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Architecting Systems of Systems for Delivery of Sustainable Value

Thomas V. Huynh
Xuan-Linh Tran
John Osmundson

Authors' Contact Information



Dr. Tom Huynh
Associate Professor
Systems Engineering
Naval Postgraduate School
Monterey, CA
(831) 656-7568
thuynh@nps.edu



Mrs. Xuan-Linh Tran
PhD Candidate
Defence and Systems Institute
University of South Australia
Adelaide, South Australia
+61 8 83023019
xuan-linh.tran@unisa.edu.au



Dr. John Osmundson
Research Associate Professor
Information Sciences
Naval Postgraduate School
Monterey, CA
(831) 656-3775
josmund@nps.edu

Purpose

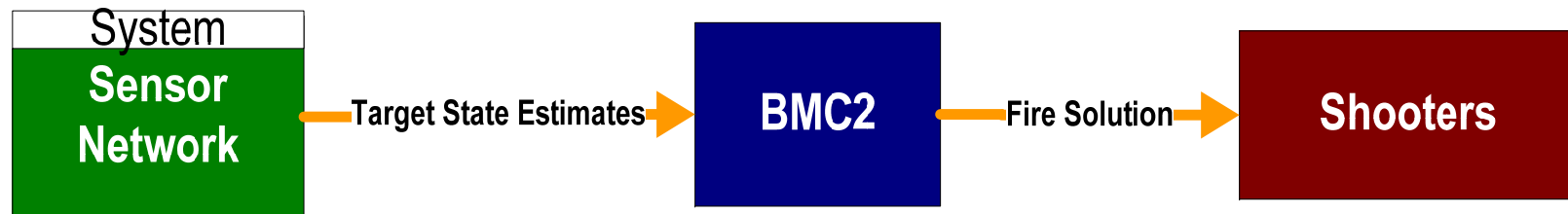
- Discuss a methodology to derive requirements on architecting a SoS to provide sustainable delivery of value
- Illustrate it with an *ad hoc* sensor network of a missile defense SoS

Agenda

- Background/ Research Questions
- Methodology
 - Systems architecting paradigm
 - Network complexity and interoperability
 - Sustainability analysis
 - Similarity principle
 - Derivation of architecting requirements.
- Distributed Sensor Fusion Problem
- Conclusion

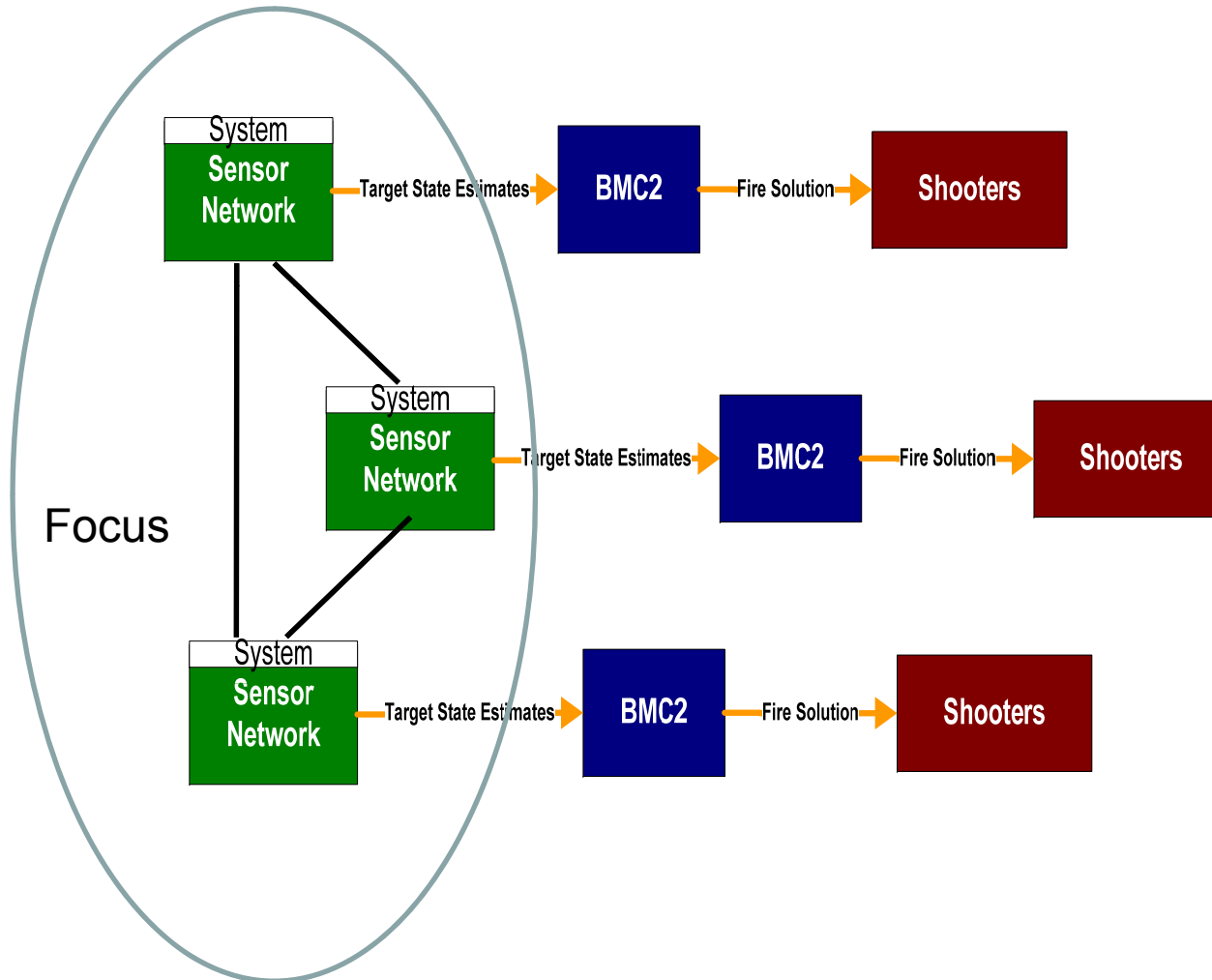
Background

- **Research objective:** To gain insights into architecting SoS for sustainable performance
- **System of systems**
 - Component systems, each of which serves organizational & human purposes and may be locally managed & optimized independently.
 - Connectivity & interoperability affected by environment dynamics
- **Sustainable performance** := continued delivery of desirable value to users in the presence of environmental or mission changes
- Missile defense system



- Sustainable network architecture necessary for sustained delivery of distributed sensor fusion performance

Missile Defense SoS



- **MD SoS** = {MD systems}
- **MD system** = {sensor network, BMC2, and shooters}
- **MD SoS sensor network** = {sensor networks organic to component MD systems | connected & interoperable}
- MD SoS sensor network provides target state estimates to MD SoS BMC2 and also to MD system BMC2s

Research Questions

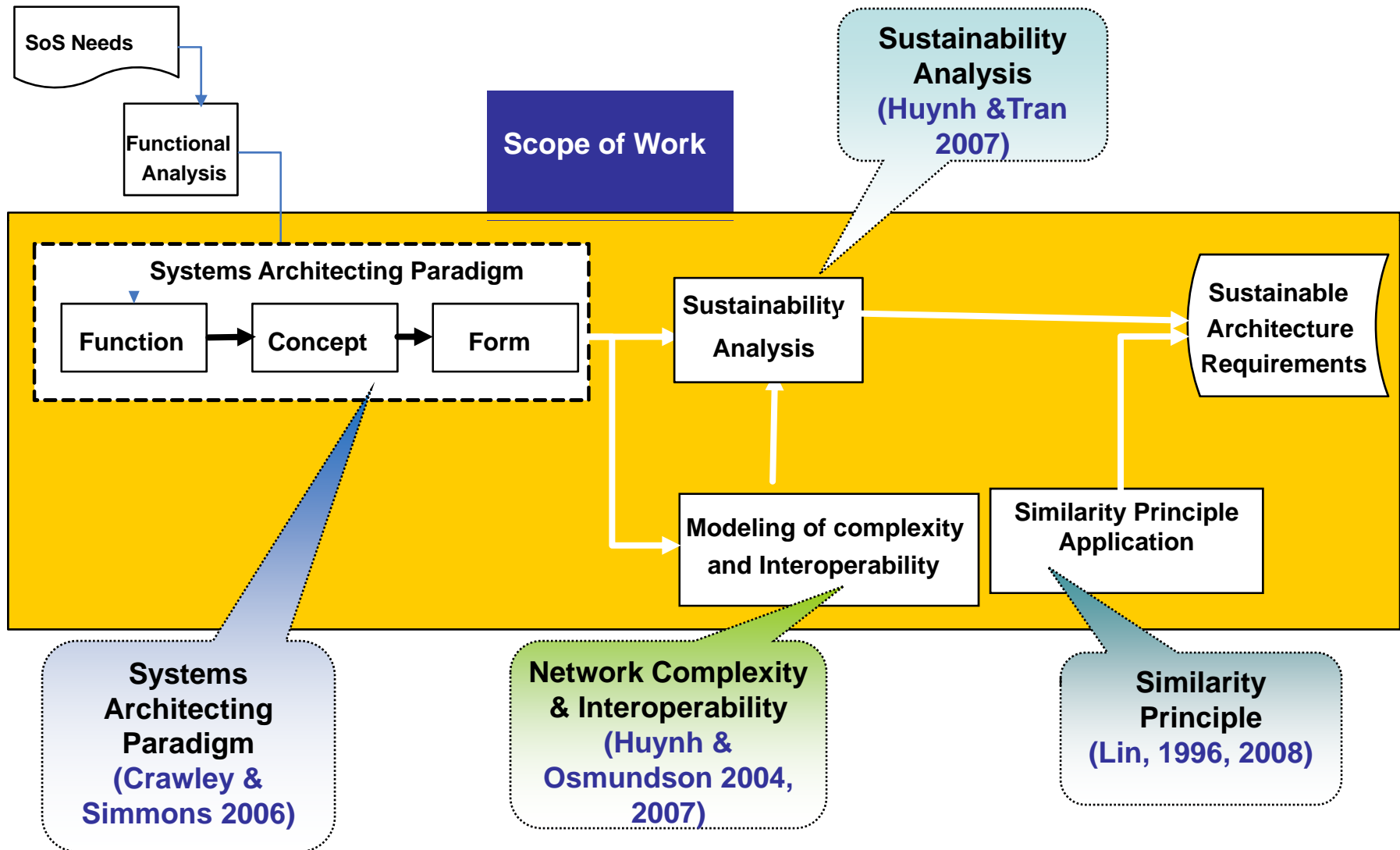
General question:

- How do we establish *requirements for architecting a SoS* that continues to deliver desirable value to users in the face of adversity caused by environmental or mission changes?

Specific question:

- How do we establish *requirements for architecting a network of sensor networks organic to member systems* for sustainable delivery of distributed sensor fusion performance in the face of adversity caused by environmental or mission changes?

Methodology



Systems Architecting Paradigm

- Architecture is “the embodiment of *concept*, and the allocation of physical/informational *function* to *elements of form*, and definition of *interfaces* among the elements and with the surrounding *context*.”
(Crawley and Simmons, 2006)

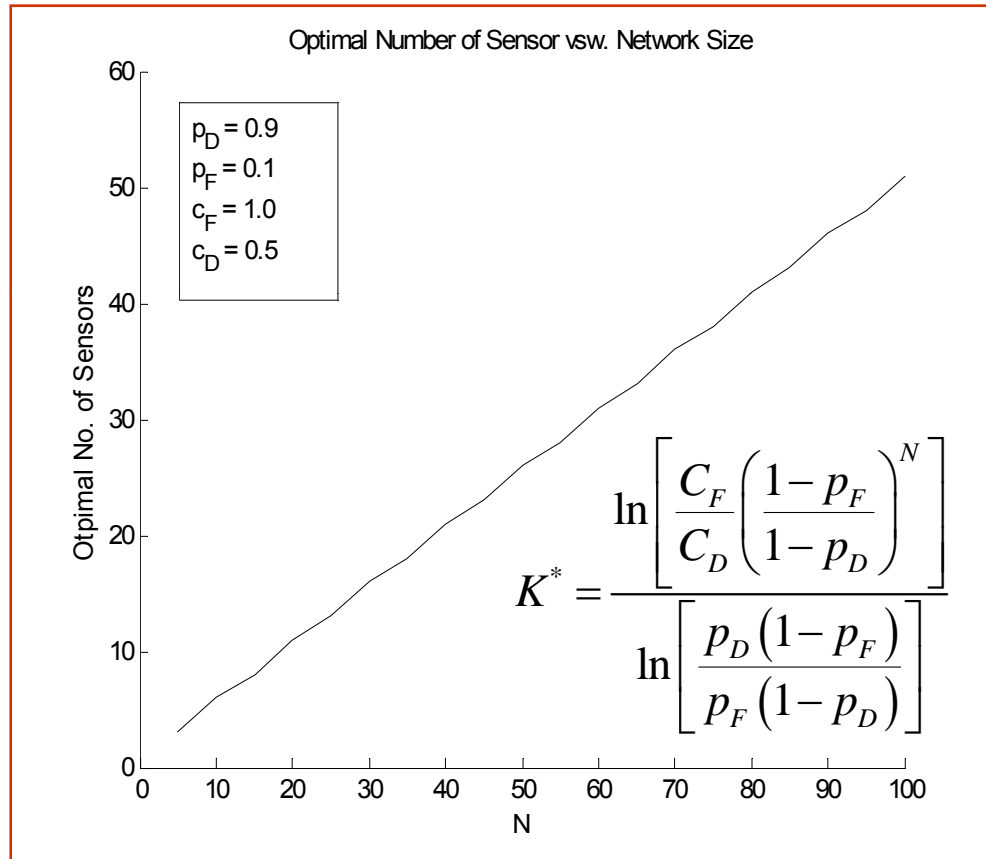


Network Complexity & Interoperability

- Network connectivity affected by success or failure of
 - Discovery
 - Connection
 - Complexity measure : $\chi_o = p_c (N - 1)$; $p_c = p_k p_d$
- Network interoperability related to
 - Interfaces among sensors
 - Interoperability: $\chi_1 = p_s (N - 1)$
- Average number of connected and interoperable sensors

$$E(X_1) = \left[1 - \left(1 - \frac{\chi_o}{N - 1} \right)^N \right] \frac{N \chi_1}{N - 1}$$

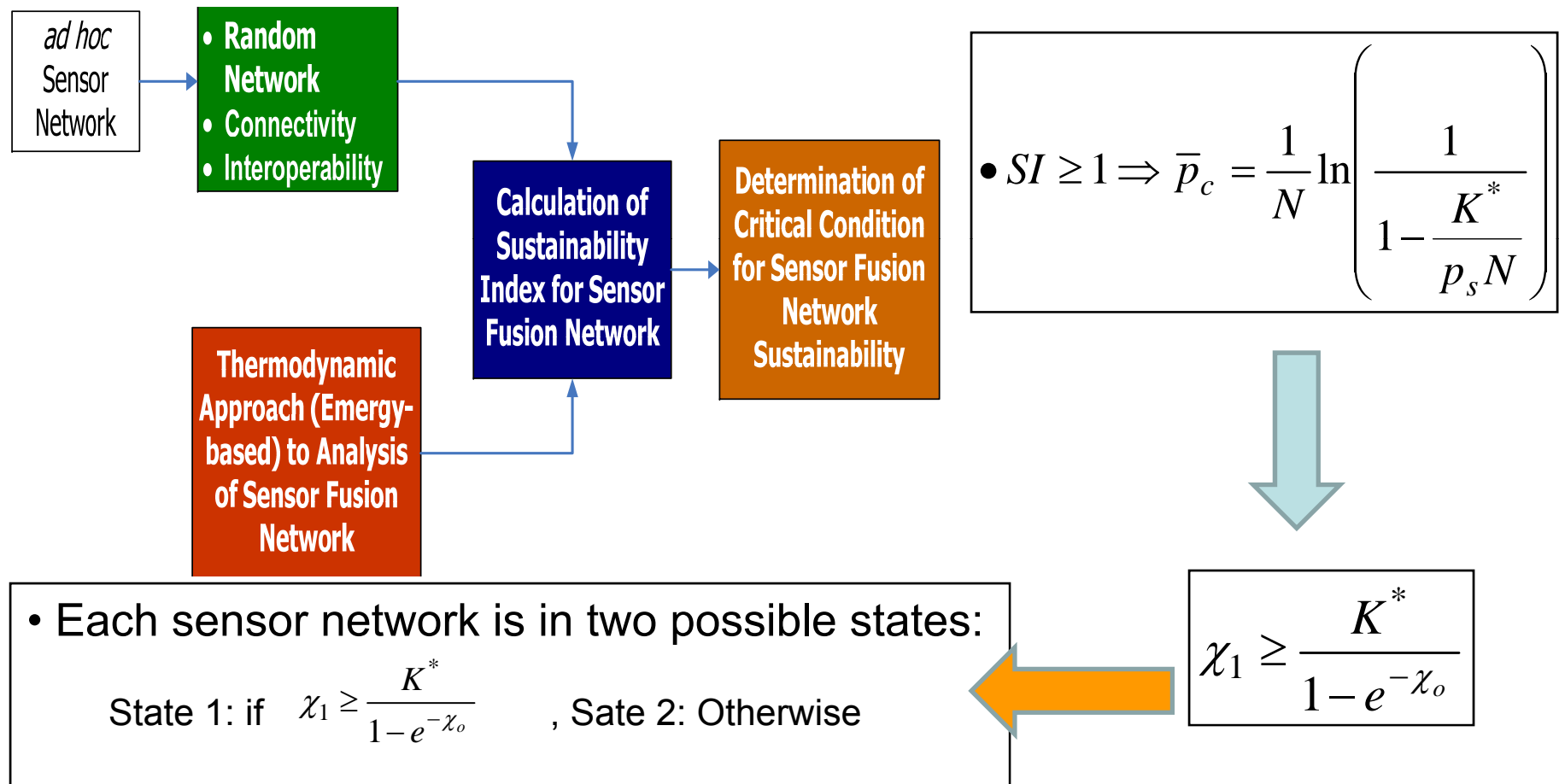
Distributed Sensor Fusion Problem



- C_F : cost of false-alarm decision
- C_D : cost of correct decision

- Large network of N sensors
 - Passing & processing all observations of a phenomenon
 - Declaring binary output
 - Phenomenon — present or absent
 - Having identical probability of detection (p_D) and probability of false-alarm (p_F)
- K -out-of- N fusion rule (Varshney, 1996)
 - Optimal number of sensors processed
 - Minimizing Bayes risk
 - Network evolution independent

Sustainability Analysis



• Each sensor network is in two possible states:
 State 1: if $\chi_1 \geq \frac{K^*}{1 - e^{-\chi_0}}$, State 2: Otherwise

$$\chi_1 \geq \frac{K^*}{1 - e^{-\chi_0}}$$

• Each network is thus a binary element of the SoS sensor network.

Similarity Principle

- Similarity Principle for a mixture of chemical species (Lin 2008): .. *the higher the similarity among the components is, the higher value of entropy of the mixture ... the more stable the mixture will be ...*
- A MD SoS viewed as mixture of the MD component systems
- A similarity principle for a SoS architecture:
“The higher the similarity among the systems of a SoS is, the higher the value of the entropy of the SoS will be, the more stable (or sustainable) the SoS will be.”

Similarity Principle (Cont'd)

- The state of maximal entropy \equiv state of maximal similarity (Lin 2008).
- Similarity in architecting a SoS sensor network \rightarrow similar ability of each MD system sensor network to provide target estimate of value to the MBC2

- Similarity index: $Z = \frac{S}{S_{\max}}$ (Lin, 1996)

- Entropy of the SoS : $S = - \sum_{j=1}^{\aleph} \sum_{i=1}^M p_{ij} \ln p_{ij}$

\aleph : number of sensor networks

M: states of the network

p_{ij} : probability that the sensor network j is in state i , and $\sum_{i=1}^M p_{ij} = 1$

- Max entropy : $S_{\max} = \ln W$

W : number of possible states of the SoS sensor network.

Requirements Derivation

- Similarity index: $Z = -\frac{1}{S_{\max}} \sum_{j=1}^{\aleph} \sum_{i=1}^M p_{ij} \ln p_{ij}$
 $\aleph = 3$ and $M = 2$

- Z is max if, for large N , $\Pr \left(p_c \geq -\frac{\ln \left(1 - \frac{K^*}{p_s N} \right)}{N} \right) = \frac{1}{2}$

- SoS sustainability \rightarrow requirements on each system network sensor:

$$\chi_1 \geq \frac{K^*}{1 - e^{-\chi_o}}$$

$$p_s = \frac{K^*}{N \left(1 - e^{-NF^{-1}\left(\frac{1}{2}\right)} \right)}$$

p_c : random variable with a cdf F

Conclusion

- A general methodology to derive requirements on architecting a SoS to provide sustainable delivery of value.
 - Subscribing to systems architecting paradigm (Crawley & Simmons 2006)
 - Modeling network complexity and interoperability (Huynh & Osmundson 2004, 2007)
 - Performing a sustainability analysis (Huynh & Tran 2007)
 - Invoking a similarity principle (Lin 1996, 2008)
 - Deriving the MD SoS network architecting requirements.
- Application to binary hypothesis distributed sensor fusion in an *ad hoc* SoS sensor network to provide sustainable delivery information for use in a missile defense system.
- Establishment of constraints on the network connectivity and interoperability measures.
- Extension of application to derivation of requirements on other MD system components such as the MD BMC2 element

BACKUP SLIDES

from (Huynh & Tran 2007)

Thermodynamic Framework for Ecologically Conscious Process Systems Engineering*#

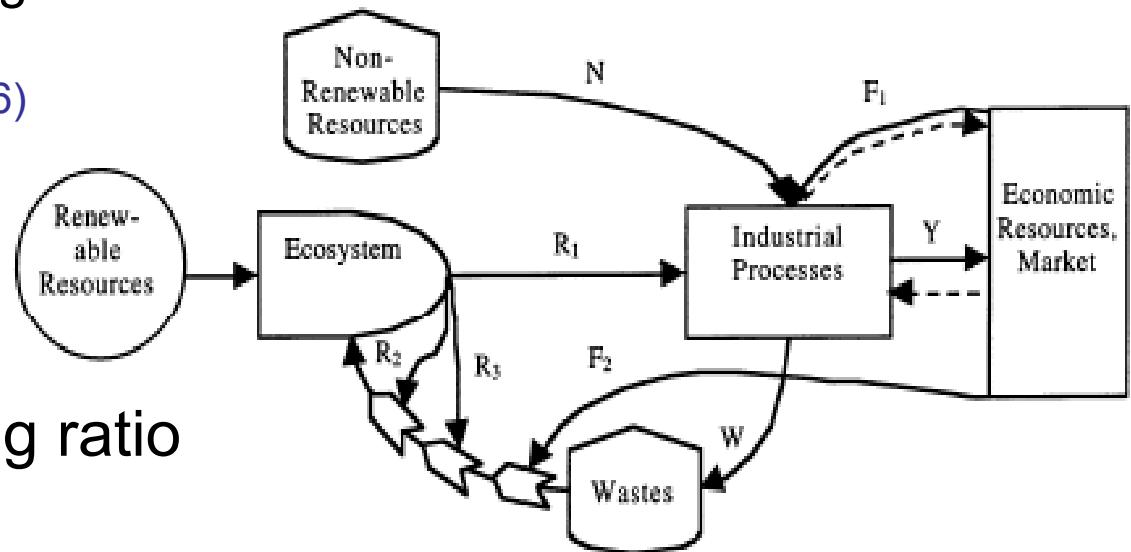
- Thermodynamic approach
 - including input from both ecological and economic resources
 - analyzing industrial and ecological processes together
 - based on the fact that
 - growth and sustenance of both industrial and ecological processes limited by available energy
 - energy conversion to useful work (**exergy**)
- Embodied energy (**emergy**)
 - energy used directly or indirectly to make a product or service (Odum, 1988)
 - a measure of ecological cost
 - Emergy, M , related to exergy, B ,
 - $M = \tau B$; where τ : transformity
- Emergy analysis of industrial and ecological processes → insight
 - environmental performance
 - sustainability of industrial process
 - Product

(# Huynh & Tran 2007)

* (Bakshi, 2000)

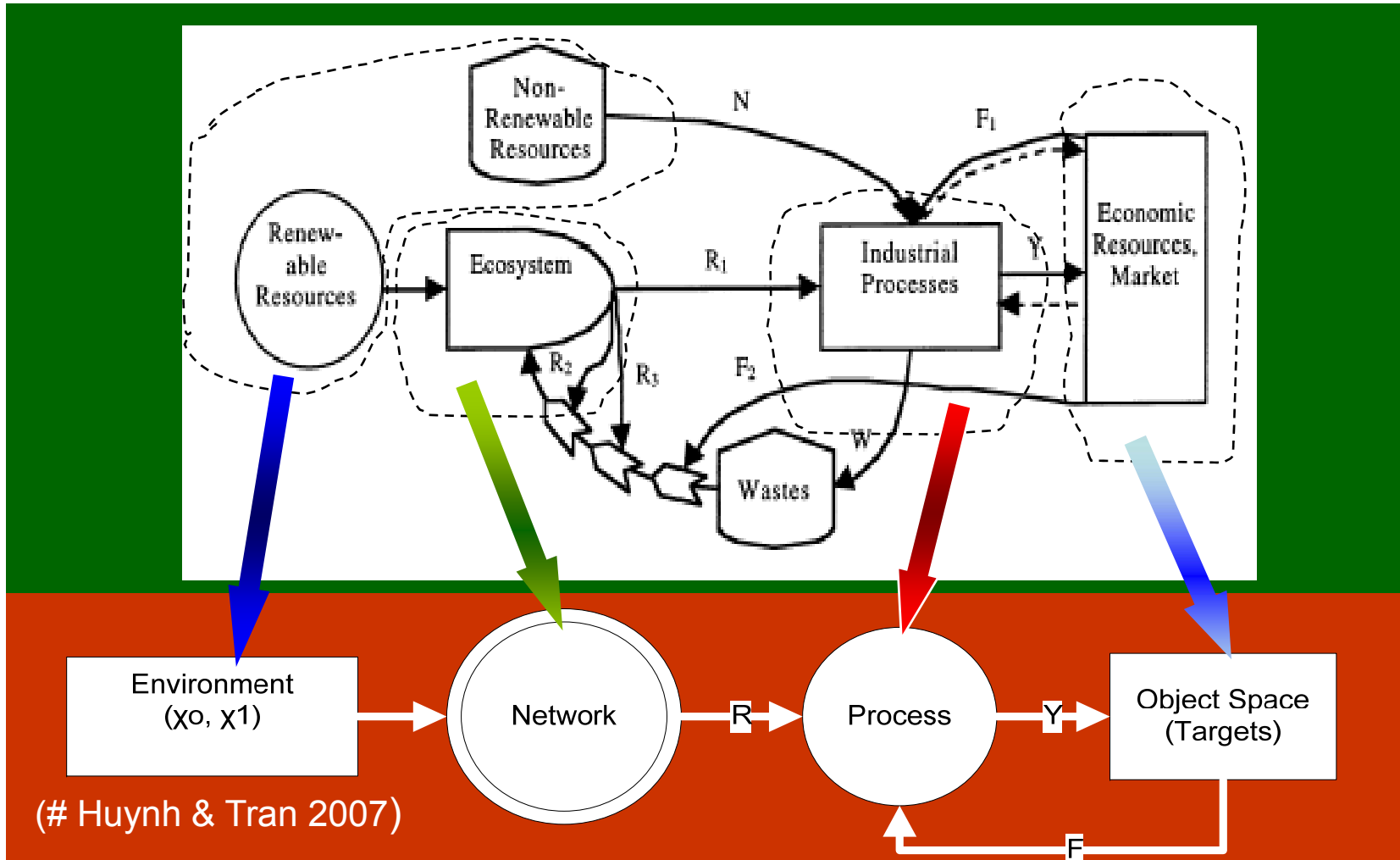
Process/Product Sustainability Analysis#

- Net emergy
 - Energy gained by economy in exchange for providing its services
 - $M_{net} = Y - F_1$ (Odum, 1996)
- Emergy yield ratio
 - Emergetic return on investment
 - $EYR = Y / F_1$
- Environmental loading ratio
 - Stress on the local environment (Brown & Ulgiati, 1997)
 - $ELR = (F_1 + N) / R_1$
- Sustainability index
 - $SI = EYR / ELR$



(# Huynh & Tran 2007)

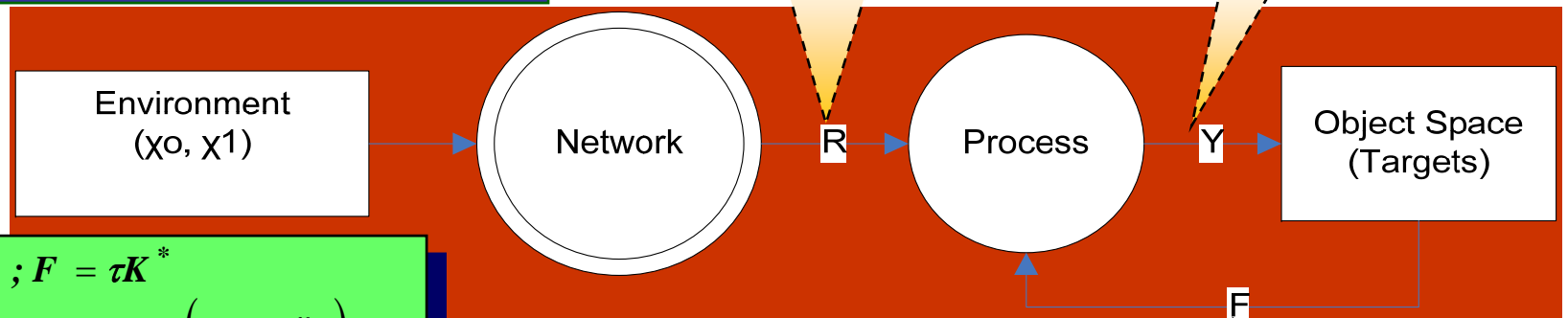
Mapping from Industrial Process to Sensor Fusion#



(# Huynh & Tran 2007)

Sensor Network Sustainability Index#

- $Y - F :=$ net energy associated with object space
- $EYR = Y/F$ (emergetic return on network performance)
- $ELR = 1$ (network "loading" ratio)



- $Y = \tau \bar{X}_1; F = \tau K^*$
- $SI = \frac{EYR}{ELR} = \frac{Y}{F} = \frac{(1 - e^{-\chi_0}) \chi_1}{K^*}$
- $SI \geq 1 \Rightarrow \bar{p}_c = \frac{1}{N} \ln \left(\frac{1}{1 - \frac{K^*}{p_s N}} \right)$

Sustained Performance

$$\chi_0 \geq \ln \left(\frac{1}{1 - \frac{K^*}{\chi_1}} \right)$$

$$\bar{\chi}_1 > K^*$$

Energy (unity function of K_{opt})