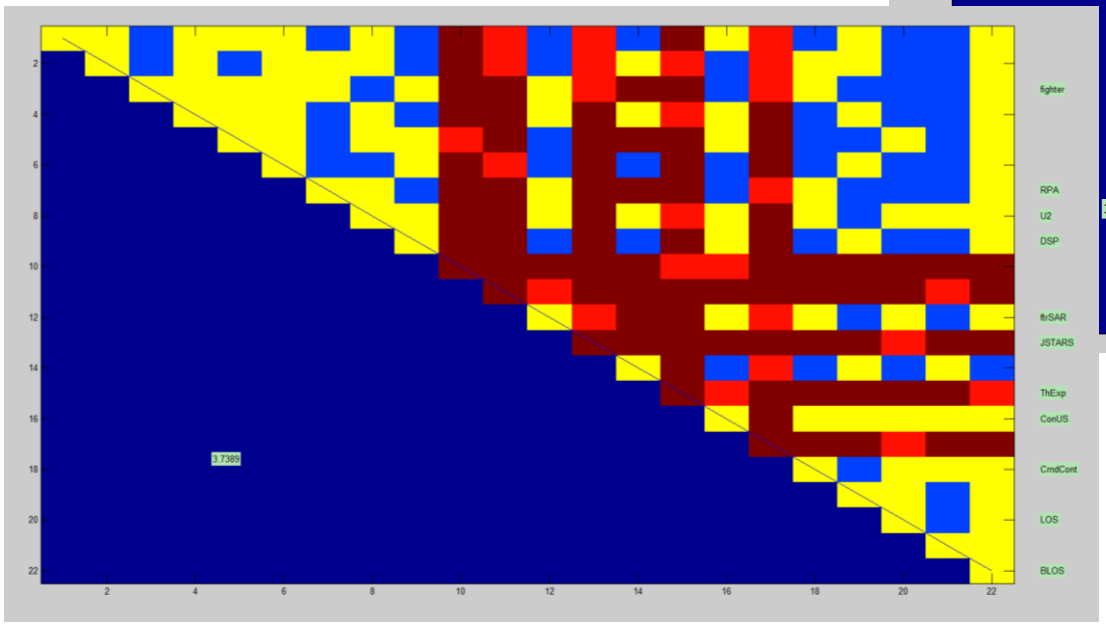
- Genetic Algorithm is used to generate candidates for SoS meta-architecture.
- Genetic algorithms work in an iterative process through many generations.
- A new set of genes is a result of random parent selection, cross over and mutation.
- As a result, the new combinations are efficiently explored based on available knowledge to find a new generation with better fitness. That is, a better objective function value.

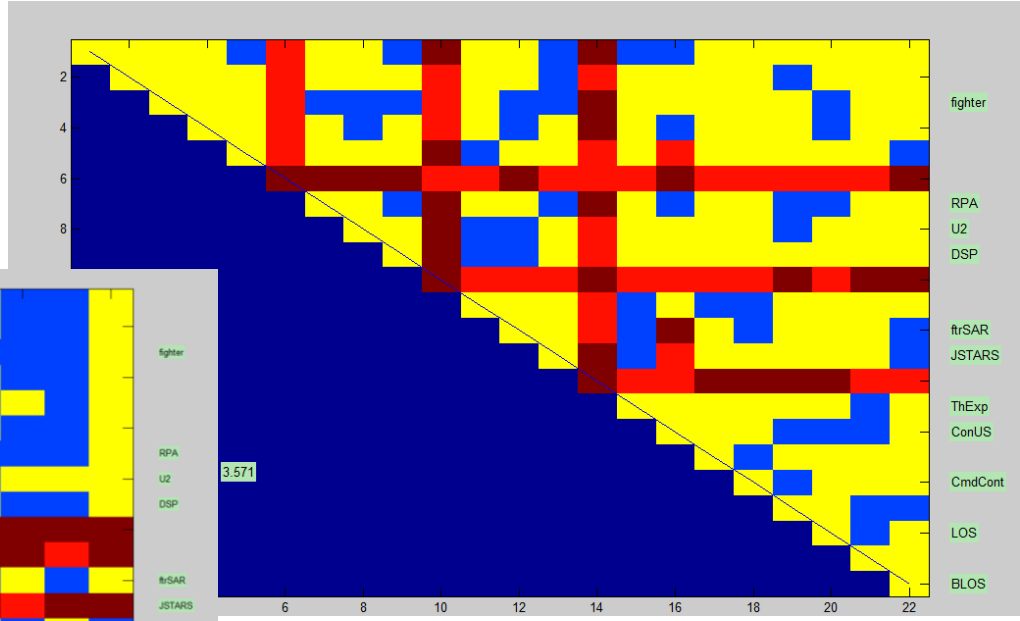
Searching for SoS Meta-Architecture



Genetic Algorithm Search Operation

Final GA selection; Fitness = 3.7389

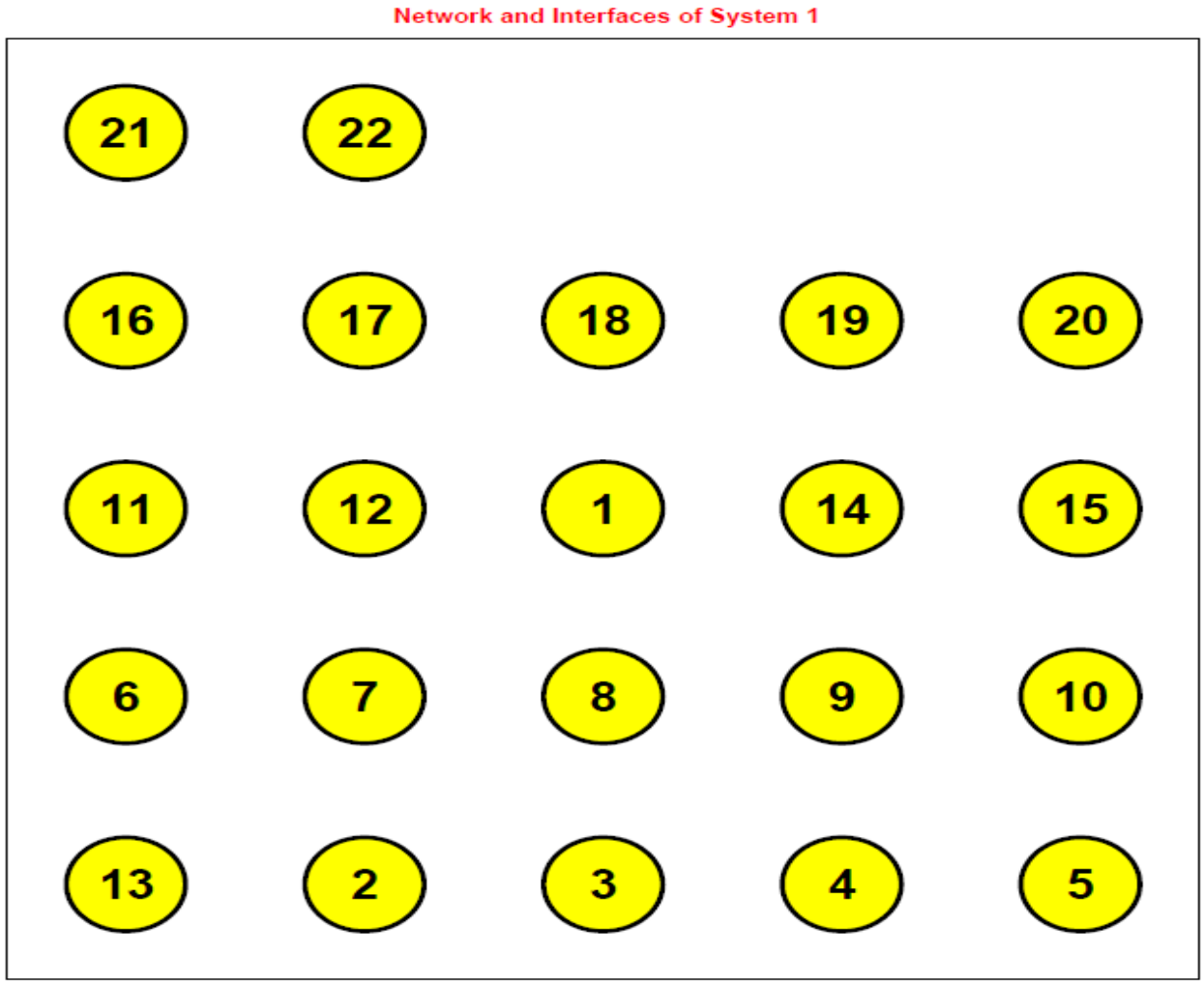




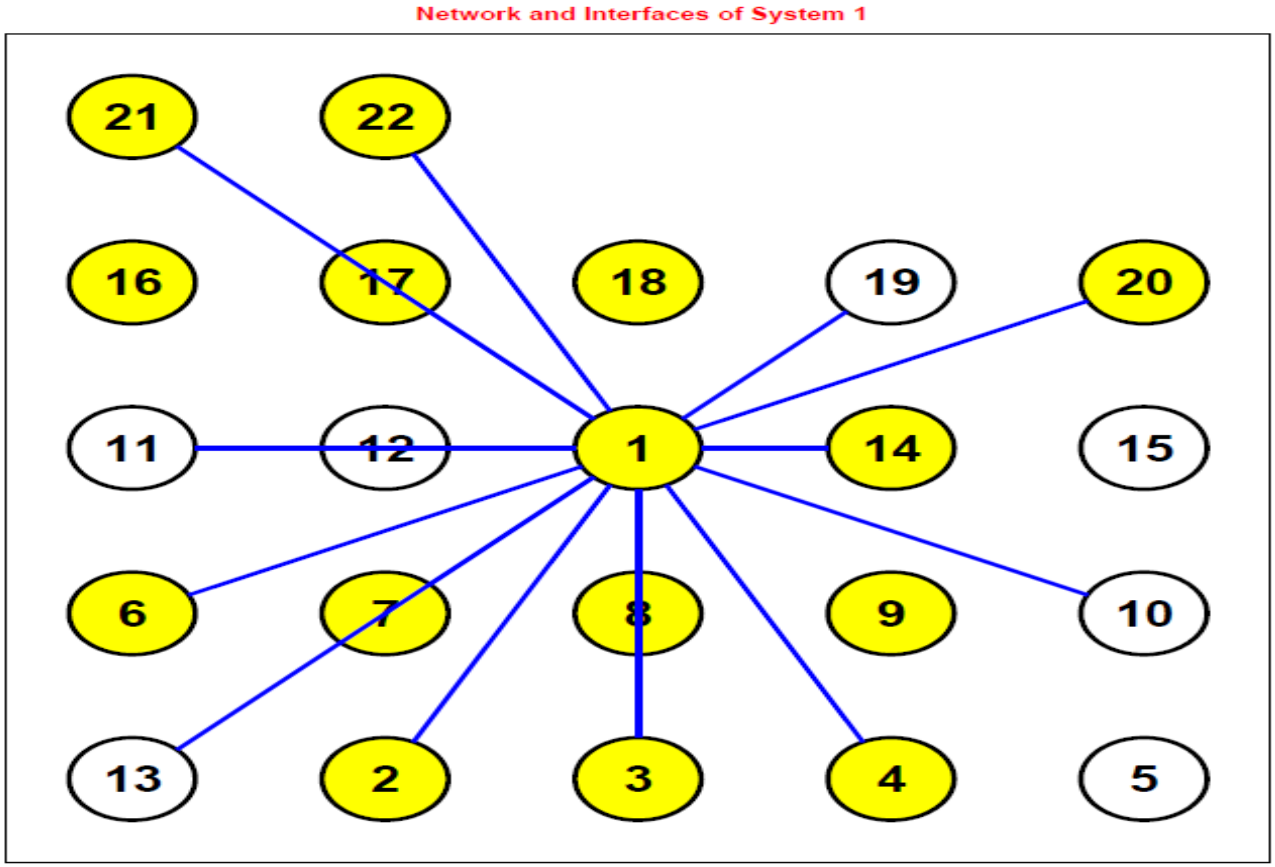
Initial population best chromosome
Fitness = 3.571 (worst was 1.28)

Systems are on diagonal, interfaces at i-j intersections
Yellow/green – feasible/used; Blue – feasible/unused
Red – infeasible/used; Brown – infeasible/unused

Searching for SoS Meta-Architecture

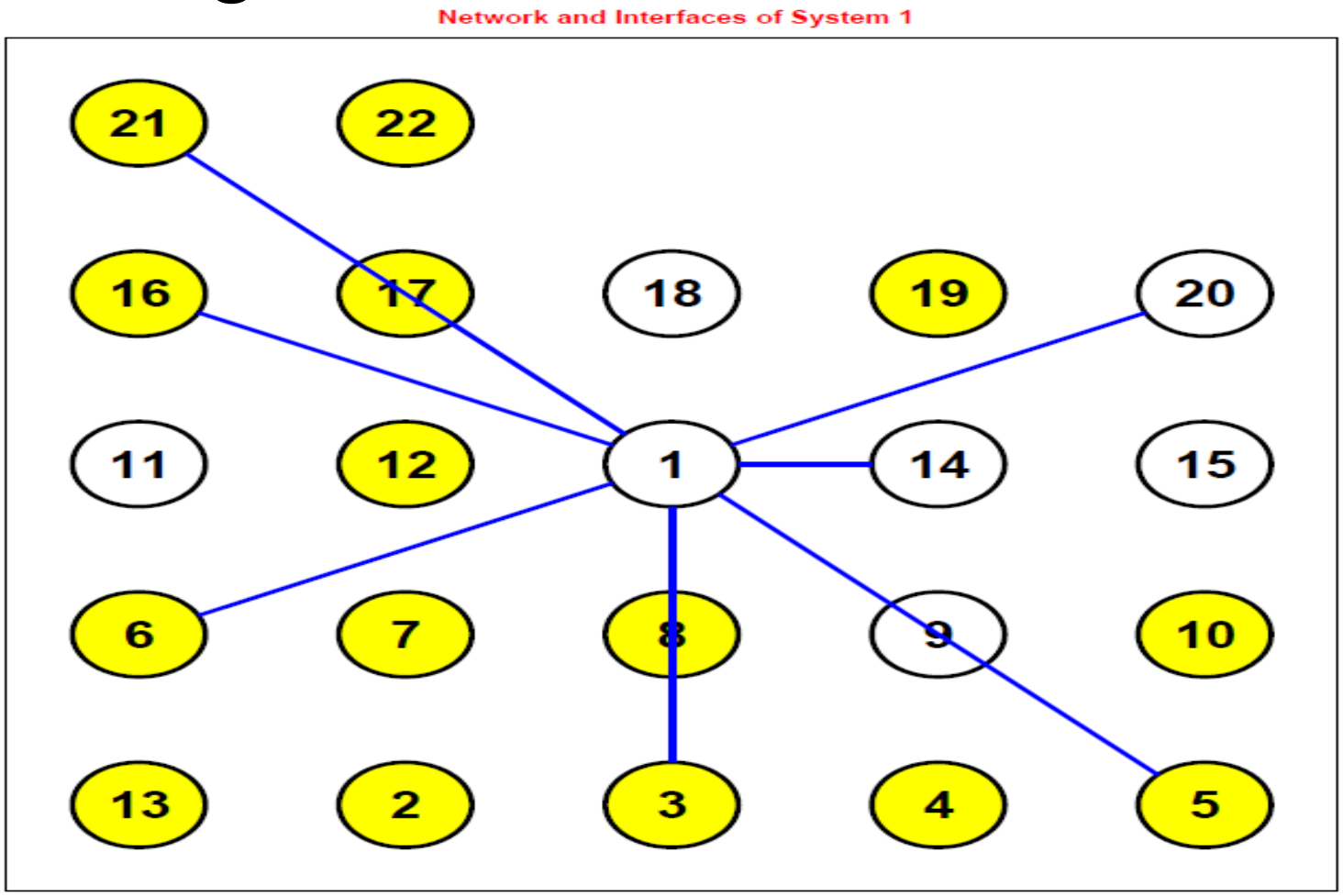


Searching for SoS Meta-Architecture



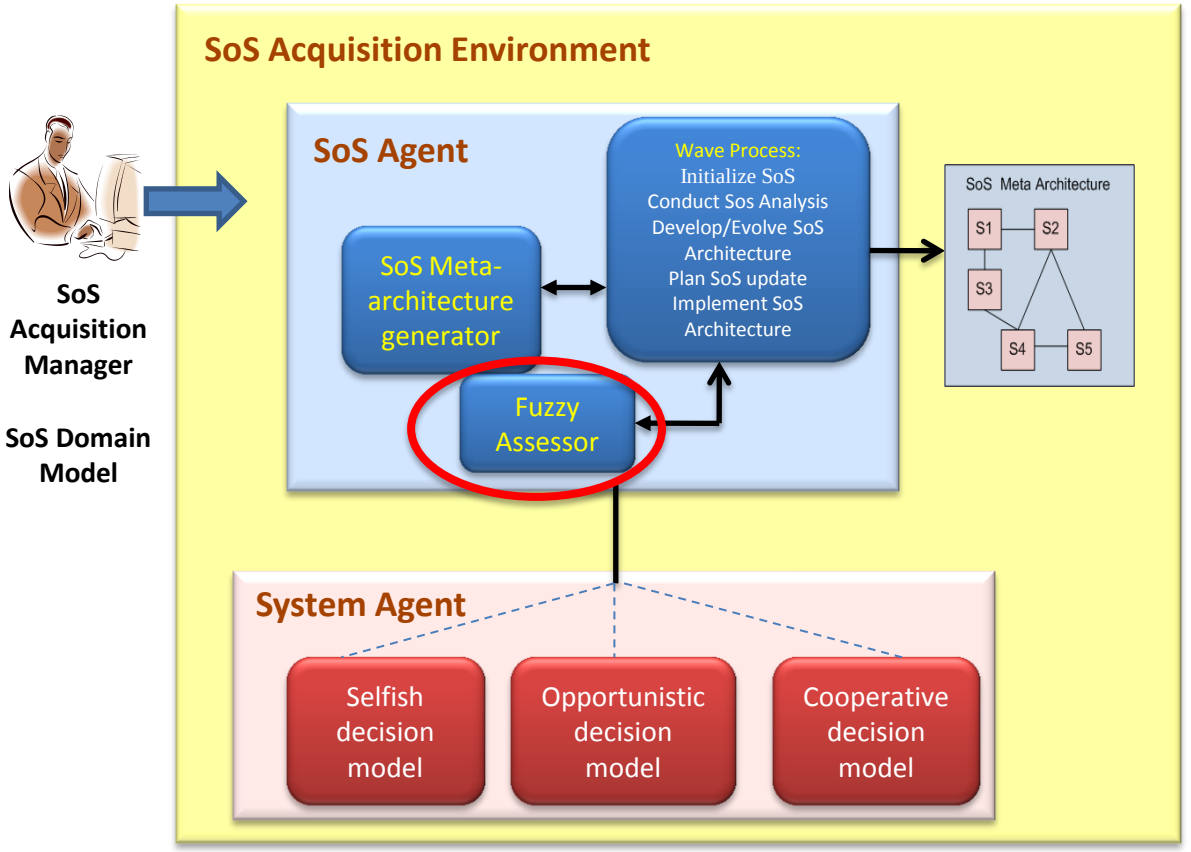
Good Architecture

Searching for SoS Meta-Architecture

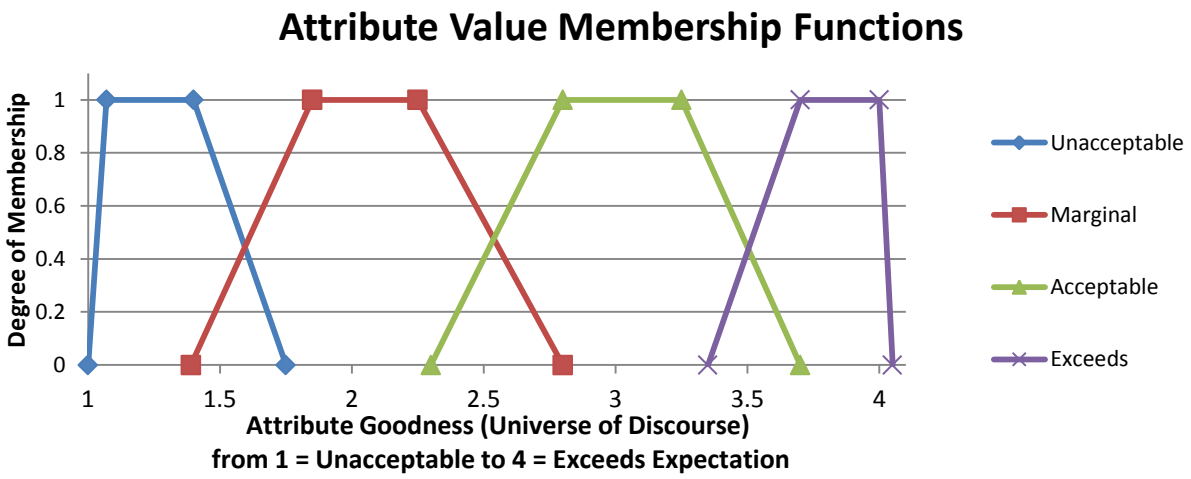


Mediocre Architecture

Fuzzy Assessor for Meta-Architecture to Calculate the Best SoS Architecture



Fuzzy Assessment for Multi-Attribute SoS Architectures

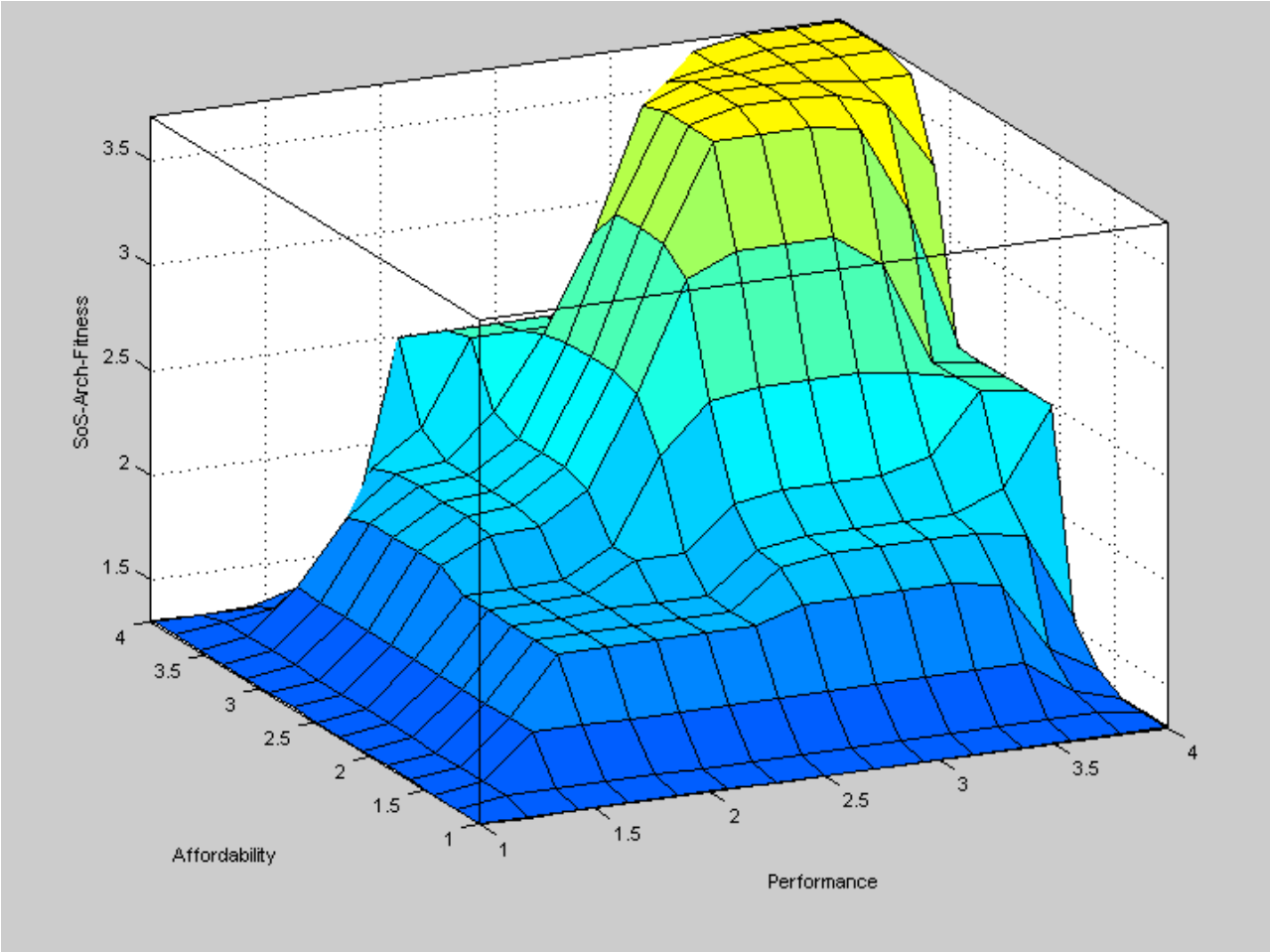


Attribute evaluations themselves are well suited to fuzzy logic approaches because of the difficult nature of boundaries between subjective evaluation ranges. A particular SoS architecture (chromosome) may fall partially into an Acceptable, and partly into a Marginal set.

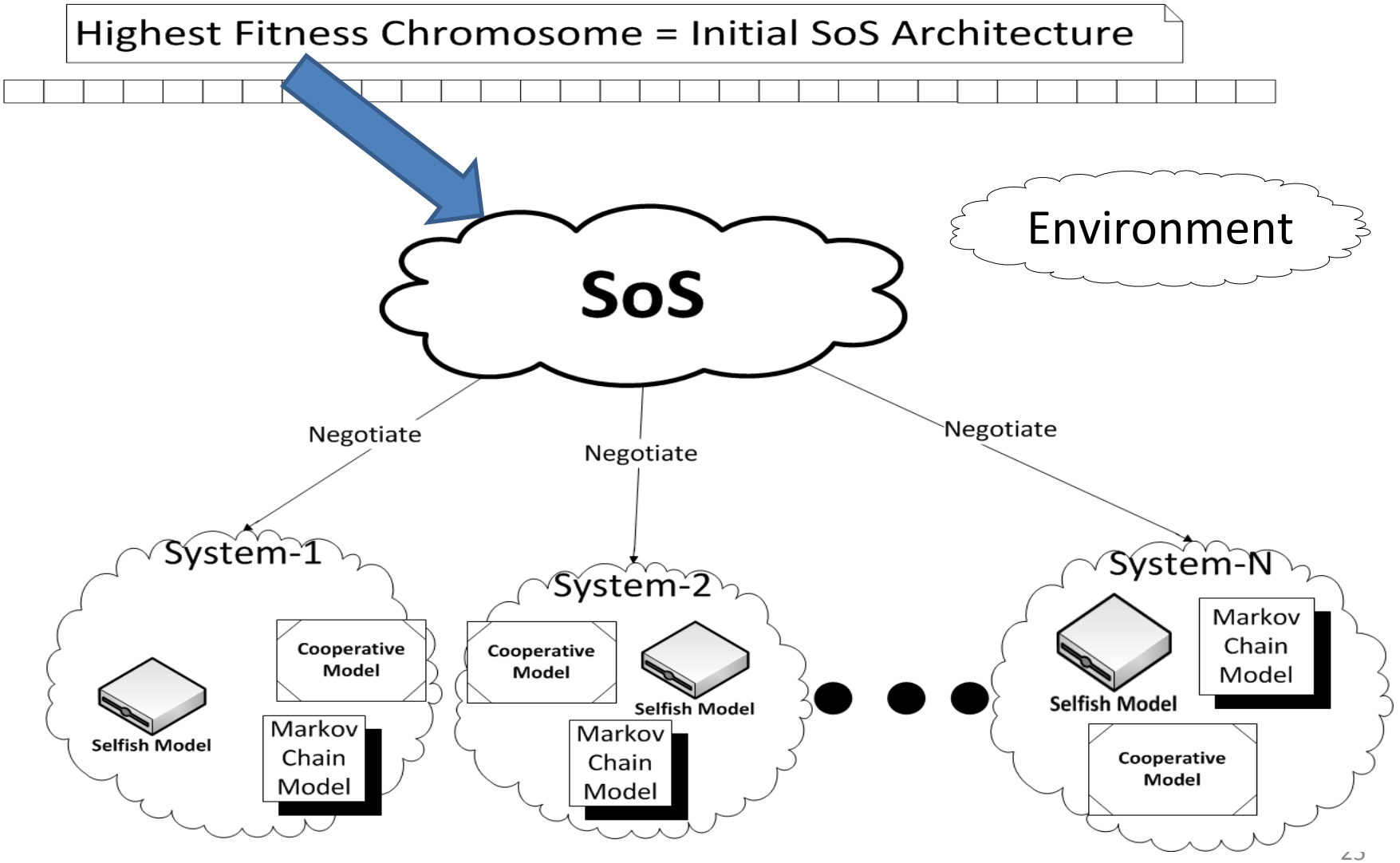
Fuzzy Assessor

- The Fuzzy Assessor is used to evaluate the fitness of an architecture chromosome.
- Fitness will be judged by a combination of the attributes of an architecture, such as:
  - Affordability, Performance, Robustness, Flexibility, Scalability…
  - Others, as developed through guided discussions with Stakeholders and Subject Matter Experts (SMEs).
- The attributes will be domain adjusted and selectable, using guidance from SMEs.
- Fuzzy membership functions Φ_k (derived from stakeholder views) describe the degrees of goodness in each attribute area.
- Fuzzy rules ρ_k (also derived from stakeholder views) combine the attributes into an overall fitness measure.

Fuzzy Inference System Output Surface



Modeling SoS as Complex Systems



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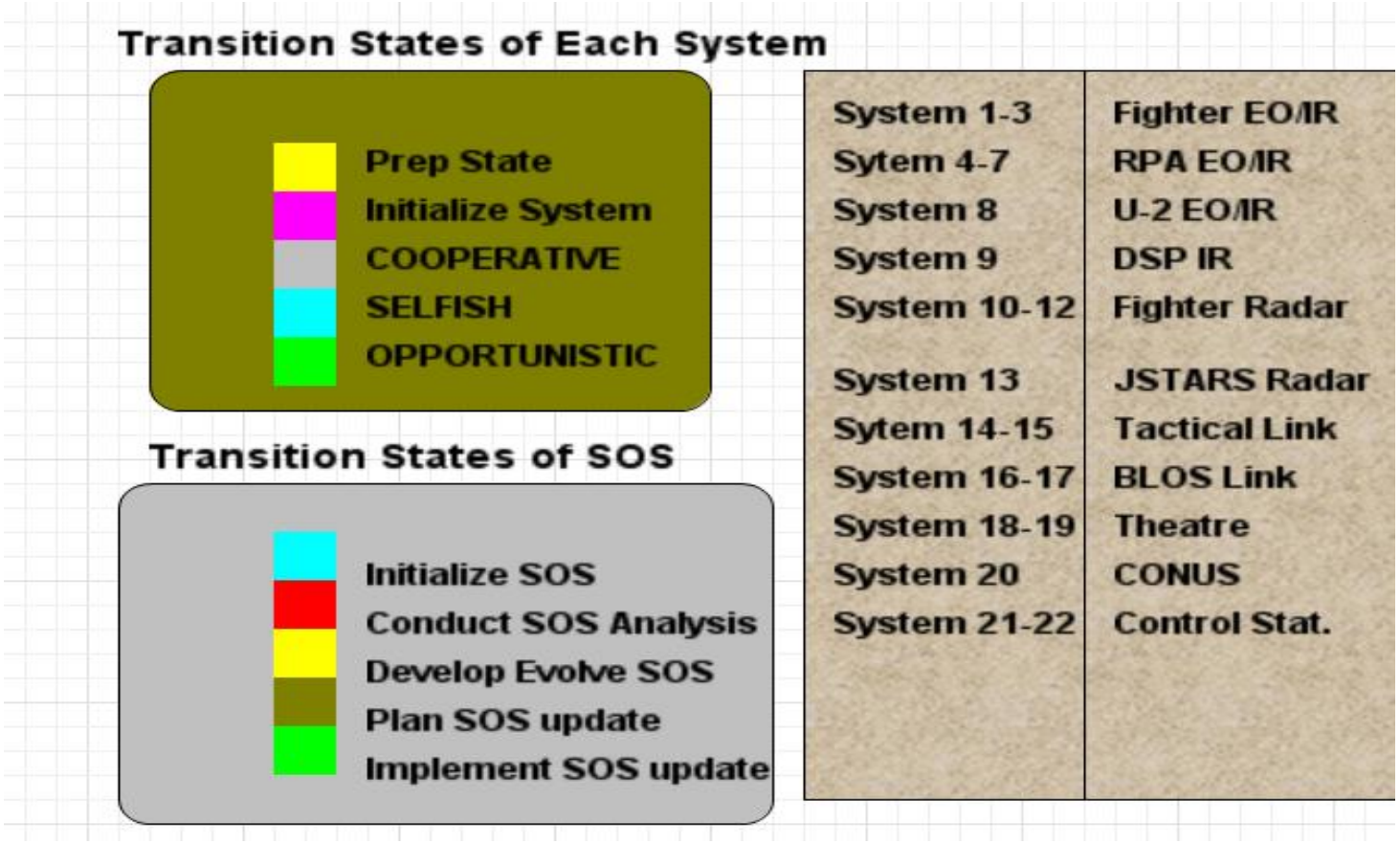
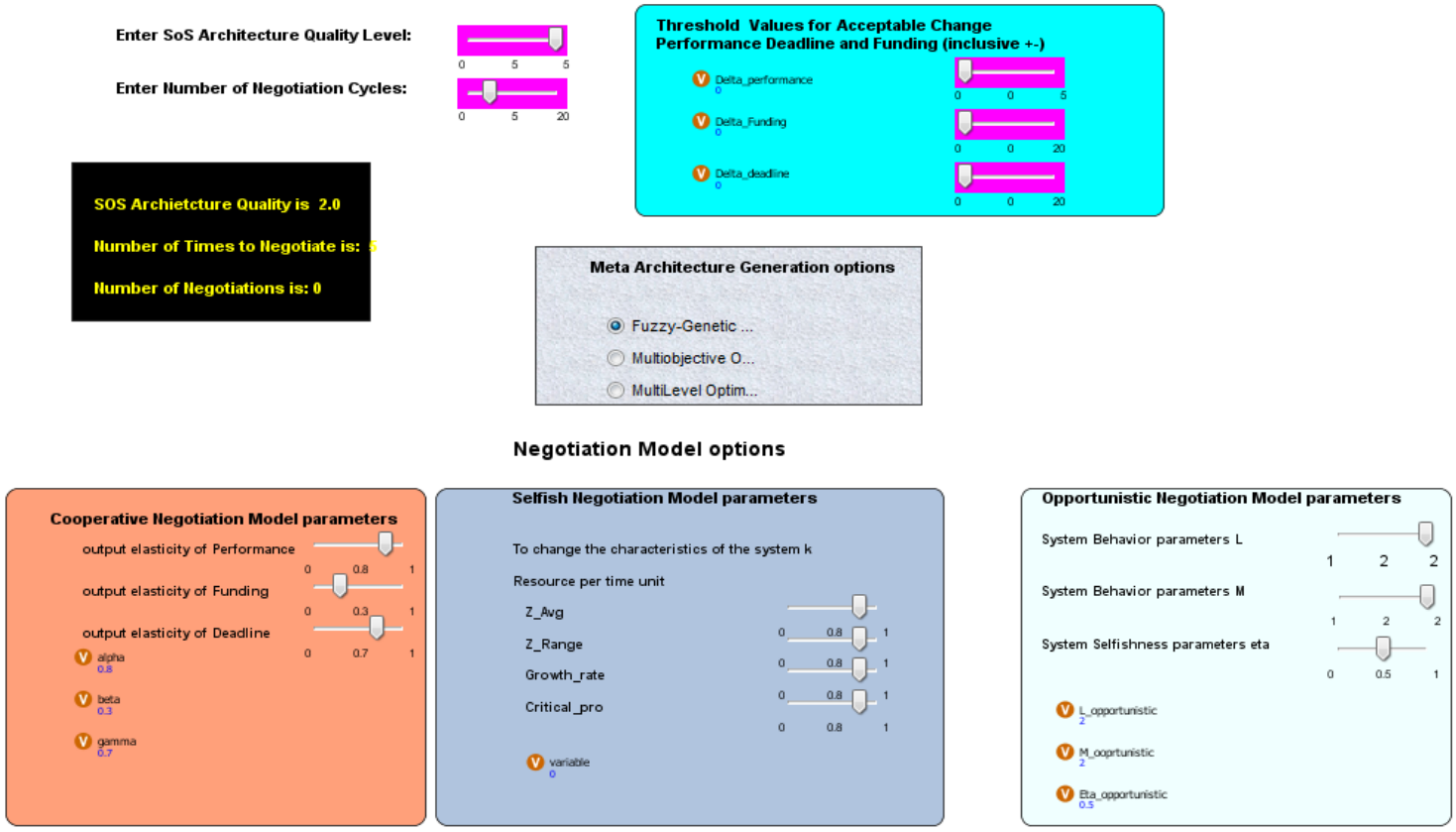


Negotiating Between SoS and System Providing Capability to SoS

- Rules of Engagement for SoS Agent.
- System Negotiation Models: They are incorporated in the ABM simulation as MATLAB executable called by the environment.
  - Cooperative.
  - Selfish.
  - Opportunistic.

User–Inputs for Negotiation Models



Concluding Remarks

- SoS are systems at the edge of chaos
- SoS can be represented as networks
- It is important to understand emergence in SoS context
- Tools for SoS architecting should provide capabilities to analyze SoS as complex systems with cant properties including
  - Individual systems
  - Interactions
  - Operation
  - Diversity
  - Operational environment
  - Activities

Concluding Remarks

- SoS acquisition wave model responds nicely with space, time, complexity and self organization attributes of complex systems.
- Mathematical models can be developed in formulating the dynamics of SoS systems.
- Meta-architecture is the driving force in creating the behavior of SoS as in the case in complex systems.
- Rules of engagement incorporated with meta-architecture creates the emergent behavior of SoS.

Concluding Remarks

- Acknowledged SoS is a point in the spectrum of complex systems.
- Agent Based Architecture model framework can support decision making of the acknowledged SoS manger in negotiating SoS with participating systems
- It is possible to produce a SoS meta-architecture using genetic algorithms with fuzzy logic based inference providing a fitness assessor.
- ABM model and the approach need to be validated with a real life experiment.

Acknowledgement

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