CITY UNIVERSITY LONDON

"Systems Complexity: The Paradigm of System of Systems "

NICOS KARCANIAS

SYSTEMS & CONTROL RESEARCH CENTRE

School of Mathematics, Computer Science and Engineering
City University London

N.Karcanias@city.ac.uk

Complexity Science Workshop
18, 19 June 2015 City University

CITY UNIVERSITY LONDON

OVERVIEW OF THE PRESENTATION

★ **BASIC OBSERVATION:**

TRADITIONAL SYSTEMS ARE THE COMPOSITE SYSTEMS CHARACTERISED BY AN INTERCONNECTION TOPOLOGY

★ ***INTEGRATED SYSTEM OPERATIONS:***

THE SYSTEM IS INTERCONNECTED AT THE INFORMATION & OPERATIONAL LEVEL WITH GENERAL RULES NOT EXPRESSING A TOPOLOGY

⇩

"SYSTEMS OF SYSTEMS"

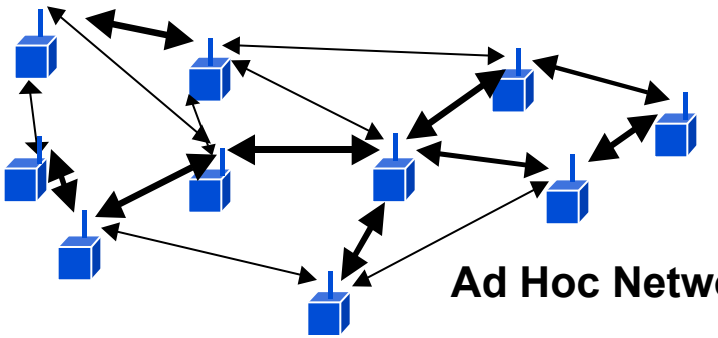
CITY UNIVERSITY LONDON

Challenges in Engineering Design and Operations:
Complex Systems Engineering & Complexity

CITY UNIVERSITY LONDON

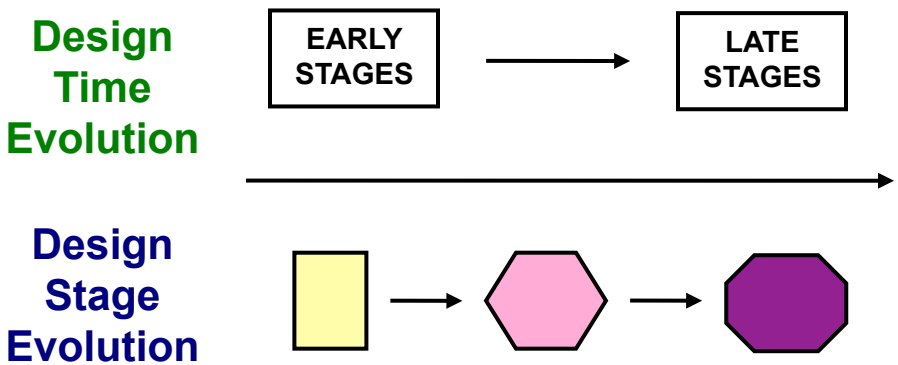
COMPLEX DISTRIBUTED SYSTEMS

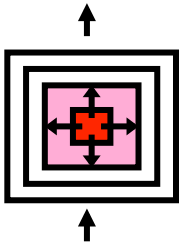
- Integration of Design / Operations of Technological Processes
- Power GENERATION & DISTRIBUTION Systems under Market De-regulation
- Networks of SYSTEMS: Control of Communication/ Traffic NETWORKS
- RAILWAY SYSTEMS AND OPERATIONS



Ad Hoc Networks

Operational Embedding





Top-Down
Bottom-Up

EXAMPLES OF SYSTEMS OF SYSTEMS

Industrial Production

Freeways

Transportation SoS: Roads +GPS+ ONSTAR

What is a System of Systems ?

Air traffic

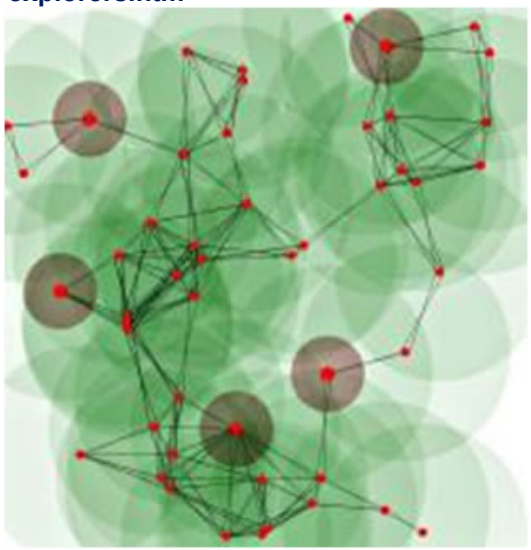
Aircraft

CITY UNIVERSITY LONDON

Wireless Sensor Networks

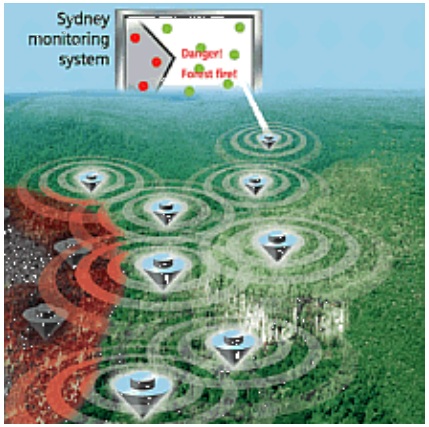
www.robaid.com/robotics/sensor-networks-of-freely-drifting-autonomous-underwater-explorers.htm

- Environmental coverage
- Warning systems: fire detection/tsunami
- Defense applications: intruder detection, border surveillance
- Coverage: Search and rescue applications, toxic substance detection



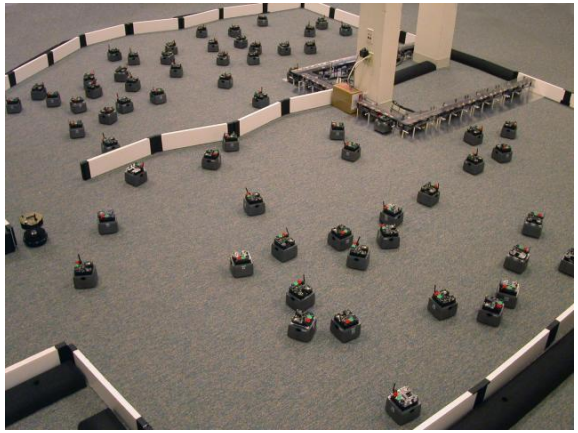
www.siemens.com/innovation/en/publikationen/publications_pof/pof_spring_2003/security_articles/sensor_networks.htm

web.engr.oregonstate.edu/~thinhq/re_sensor_network.html



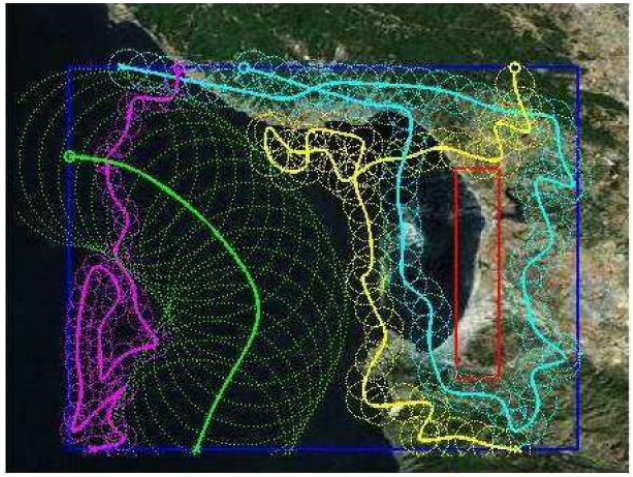
CITY UNIVERSITY LONDON

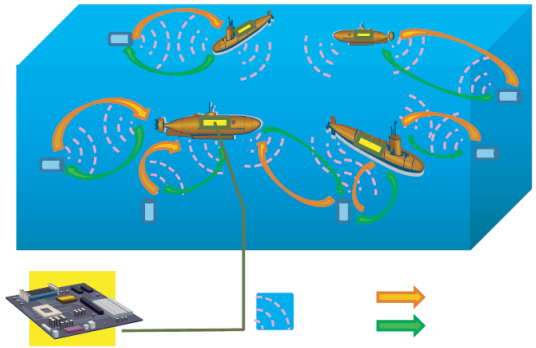
Networked Mobile Robots



www.robotreviews.com/news/2009/10/21/former-irobot-lead-research-scientist-to-tell-the-truth-about-robotics

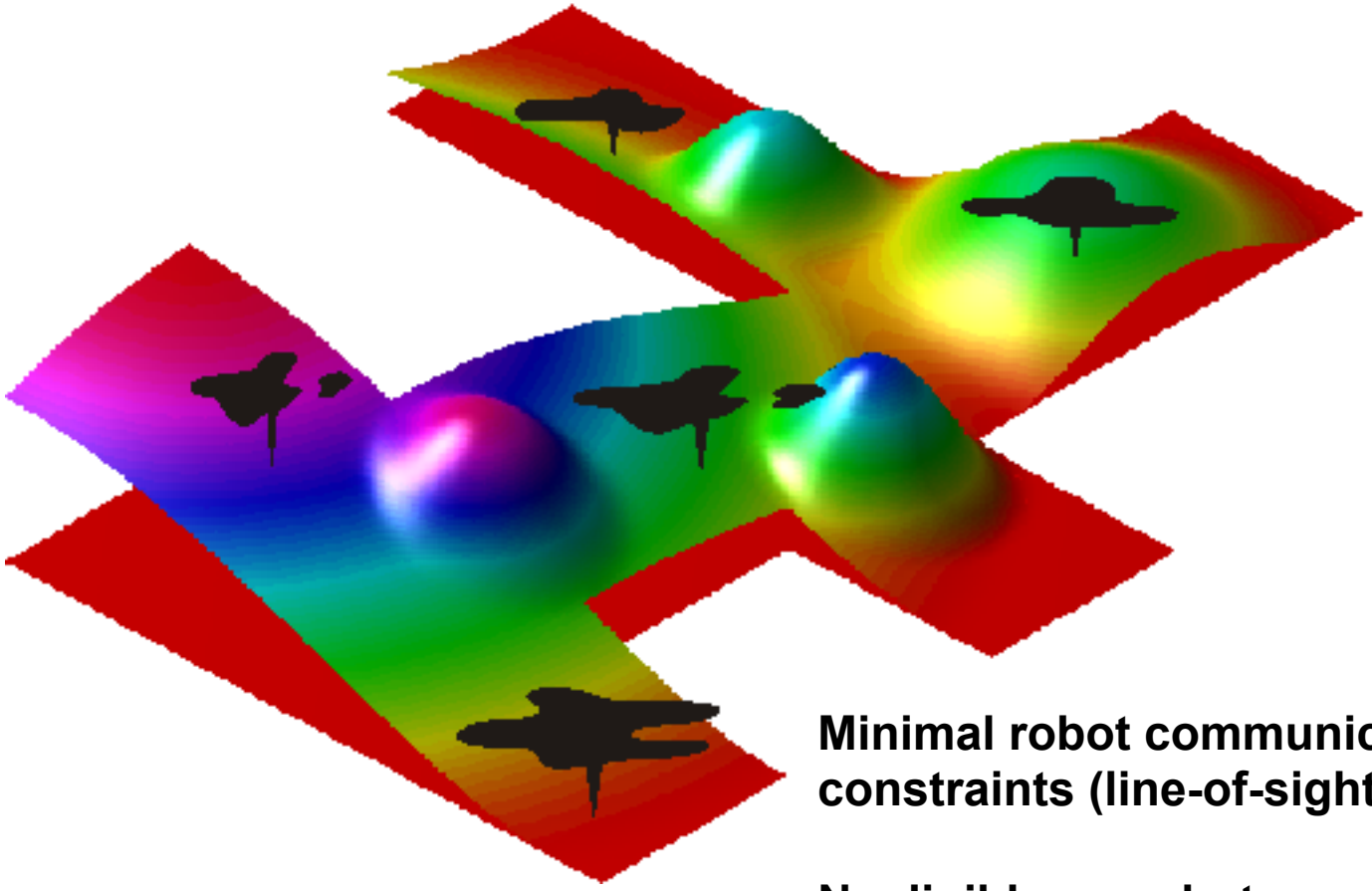
"Cooperative coverage using receding horizon control", Ahmadzadeh et al., ECC'07, pp. 2466-2470





"Cooperative vision-based multi-vehicle dynamic coverage control for underwater applications", Wang, Hussein, CCA'07, pp/. 82-87

Actual Spatial/Temporal Robot Network Environment Description



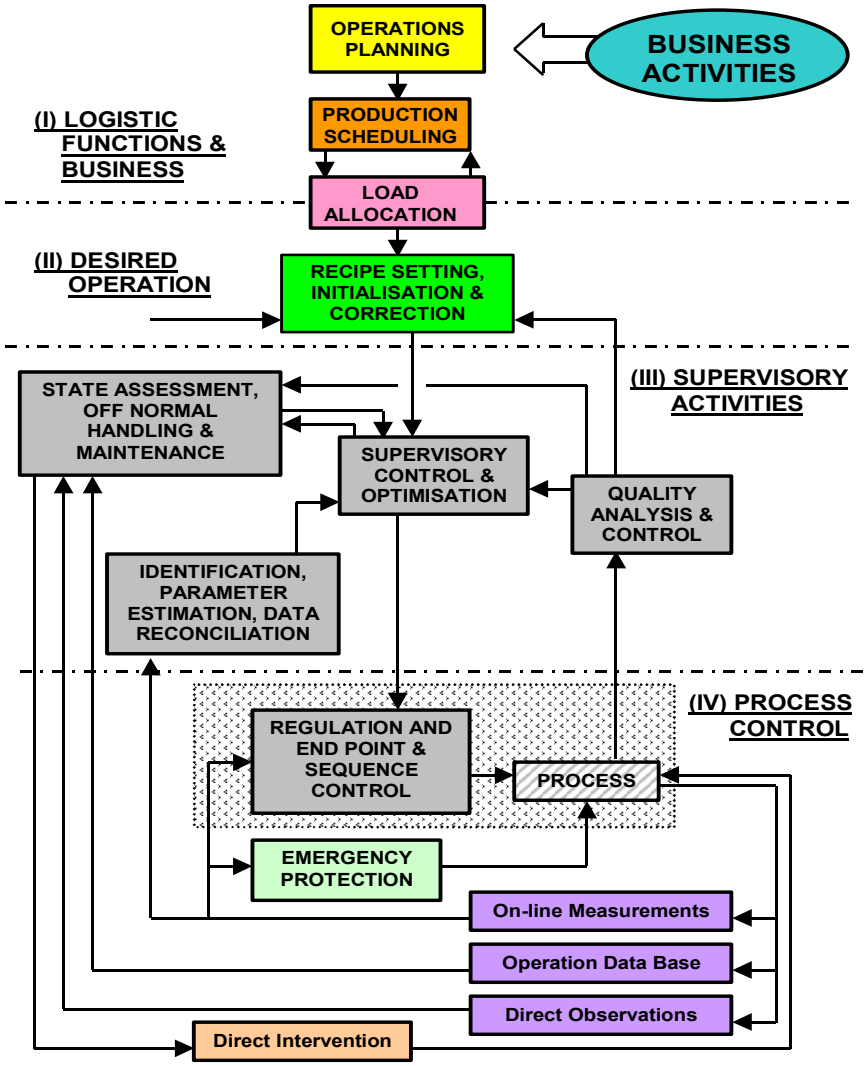
Minimal robot communication constraints (line-of-sight, etc.)

Negligible on-robot energy constraints

CITY UNIVERSITY LONDON

INTEGRATED PROCESS OPERATIONS

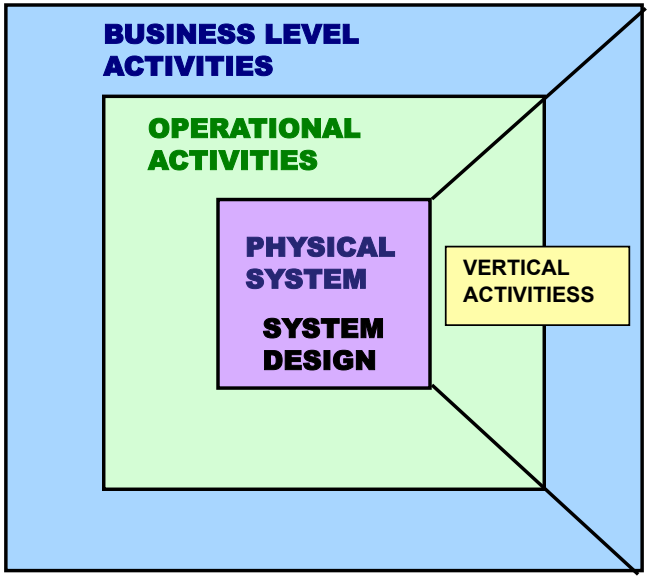
Integrated System



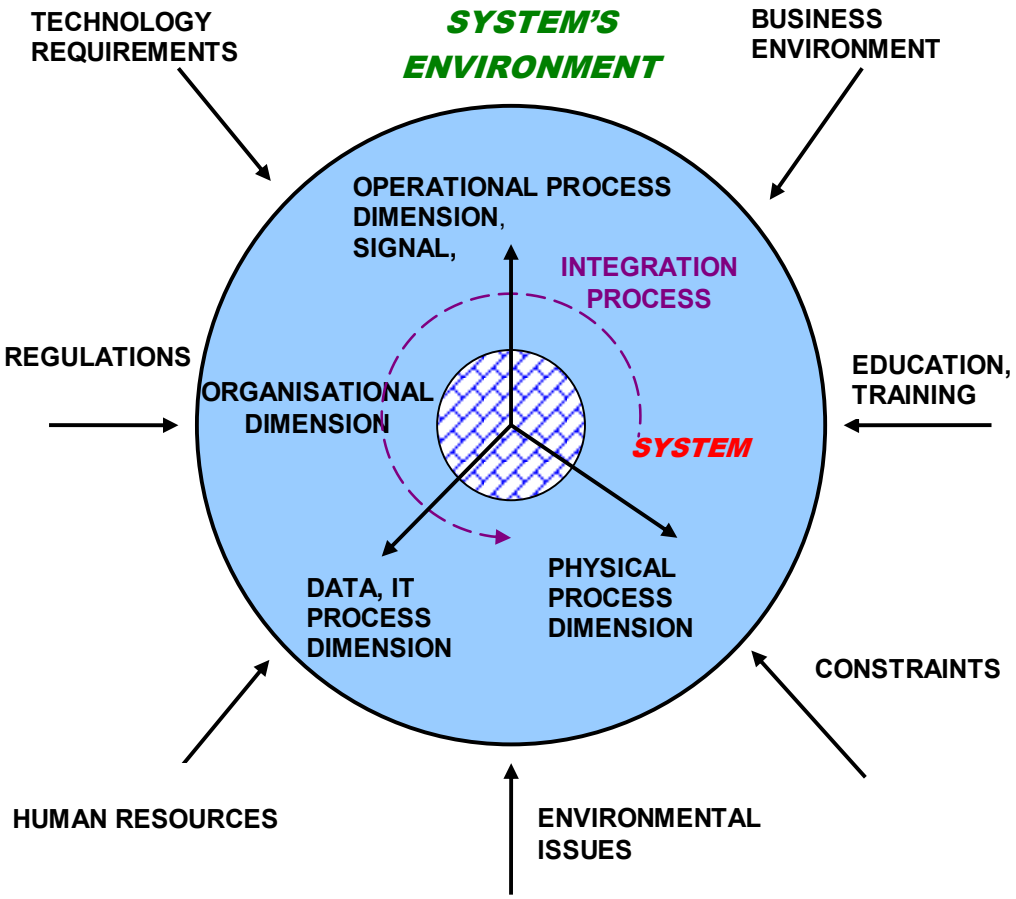
Systems Classification:
Discrete, Continuous, Mixed (Batch)

INTEGRATED SYSTEMS

THE INTEGRATED VIEW OF THE SYSTEM

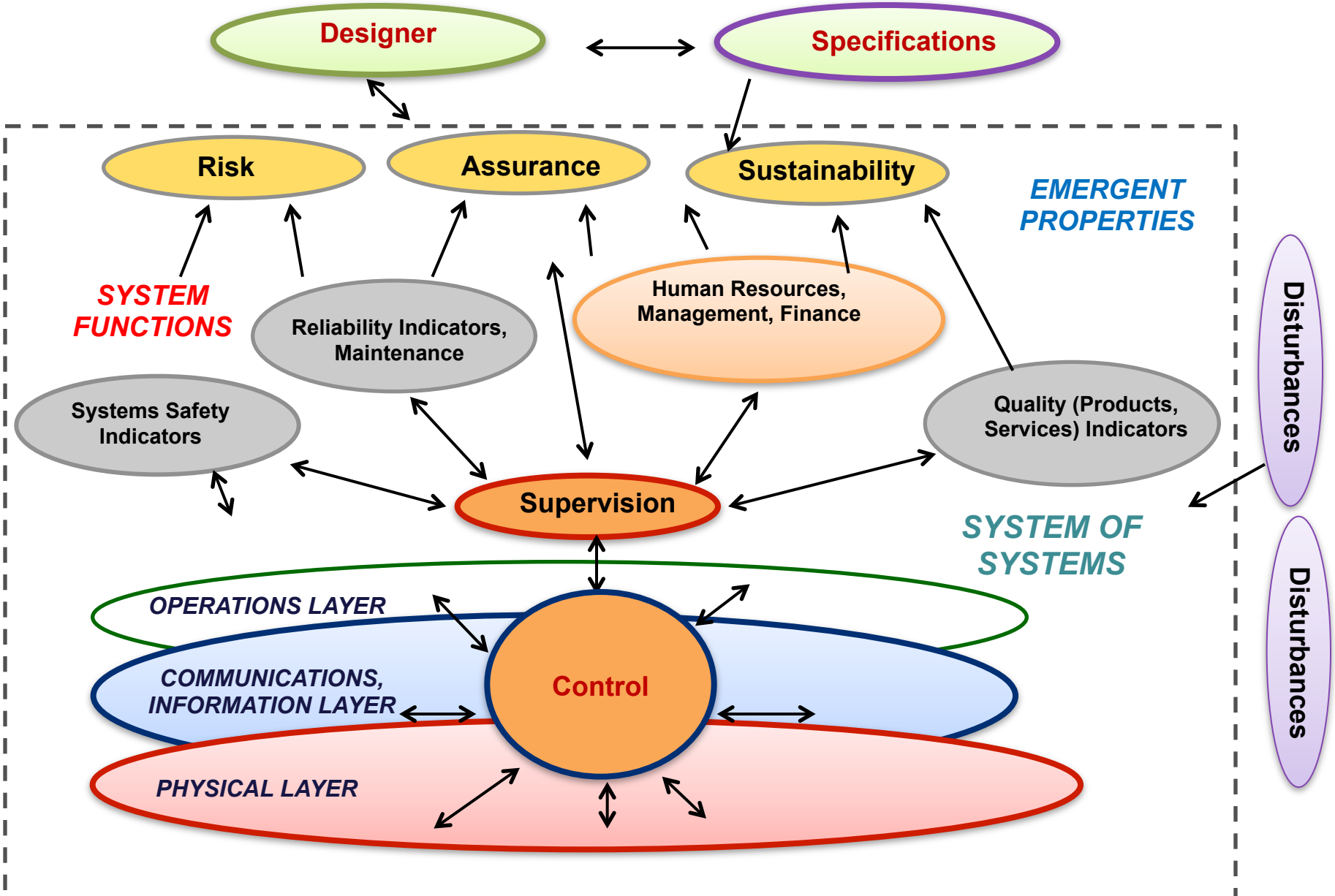


THE SYSTEM MULTIDIMENSIONALITY



CITY UNIVERSITY LONDON

LARGE SCALE INTEGRATED SYSTEM



CITY UNIVERSITY LONDON

System of Systems: Empirical Characterisation

- **SoS:** A meta-system consisting of multiple autonomous embedded complex systems that can be diverse in:

  - ✓ **Technology**
  - ✓ **Context**
  - ✓ **Operation**
  - ✓ **Geography**
  - ✓ **Conceptual frame**

Distinctions

- **An airplane is not SoS, but an airport is a SoS.**
- **A robot is not a SoS, but a robotic colony (a swarm) is a SoS**

CHALLENGES: NEW ROLE OF INTERCONNECTION RULE + NOTION OF THE INTELLIGENT SYSTEM

CITY UNIVERSITY LONDON

THE DEFINITION OF THE SYSTEM

SYSTEM ⟺ **OBJECTS + + INTERCONNECTIONS+ +BOUNDARIES – ENVIRONMENT**

(PURPOSE)

OBJECTS: ⟺ **SUBSYSTEMS, BASIC ELEMENTS**

INTERCONNECTIONS: ⟺ **TOPOLOGY, RELATIONS**

BOUNDARIES: ⟺ **EMBEDDING IN A LARGER SYSTEM**

⇩

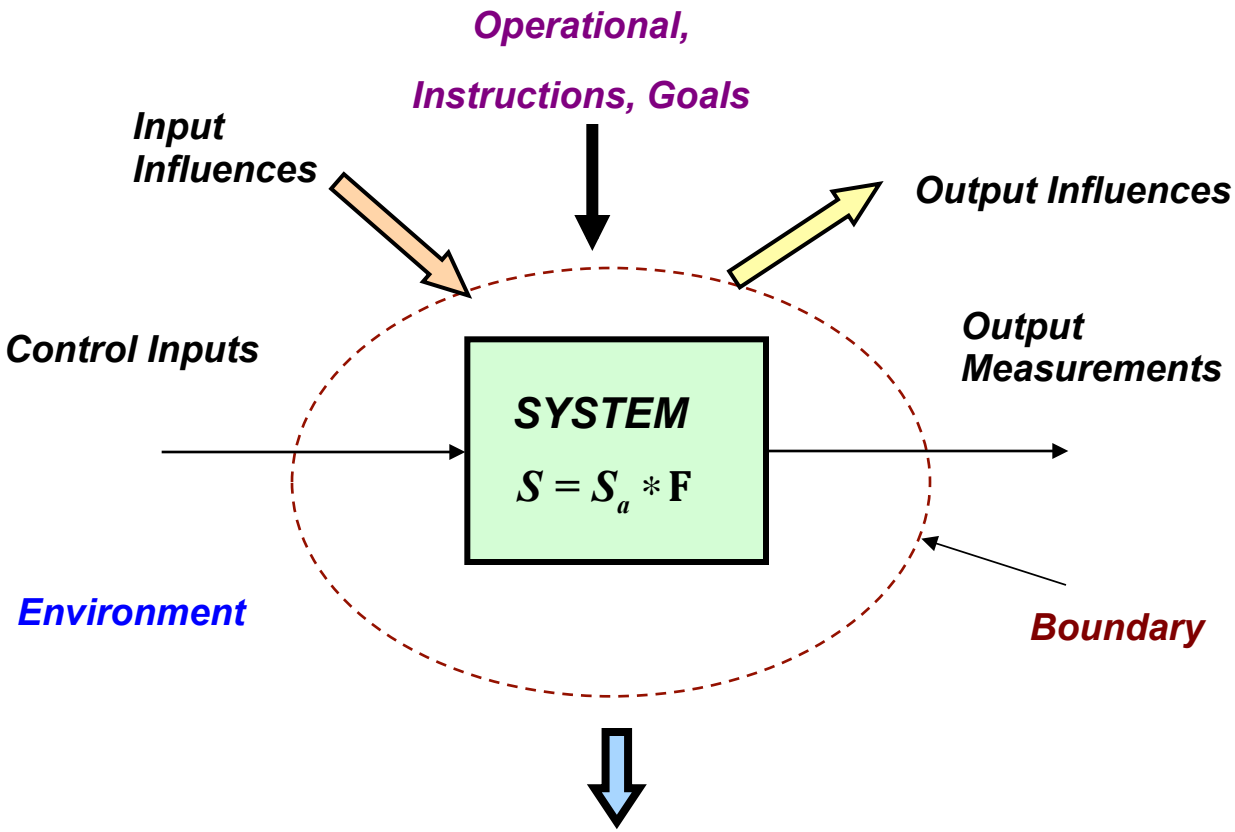
System Behaviour is different than the Aggregate of its parts

⇩

EMERGENT PROPERTIES

CITY UNIVERSITY LONDON

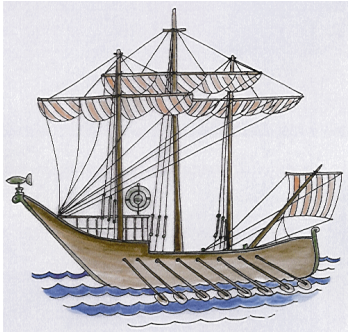
THE SYSTEM: TOPOLOGY, ENVIRONMENT & VARIABLES



EMERGENT PROPERTIES

CITY UNIVERSITY LONDON

KALLICRATIDES NOTION OF THE SYSTEM



BASIC ELEMENTS OF THE DEFINITION

- BASIC ELEMENTS, OBJECTS
- RELATIONSHIPS BETWEEN OBJECTS
- PURPOSE OF THE SYSTEM, GOALS
- SYSTEM ENVIRONMENT

- **The Lakonian, and Pythagorean Kallicratides:**

(*« ! "#$ %$& ' (") *+,μ%($+-»* (Doric dialect in the Anthology of J. Stobaei, Economicos, 16, 485):

> "Any system consists of contrary and dissimilar elements, which unite under one optimum and return to the common purpose".

Examples:

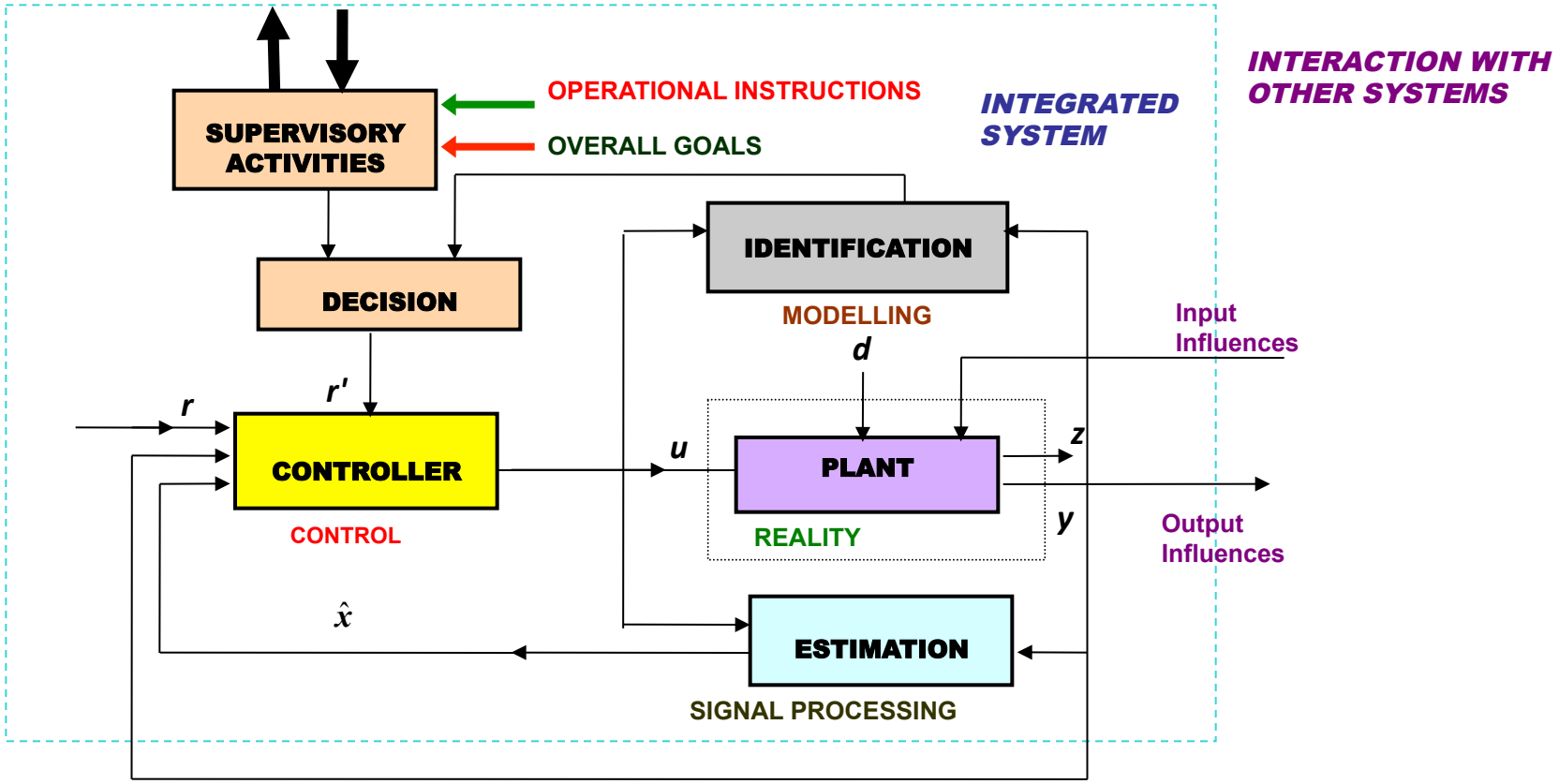
- The system of dance in the singing societies
- The system of the crew in a ship
- The family (the household)

THE INTEGRATED INTELLIGENT SYSTEM

THE INTELLIGENT SYSTEM:

Signal Processing, Modelling, Estimation, Computations Decision Making and Control

AUTONOMOUS INTELLIGENT AGENT



CITY UNIVERSITY LONDON

GENERALISING THE NOTION OF INTERCONNECTION TOPOLOGY

INTERCONNECTION TOPOLOGY FORMS

- **FIXED INTERCONNECTION TOPOLOGY**
  Traditional Composite Systems

- **SYSTEM ORGANISATION**
  Information and Control Structures, Operability ?

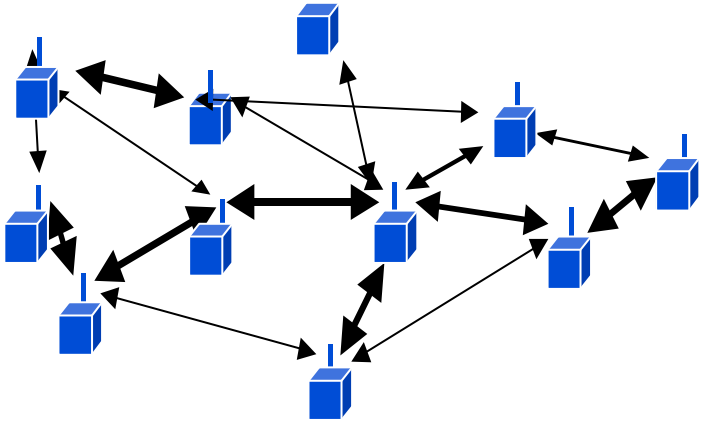
- **EVOLVING INTERCONNECTION TOPOLOGIES ??**
  Lifecycle Problems, Re-engineering

- **AD HOC, STOCHASTIC INTERCONNECTIONS ??**
  Communication Networks

- **NOTION OF SYSTEM PLAY ????**
  System of Systems

CITY UNIVERSITY LONDON

SYSTEM OF SYSTEMS



▲ ***Composite Systems*** : Composite notion

- Subsystems are not necessarily integrated.
- An interconnection topology is defined on the information Structures of the subsystems.

A Collection of independent systems interacting through an interconnection topology which are part of a central goal defining rule / game.

▲ ***System of Systems*** : Composite notion

- Subsystems are integrated systems acting as Independent intelligent agents.

+

- The new notion of the **"play"** is introduced where the subsystems behave as "actors".

+

- A central Goal, frequently associated with a Game is defined where the subsystems participate as agents subject to the constraints of the play.

CITY UNIVERSITY LONDON

SYSTEM PLAY AND ITS DESCRIPTION

SYSTEM PLAY: A RULE, SENARIO DEFINING THE OPERATIONAL RELATIONSHIPS BETWEEN THE INTEGRATED AND INTELLIGENT SUBSYSTEMS

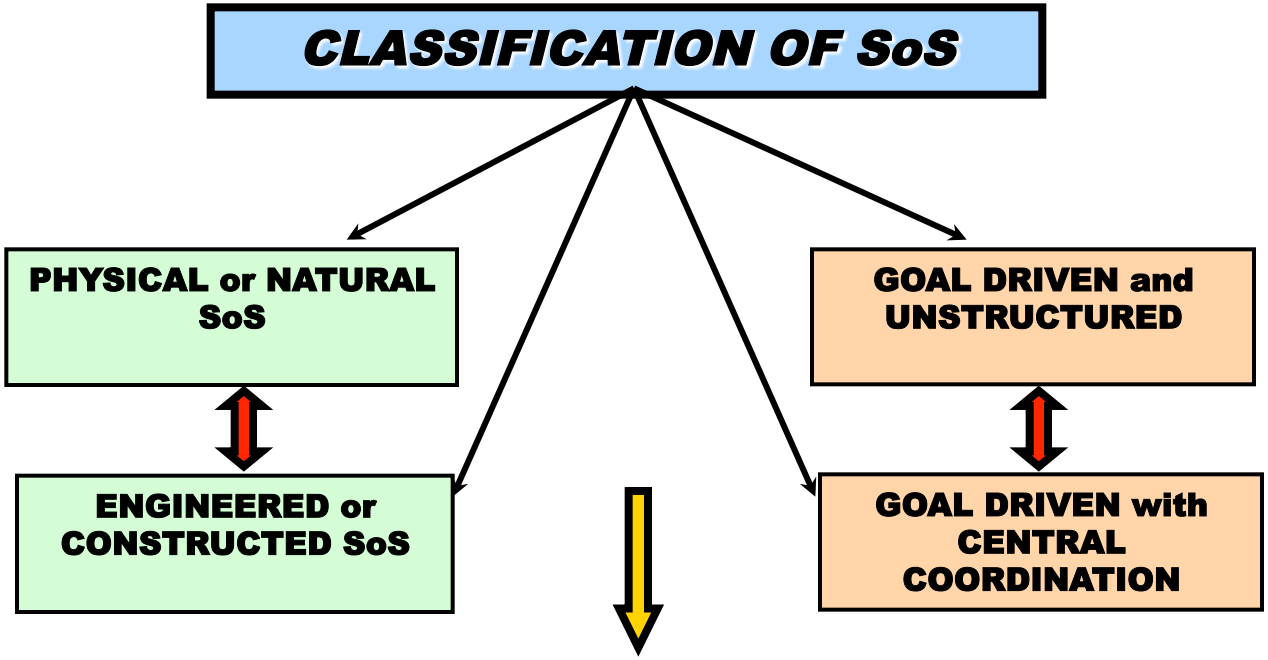
APPROACHES FOR CHARACTERISATION OF THE SYSTEMS PLAY:

- CO-OPERATIVE CONTROL
- MARKET-ECONOMICS BASED COORDINATION TECHNIQUES
- POPULATION CONTROL METHODS
- COALITION GAMES

⋮

CITY UNIVERSITY LONDON

CLASSIFICATION OF SoS

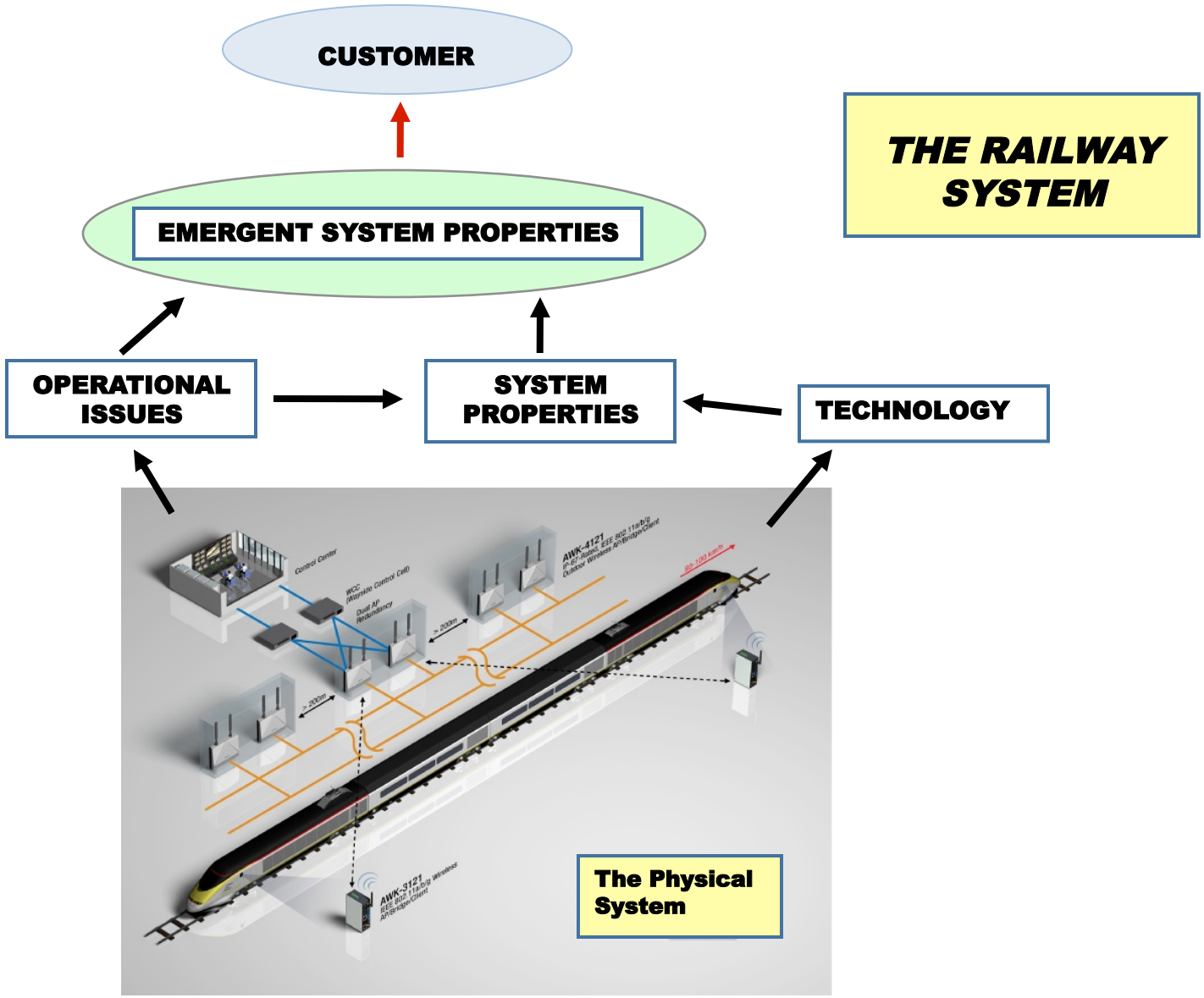


SoS Classification Elements

- ***System Goal***
- ***Systems Organisation***
- ***System Play***

CITY UNIVERSITY LONDON

RAILWAYS AS A SYSTEM OF SYSTEMS



CITY UNIVERSITY LONDON

RAILWAYS AS A SYSTEM OF SYSTEMS

EMERGENT PROPERTIES

- Safety
- Reliability of Service
- Financial Viability, Cost
- Resilience of Operations, Sustainability
- Reduced Carbon Footprint

OPERATIONAL ISSUES

- Timetabling
- Mode of Operations
- Integration with Other Modes
- Pricing of services
- Ownership of the System & Services

THE PHYSICAL SYSTEM

- Infrastructure: Lines, Stations etc
- Signalling
- Rolling Stock
- Human Element

TECHNOLOGY & DESIGN

SYSTEM PROPERTIES

- Improved Track Quality
- Electric & Portable Fuel
- Onboard Energy Storage & Regeneration
- Optimising Energy Efficiency
- Maximising Capacity
- Quality of Ride etc

Customer

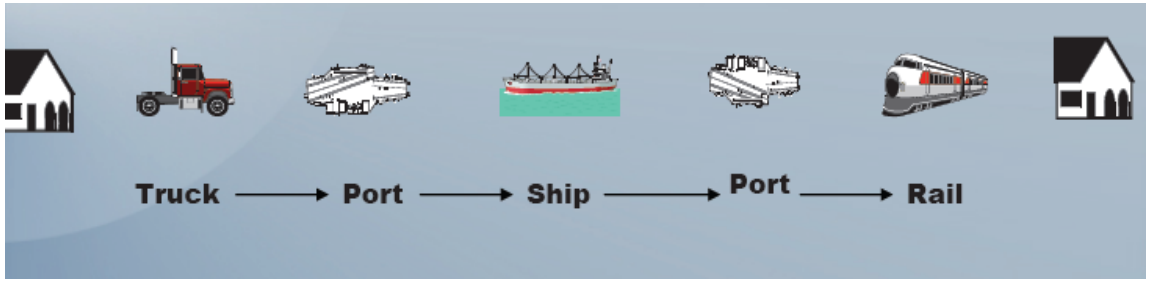
OPERATIONAL SYSTEM LEVEL

THE RAILWAY SYSTEM

PHYSICAL SYSTEM LEVEL

CITY UNIVERSITY LONDON

MULTI-MODAL TRANSPORT SYSTEM



Class: *Multi-Modal Transportation System*	
Attributes:	▲An aggregate of interrelated single mode transportation systems composite systems themselves; ▲The single modes are sustainable functioning systems on their own; ▲There's mission dependency and criticality in the availability of each mode; ▲Constituent systems do not have specialised functions/roles.
Operations:	▲Combination of diverse modes manifests desirable emergent properties such as lower cost, faster transport etc. ▲Emergence is not sustained with the loss of constituents ▲Emergence is weakened when constituents are at fault state ▲Has normal, degraded and failed operational states ▲In an operational context, there's an additional emergency state

CITY UNIVERSITY LONDON

EMERGENT PROPERTIES

Class: ***Emerging Property***	
Attributes:	▲ A physical or virtual feature arising from a whole system ▲ Not present in constituents alone ▲ May be physical or virtual ▲ May not be discernable to the observer ▲ Has varying degrees of strength currently viewed as weak and strong
Operations:	▲ Is context dependent ▲ Is lost when the whole is taken apart ▲ Is weakened or lost when the whole is at fault (in constituent or topology) ▲ Is mainly dependent on critical constituents

CHALLENGE: QUANTIFICATION, MEASUREMENT OF EMERGENT PROPERTIES

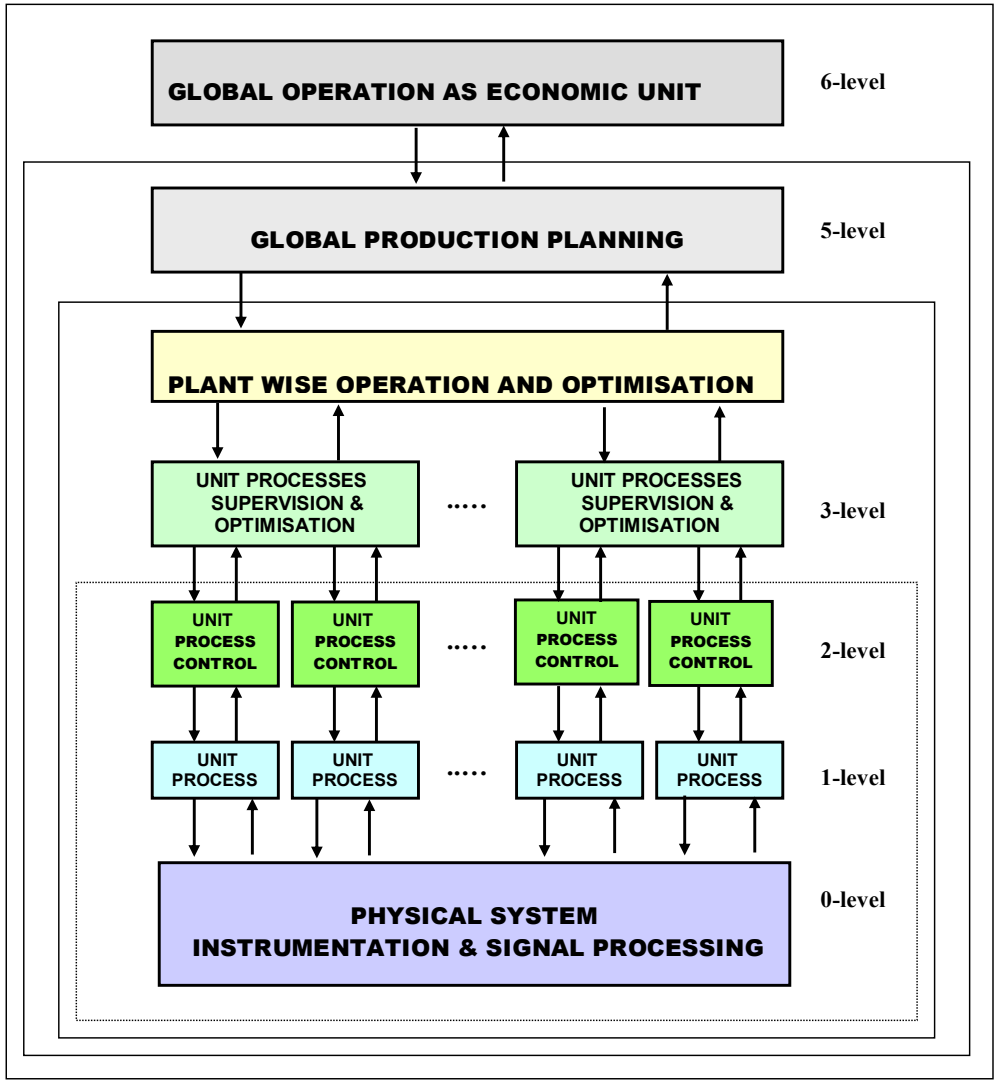
CITY UNIVERSITY LONDON

SYSTEMS ORGANISATION

PROBLEM: ORGANISATION OF INFORMATION AND CONTROL-DECISION MAKING STRUCTURES

CLASSIFICATION:

- HIERARCHICAL ORGANISATION
- HETERARCHICAL ORGANISATION
- HOLONIC ORGANISATION
- OTHERS (BIONIC, GENETIC, FRACTAL, RANDOM)



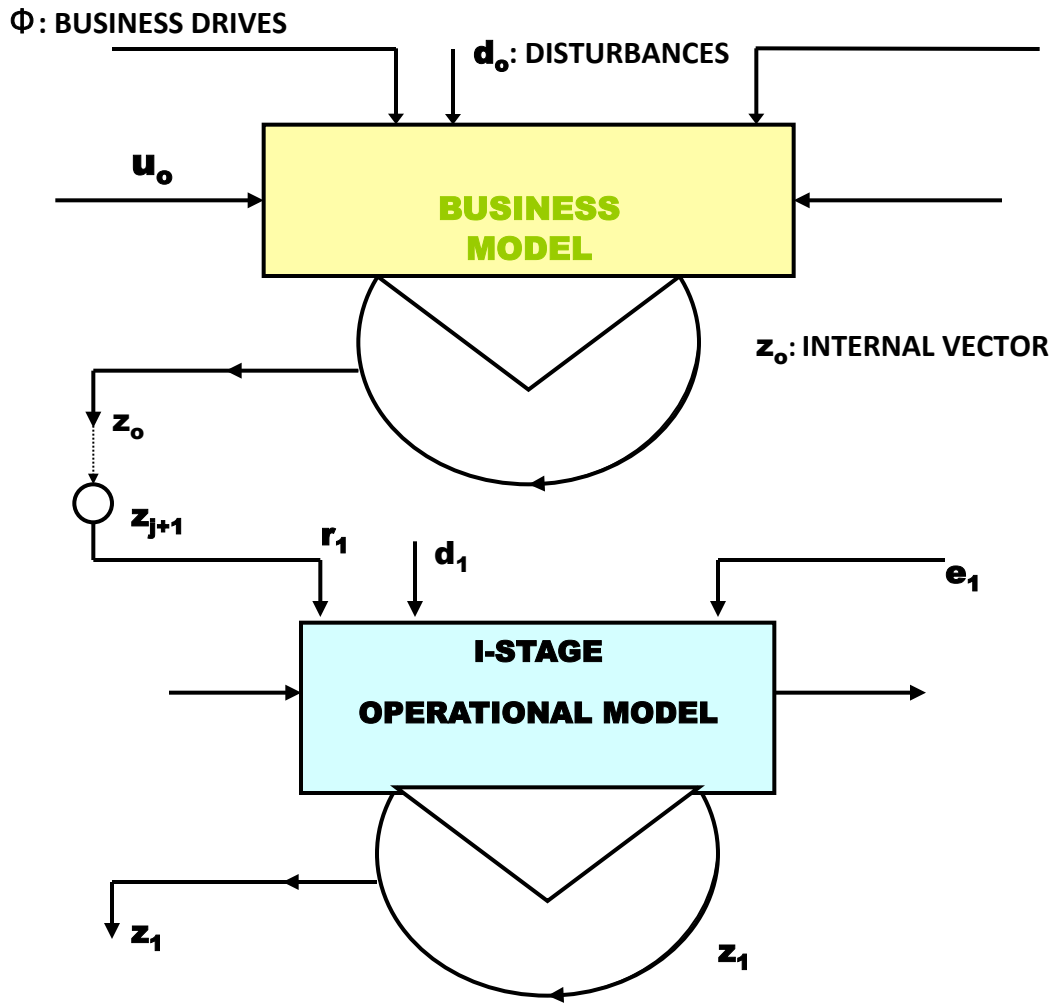
HIERARCHICAL ORGANISATION

CITY UNIVERSITY LONDON

CONTROL ARCHITECTURE IN A HIERARCHICAL ORGANISATION

▲ Integration of Operations in Technological Processes:

- HYBRID SYSTEMS
- "TOP DOWN": GLOBAL CONTROLLABILITY
- "BOTTOM UP"



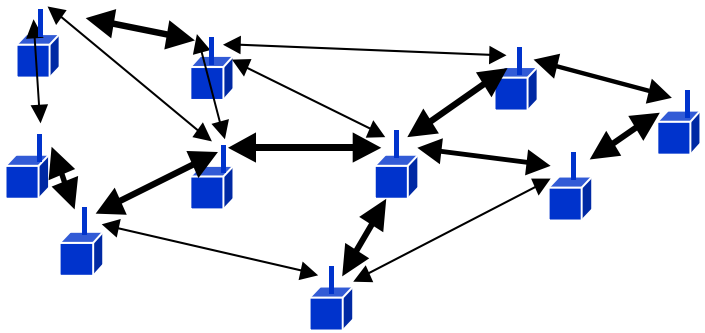
CITY UNIVERSITY LONDON

HOLONICS AND MANAGEMENT OF COMPLEXITY

▲ COMPLEX SYSTEMS ARE PRODUCTS OF AN UNCONTROLLED EVOLUTIONARY PROCESS

▲ REDESIGN REQUIRES MANAGEMENT & REDUCTION OF OVERALL COMPLEXITY

Complex System



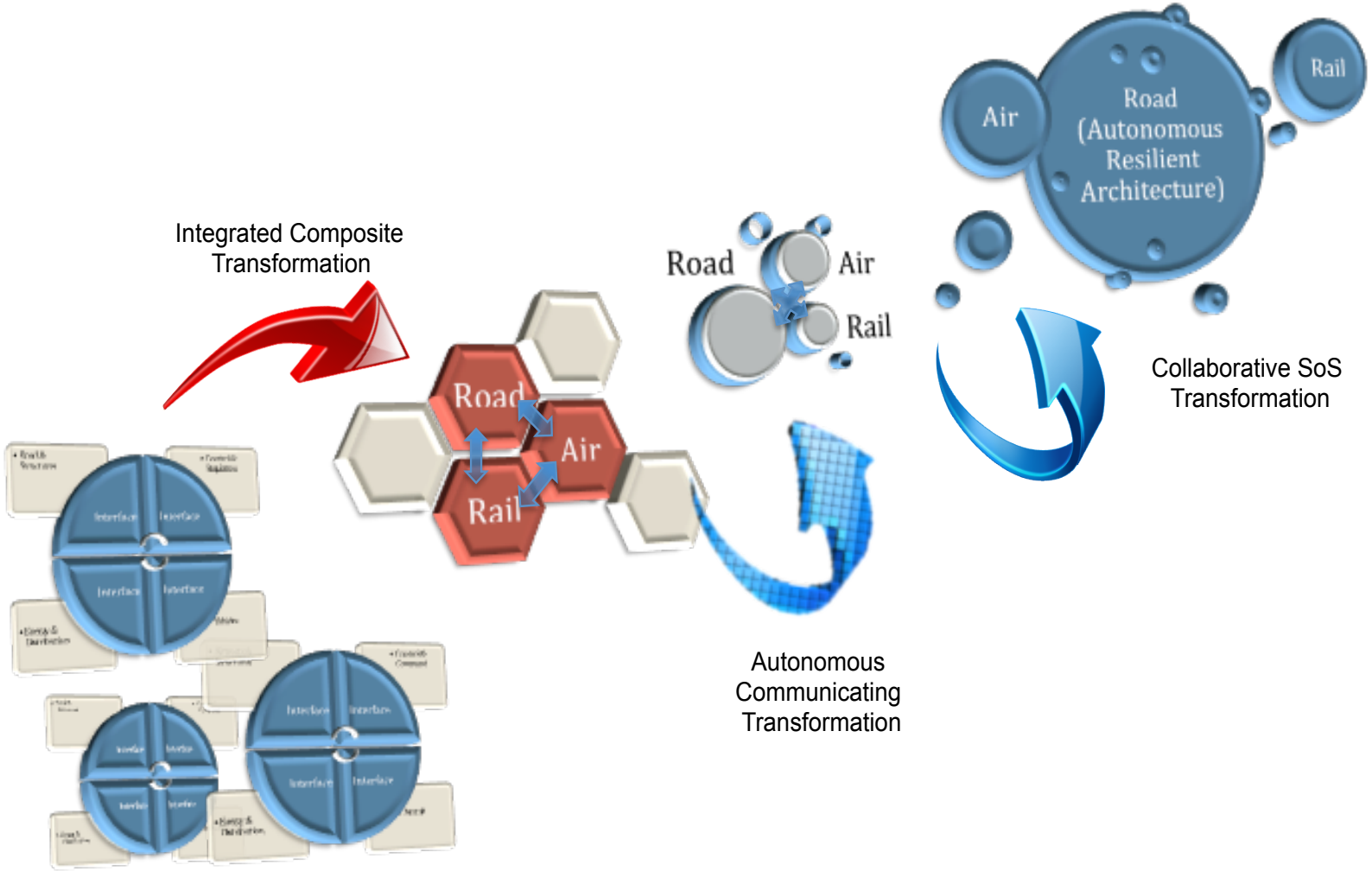
Complex system can arise and survive if they consist of stable, *autonomous* subsystems, each of them capable of surviving disturbances, but that are meanwhile able to *cooperate* to form a more complex, stable system (Arthur Koestler)

HOLONIC ORGANIZATION: Highly distributed organization of subsystems, where intelligence is distributed over the individual entities, subsystems, which are cooperative, intelligent, autonomous modules, called "holons." The subsystems work together in temporary hierarchies, the "holarchies" to achieve a global goal.

"Holon'": A combination from the Greek *holos,* meaning "whole" with the suffix -an, which, as in proton or neutron, suggesting a particle or part (Arthur Koestler)

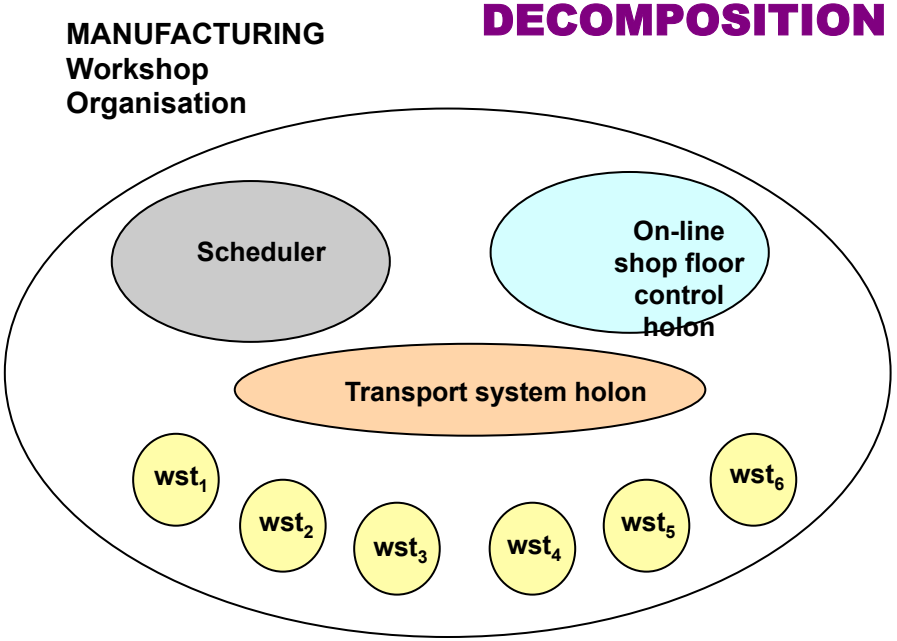
CITY UNIVERSITY LONDON

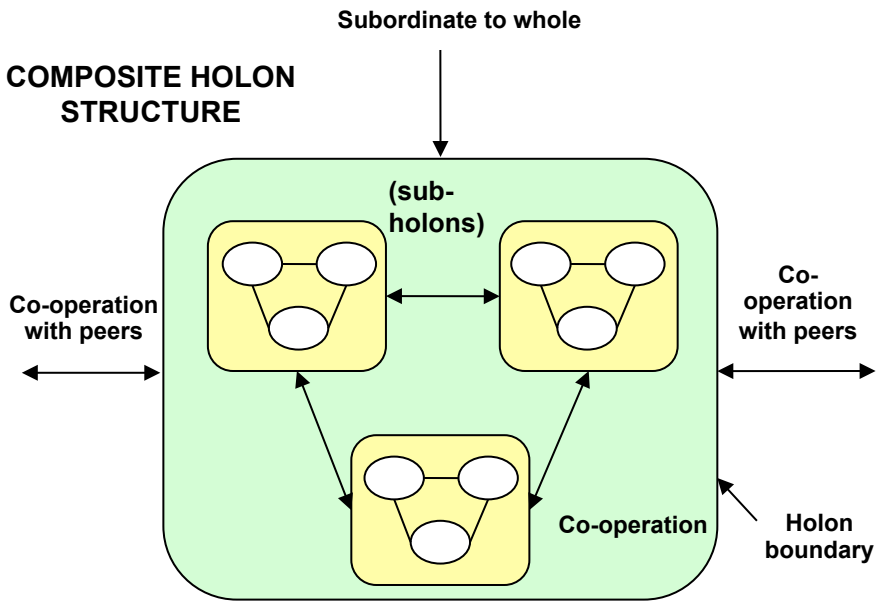
EVOLUTIONARY SoS TRANSFORMATION ROADMAP



HOLONIC DECOMPOSITION & COMPLEXITY

COMPLEX SYSTEM DECOMPOSITION





HOLONIC ORGANIZATION: Preserves the stability of a hierarchy while providing the dynamic flexibility of a heterarchy and combines high performance with robustness against changes and disturbances.

CITY UNIVERSITY LONDON

COMPLEX SYSTEMS : SoS & SES THEORY CHALLENGES

▲ STRUCTURE EVOLVING SYSTEMS:

- REPRESENTATION OF FORMS OF EVOLUTION
- ANALYSIS & DESIGN OF LARGE SCALE INTEGRATED SYSTEMS
- INTEGRATING "TOP DOWN" & "BOTTOM-UP" APPROACHES
- EARLY-LATE DESIGN AND SYSTEM EVOLUTION
- ORGANISATION OF CONTROL & INFORMATION STRUCTURES, & DECENTRALISATION
- DESIGN UNDER UNCERTAINTY
- REDESIGN AND SYSTEM RECONFIGURATION

▲ SYSTEM OF SYSTEMS:

- THE REPRESENTATION PROBLEM
- FROM UNDERSTANDING TO EMERGENCE & DIAGNOSTICS
- REDUCTION AND MANAGEMENT OF COMPLEXITY BY HOLONIC ORGANISATION
- GAME THEORY & DESIGN METHODOLOGIES
- SYSTEMS INTEGRATION: DESIGN, OPERATIONAL & BUSINESS ASPECTS

CITY UNIVERSITY LONDON

COMPLEX SYSTEMS CHALLENGES FOR TECHNOLOGICAL PROCESSES

- SYSTEMS Integration of Design, Operations & BUSINESS ASPECTS OF TECHNOLOGICAL PROCESSES
- SYSTEM OF SYSTEMS: FROM UNDERSTANDING TO DESIGN METHODOLOGIES
- ORGANISATION OF CONTROL & INFORMATION STRUCTURES, & DESIGN OF DECENTRALISATION
- REDUCTION AND MANAGEMENT OF COMPLEXITY BY HOLONIC ORGANISATION
- ANALYSIS & DESIGN OF LARGE SCALE INTEGRATED SYSTEMS: COMBINING THE "TOP DOWN" & THE "BOTTOM UP" APPROACHES
- DESIGN UNDER UNCERTAINTY
- OPERATIONAL FLEXIBILITY, REDESIGN AND SYSTEM RECONFIGURATION

⋮

CITY UNIVERSITY LONDON

SELECTED REFERENCES

N. KARCANIAS, 1994. "The selection of input and output schemes for a systems and the Model Projection Problems", KYBERNETICA, Vol. 30, No. 6, pp 585-596, 1994.

N. KARCANIAS, 1994. "Global Process Instrumentation: Issues and Problems of a System and Control Theory Framework", Measurement, Vol.. 14, pp 103-113.

N. KARCANIAS, 1995. "Integrated Process Design: A Generic Control Theory/Design Based Framework", Computers in Industry, Vol. 26, pp 291-301.

N. KARCANIAS, 1996. "Control Problems in Global Process Instrumentation : A structural Approach". Computer Chem. Engin., Vol.. 20, 1101-1106, 1996

N. KARCANIAS, 2008. ""Structure Evolving Systems and Control in Integrated Design" IFAC Annual Reviews in Control, Volume 32, Issue 2, December 2008,pp 161-182;

A.G. HESSAMI and N. KARCANIAS, 2010. "System Assurance, Complexity and Emergence: The need for a Systems Based Approach" in "Communications in Computer and Information Science, Springer, Editors: Sérgio Tenreiro de Magalhães, Hamid Jahankhani and Ali G. Hessami; Volume 92, 2010, pp 202-215; DOI: 10.1007/978-3-642-15717-2

N. KARCANIAS and A.G. HESSAMI, 2011. "System of Systems and Emergence. Part 1: Principles and Framework", Part 2: Synergetic Effects and Emergence" Proceedings of ICETET 2011, 4th International Conference on Emerging Trends in Engineering and Technology, SV129, November 18-20, Port Louis, Mauritius.