Citation: Karcanias, N., Hessami, A. G. & Alonso, E. (2015). Complexity of Multi-Modal Transportation and Systems of Systems. Paper presented at the 47th Annual Universities' Transport Study Group Conference (UTSG 2015), 24 Dec 2014 - 5 Jan 2015, London, UK.

Complexity of Multi-Modal Transportation and Systems of Systems

Prof Nicos Karcanias
Head of the Systems and Control Research Centre
City University London

Prof Ali G. Hessami
Director of R&D and Innovation
Vega Systems

Dr Eduardo Alonso
Deputy Head of the Department of Computer Science
City University London

Abstract

The multi-modal transportation comprising diverse infrastructures, means & operations, energy resources, rules & regulations and a broad community of stakeholders constitute a complex yet real candidate for formalisation, analysis and optimization. It is shown that the complexity of the system is best described by viewing the challenges of its complexity as a *System of Systems (SoS)*. The objective of this paper is to make an attempt to define and formalise the loose concept of "System of Systems" within the standard framework of Systems Theory and exploit this new theoretical foundation as a basis for understanding, characterisation, evaluation, assessment and management of complexity, relationships and optimal performance in a multi-modal transportation context. The longer term objective is to develop a robust systems framework for scientific treatment of requirements, constraints, risks, resilience, capacity, performance and trade-offs in multi-modal transportation setting.

1. The Problem

In the last ten years a lot of interest has been given to the concept of *"System of Systems"* [26], [27] which has emerged in many and diverge fields of applications. The term has been linked to problems of complex nature, but so far it has been used in a very loose way, by different communities with no special effort to give it a precise definition and link it to the rigorous methodologies, concepts and tools of the Mathematical System Theory. Establishing the links with the traditional approaches is essential, if we are to transfer and appropriately develop powerful and established analytical tools to a field that is unstructured and where very little progress has been made as far as development of a generic and unifying methodology. The area of Transportation has a number of challenging problems which may be addressed within the new framework of *"System of Systems" (SoS)*. Studying complex problems in Transportation such as increasing capacity of transportation systems under increased demand and strict financial constraints requires methodologies for System Segregation, which really implies development of methodologies for complex system problem decomposition, as well as understanding deeply the implications of the *"System of Systems"* nature of many of the transportation problems. The main objective of this paper is to make an attempt to place the loose concept of *"System of Systems"* within the standard framework of Systems Theory [17], [18], [19] that is suitable for some further formal development and then relate the concept to issues related to transportation. To achieve this, we need to demonstrate the links and highlight the differences with the well established concepts, developed for the traditional engineering paradigms and analyze the context of the emerging paradigms. A central issue to the study of *"System of Systems"* are issues of decomposition of such problems in a way that facilitates their study. Possible ways to achieve this is to understand the challenges of the *SoS* nature of the problem and deploy concepts from Intelligent Manufacturing and in particular the *Holonic Manufacturing paradigm* [37].

We approach the study of *Multi-Modal Transport System* (*M-MTS*) as a *SoS* by examining a number of particular features which give it this distinct character. As such, the paper also considers a new approach to *SoS* characterisation, which describes the complexity aspects of a Multi-Modal Transport System. This is essential to identify the elements of deviation of *M-MTS* linked to the new paradigm, referred to as *SoS*. Given that the new notion appears frequently in the context of *Complex System* studies, we also consider issues related to the classification of the different notions of complexity emerging in engineering studies. The term *Complex Systems* is used by different communities with very diverge interpretations of the notion. Classifying the different aspects of system complexity is important, in placing the features of the new notion in the context of systems complexity. To define the notion of *"System of Systems"* it is essential to explain its differences with the standard notion of *"Composite Systems".* It is worth noting that there are many similarities between complexity issues in *M-MTS* and similar problems in *Integrated Manufacturing System* (*IMS*) [6], [25].

Reviewing *SoS* issues in Integrated Manufacturing provides useful information and knowledge that can be used in the context of *M-MTS.* We then examine the multi-modal transportation systems' attributes and characteristics against the notions of "*System of Systems"* and attempt to demonstrate the way the traditional composite system view has to be modified to cover the new notion. An issue linked to the study of *SoS* is the complexity of interactions between the components of the new entity. Some ideas from *Holonic Manufacturing* may be used to address the problem of system decomposition lying at the heart of the study of complexity of transportation problems. The new interpretation sets the scene for a fresh perspective on the understanding, exploitation, optimisation and assurance in multi-modal transportation paving the way to enhance throughput and resilience in these complex real-time systems.

2. The Multi-modal Transportation System

The development of a systems framework for general systems is not a new activity [17,18]. However, such developments have been influenced predominantly by the standard engineering paradigm and as a result they failed to cope with new paradigms such as those of the business processes, data systems, biological systems, and emerging complex systems paradigms.

Our task here is to reconsider existing concepts and notions from the general Systems area [19], detach them from the influences of specific paradigms, generalise them appropriately to make them relevant for the new challenges and then use them to define the notion of *"System of Systems"* and deploy them to the study of *Multi-Modal Transport System* (*M-MTS*). We follow a conceptual systems approach that may lead to formal notions as described in [30].

Some transportation systems such as air transportation are considered as complex real-time system of systems comprising an extensive suite of stakeholders, support and operational systems and operational procedures. The distributed networked nature of these systems manifests characteristics and emergence that are hybrids of composite and system of systems. Multi-modal transportation involves deployment of more than one mode of transport in the delivery of the service by the *Mluti-Modal Transport Operator* (MTO). This may involve any combination of road, rail, sea and air transportation as the logistics and economic requirements dictate. This offers a number of benefits typically comprising loss minimisation at shipment points, faster more efficient transport, higher reliability, simplified documentation, cost reduction and improved transit time to name a few.

We examine the multi-modal transportation as a potential hybrid system aiming to identify architectural, structural and behavioural adaptations that can lead to enhancement of their emergence as a system of systems. A class definition for this hybrid form of transportation aiming to distil key characteristics, which require further enhancement to render system of system qualities, is given in Table 1.

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

Table 1: The definition of a Multi-Modal System as a UML Class

An urban transportation system comprising road (cars and buses) and rail (metros and regional railways) requires high degrees of resilience and availability as a public dependable service. The challenge lies in the identification of features and interfaces that can transform a composite yet poorly coordinated system of transportation modes into a cooperative system of systems. Recognising similarities between *M-MTS* and other areas of complex engineering, such as the Integrated Manufacturing System (*IMS*), provides useful concepts and experience with the potential to enhance our understanding of complexity in *M-MTS.*

3. Integrated Manufacturing and its Similarities to Multi-Modal Transport Systems

The problem of "Integrated Manufacturing System" (*IMS*) has similar complexity issues to *M-MTS.* We consider the paradigm of continuous processes [6], [23] which are selected because they contain almost all challenges that emerge in complex system formation. They are characterised by strong couplings between the different technical operational stages, as well as enterprise issues on one hand and design – redesign problems [24], [25] on the other. The overall integrated manufacturing system seen from the outside business world (the system environment) may be represented by the following diagram [7]

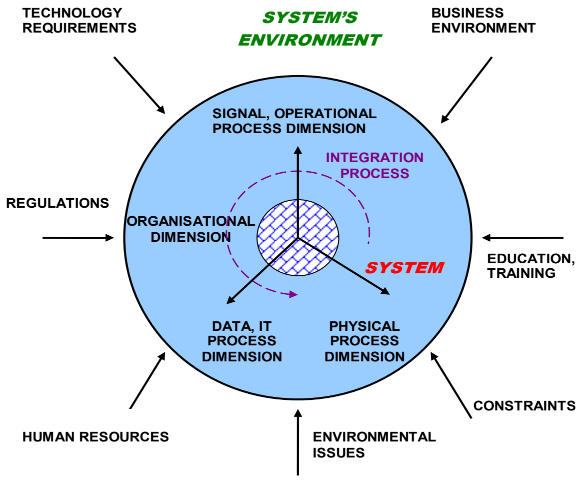

Figure 1: Basic System Shell of Manufacturing Integration

where activities are grouped in the four main dimensions which in general interact strongly between themselves. Such a system, viewed externally, demonstrates features of a complex system, but seen from the inside may be viewed as a *system of systems* with strong interactions between the subsystems. The main dimensions, of this complex system are: (i) Physical Process Dimension; (ii) Signals, Operations Dimension; (iii) Data, IT, Software Dimension; and (iv) Organisational Dimension.

The Physical Process Dimension deals with the physical process itself and the traditional views of the Engineering Process. The Signals, Operations Dimension is concerned with the study of the different operations, functions based on the Physical Process and it is thus closely related to operations for production. Such processes were designed in the past as independent systems with minimal interactions with the physical process. The extensive use of IT has increased considerably the interaction between these processes and the physical system. Signals and information extracted from the process are the fundamentals and the problem of integration is concerned with understanding the connectivities between the alternative operations, functionalities and having some means to regulate the overall behaviour. The different functionalities, processes introduced are integrated to the physical system itself and become IT system representations of these processes. Both design and operations generate and rely on data and deploy software tools and the processing of data introduces additional systems, which are strongly linked to the management of the different processes and the physical system itself. Compatibility and consistency of the corresponding data structures and software tools expresses the problem of connection of IT systems. There are different ways of organising the interaction of the different functionalities and their IT representations with the physical process and this expresses the organisational dimension of the overall system. The latter represents a way of linking processes and expresses a higher level of “*connection topology”* that will be referred to as *complex system organisation.*

Additional issues of complexity in *IMS* are due to hierarchical forms of organisation, present in most of the cases of continuous process systems characterised by a hierarchical nesting architecture [7], [16]. An overview of the *M-MTS* is given in the diagram in Figure 2, where we clearly distinguish the lower physical layer referred to as *transport networks* (including, infrastructure, communications, data), the operational referred to as *multi-modal transport scenario,* a number of *emergent properties*, such as safety, risk, assurance and finally the control structure represented by the *co-ordinator*. The physical layer has distinct topologies and interaction is introduced through the tasks which have to be performed as part of the execution of a *multi-modal transport scenario.* Note that the study of emergent properties is complicated due the strong interactions introduced at the higher level due to the non-simple relation between emergent properties and the physical and operational layers. The complexity of such interactions may be explained by analysing the *SoS* structure of *M-MTS.*

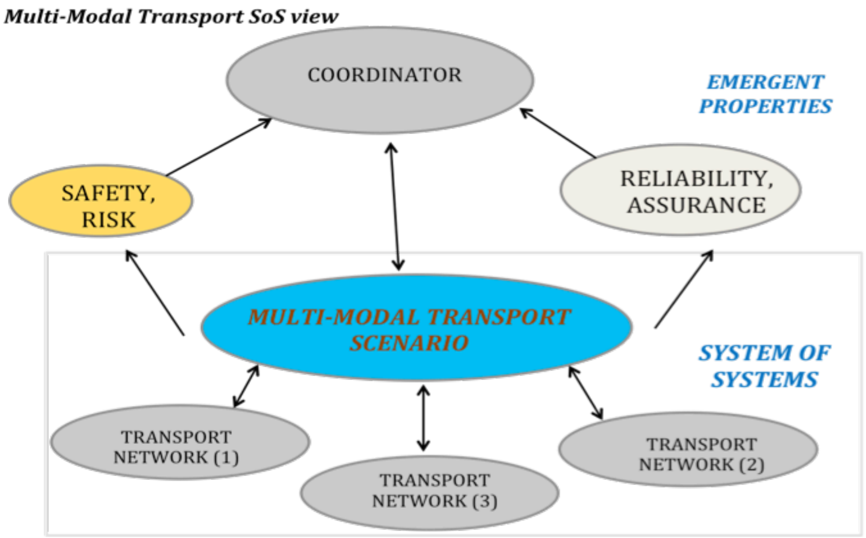

Figure 2: Multi-Modal Transport as an *SoS*

4. Systems, Complexity and Emergent Properties

The definition of a system that is given here is rather general and aims to encompass many paradigms (including the traditional engineering and business ones).

Definition (1) [18], [19]**:** A ***system*** is an interconnection, organisation of objects that is embedded in a given environment.

This definition is general and uses as fundamental elements the primitive notions of: *objects*, *connectivities – relations* (topology), and *environment*. The notion of property, or attribute is central to a system and has intrinsic and extrinsic dimensions. An intrinsic property relates to the class of features and characteristics which is inherent and contained wholly within a physical or virtual object. The extrinsic properties are those which are not part of the essential nature of things and have their origin outside the object under scrutiny. Within the context of a system, an emergent property that is an extrinsic one is not an intrinsic property of any constituent of that system, but is manifested by the system as a whole. In a similar vein to employing the tools of systems science to define the system above, the concept of emergence is also captured as a UML Class in Table 2 [40].

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 at fault (in constituent or topology) • Is mainly dependent on critical constituents

Table 2: The definition of emergence/emergent property as a UML Class

The term "*Complex Systems"* is a generic term used to describe some of the major challenges in Science and its applications, Engineering, Biological Applications, Business, Society, Environment, etc. The term refers to problems which may be of large or small scale, centralised or distributed, have a composite nature (in terms of simpler sub-problems), high degree of interaction between subsystems, manifest a multi-facet behaviour (in terms of particular aspects), have possibly an internal organisation, demonstrate special features that may be referred to as "system of systems" and require a multidisciplinary approach for their study. It is thus clear that complexity has many different dimensions and gaining understanding for each of these dimensions is critical in developing approaches for complex systems. Systems Integration emerges as the general task that can co-ordinate the activities in the particular sub-problem areas to produce solutions which are meaningful and optimal (in some sense) for the whole. The opposite to integration is the system decomposition aiming to reduce complexity and thus manage in a better way the development of solutions to problems defined on them. The development of a systemic approach for complex problems is a major challenge. This requires ability to specialise the set of global objectives to the level of the subsystem, methods to work out solutions which are locally and globally feasible and in a sense optimal, as well as understanding of interactions between the subsystems and alternative aspects of the overall problem. Systems integration and system decomposition are multi-task, multidisciplinary problems which are central in handling the major challenges in technology, transport, economy, society, and environment.

A major classification of such systems are to those linked with *physical processes* (physics, biology, genetics etc) and those which are *man-made* (engineering, technology, management, software etc) and deal with the *"macro level"* technology. Each of the above classes has its own key paradigms, specific problems, concepts and methodologies. There exist however generic common paradigms amongst the different domains which are handled by domain specific methodologies and tools. One such common paradigm is that of systems with an evolving structure and referred to as *Structure Evolving Systems (SES)* [4] and this research is influenced by the need to address life-cycle issues. Such a class of systems emerge in natural processes of biology, genetics, crystallography etc and in man-made processes such as engineering design, networks and communications, power distribution, management, supply chain, finance and data processes. For such systems the basic processes (subsystems), and/or the interconnection topology may vary within the life-cycle of the system. In the context of the above complex system applications we may identify forms of complexity, which include [40]:

- Lack of knowledge, or difficulties in characterising the behaviour of the basic process, or sub-processes (*Unit Behavioural Complexity*).
- Complexity of computational engine associated with a sub-process (*Computational Complexity*).
- Difficulties in characterising the interconnection topology of sub-processes and/or variability, uncertainty of this topology during the system lifecycle (*Interconnection Topology Complexity*).
- Organisational alternatives for the functioning, information and decision making (control) structures in respond to goals and operational requirements (*Organisational Complexity*).
- Variability, uncertainty and multi-level couplings in the system's organisation which create difficulties in describing the overall system organization (*System of Systems Complexity*).
- Large scale dimensionality and possibly multi-component character that impacts on methodologies and computations (*Large Scale – Multi-component Complexity*).
- Heterogeneous nature of sub-processes, which in a given interconnection topology, results in hybrid forms of overall behaviour (*Hybrid Behavioural Complexity*).
- Variability and/or uncertainty on the system's environment during the lifecycle (changing goals, requirements, disturbances, structural changes) which require flexibility in organisation and operability (*Lifecycle Complexity*).

Clearly, *M-MTS* are Large Scale Systems which have been under study for many years [5]; here we will consider the special features that give them the special form of complexity referred to *System of Systems Complexity,* which describes many of the features emerging in the family of *M-MTS.*

5. The System of Systems Notion in Comparison to the Composite Systems

An aggregate of systems leads to the creation of new forms of systems which may be either described within the framework of *Composite Systems* (*CS*)*,* or demonstrate additional features which add complexity to the description and may be referred to as *System of Systems* (*SoS*). The term "*System of Systems"* has been used in the literature in different ways and a good treatment of the topic is given in [27]. Most definitions ([27], [28], [29], [30]) describe features or properties of complex systems linked to specific examples. The class of systems exhibiting behaviour of Systems of Systems typically exhibit aspects of the behaviour met in complex systems; however, not all complex problems fall in the realm of systems of systems. Problem areas characterized as System of systems exhibit features such as [35]:

- Operational Independence of Elements
- Managerial Independence of Elements
- Evolutionary Development
- Emergent Behaviour
- Geographical Distribution of Elements
- Inter-disciplinary Study
- Heterogeneity of Systems
- Networks of Systems

A literature survey and discussions on these characteristics are given in [27], [28], [29]. A more generic definition that captures the key features and which is a good basis for further development is given below [27]:

Definition (2): (i) *Systems of Systems are large-scale integrated systems which are heterogeneous and independently operable on their own, but are networked together for a common goal*. The goal, as mentioned before, may be cost, performance, robustness, etc.; **(ii)** A *System of Systems* is a "super system" comprised of other elements which themselves are independent complex operational systems and interact among themselves to achieve a common goal. Each element of a SoS achieves well-substantiated goals even if they are detached from the rest of the SoS.

Developing a generic definition for *SoS* that transcends specific domains of applications is essential for the development of systems engineering framework [36] which is needed to improve decision support for system of systems problems. The above definitions are mostly descriptive, but they capture crucial features of what a generic definition should involve; however, they do not answer the question, why is this new notion different than that of composite systems. The distinctive feature of our approach is that we treat the notion of *System of Systems (SoS)* as an evolution of the standard notion in engineering of *Composite Systems (CoS)* [32]. Developing the transition from *CoS* to *SoS* we need to identify the commonalities and differences between the two notions. We note:

(a) Both *CoS* and *SoS* are compositions of simpler objects, or systems.
(b) Both *CoS* and *SoS* are embedded in the environment of a larger system.
(c) The objects, or sub-systems in *CoS* do not have their independent goal, they are not autonomous and their behaviour is subject to the rules of the interconnection topology.
(d) The interconnection rule in *CoS* is expressed as a graph topology.
(e) The subsystems in *SoS* may have their own goals and some of them may be autonomous, semi-autonomous, or organised as autonomous groupings of composite systems.
(f) There may be a connection rule expressed as a graph topology for the information structures of the subsystems in a *SoS* .
(g) The *SoS* has associated with it a *global game* where every subsystem enters as an agent with their individual Operational Set, Goals.

We will use the definition of the system as defined in the previous section and represent it by Figure 3.

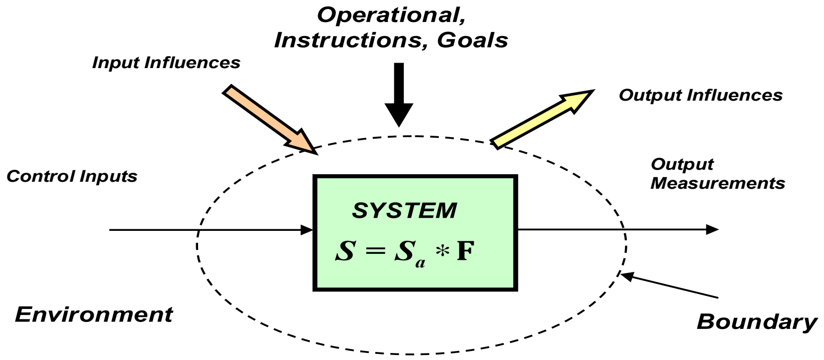

Figure 3: Integrated view of a system

In the above representation the system appears as an autonomous agent (internal system structure together with its inputs and outputs), having its operational instructions and goals and a pair of information vectors expressed by the input and output influences vectors. Furthermore, we will assume that the system under consideration has the control, modelling and supervisory capabilities integrated and thus can act as an agent with independent capabilities and thus can act as a *player in games*. We may represent such as system as in Figure 3 and it will referred to as an *integrated system* [40]. The latter term is used to distinguish it from systems which have no integrated control and information processing capabilities and which may be referred to as *simple systems.* If such a system is embedded in a larger system (Composite, or System of Systems) relations with other systems may be defined in two different ways:

(a) An interconnection topology of the graph type defined on the set of input-, output-influences subsystem information structures.
(b) A global operational rule, sometimes a game, where every subsystem enters as an agent with their individual Operational Set and Goals.

It is worth noting that a composite system appears as a system with a single goal and the second type of connection linked to an operational rule, or game does not exist. The distinguishing feature of the *SoS* case is that the subsystems participate in the composition as intelligent agents with a relative autonomy and act as players in a game. The latter property requires that the systems entering the composition are of the integrated type, with capabilities for control, estimation modelling and supervisory capabilities [40].

Definition (3): Consider a set of systems $\Sigma = \{S_i, \ i=1,2,\ldots,\mu\}$ and let F be an interconnection rule defined on the information structures of S_i systems. The action of F on Σ, defined as: $S_c = \Sigma * \mathrm{F}$ produces a new system which will be called a ***Composite System***, or the *composition of* Σ *under* F .

The information structure of each system is defined by the pair of the input and output influence vectors and the interconnection rule may be represented by a graph topology [32]. The resulted system is embedded in a larger system and it is treated as new system with its own system boundary. In the above definition the systems considered are simple and not necessarily integrated. The above definition may now be extended as follows [40]:

Definition (4): Consider a set of integrated systems $\Sigma = \{S_i, \ i=1,2,\ldots,\mu\}$, F be an interconnection rule defined on the information structures of S_i systems and let $S_c = \Sigma * \mathrm{F}$ be the resulting composite system. If G is an operational rule (sometimes a game) referred to as "*systems play*", that is defined on the systems S_i then the action of G on S_c is a new system $S^*_c = \Sigma * \mathrm{F} \bullet \mathrm{G}$ which will be called a ***System of Systems***, or the F , G *composition of* Σ.

In the above definition the notion of *SoS* emerges as an evolution of *CoS* since the systems are assumed to be integrated, i.e. having capabilities for information processing and thus they are capable to act as agents and participate in games of some type. We assume an interconnection topology defined on the information structures of the components, but this may not necessarily be strong and some sub-systems may be entirely autonomous. Note that the transition from the *CoS* to *SoS* has a fundamental step from the simple systems to the integrated systems assumption for the subsystems. The *System of Systems* notion emerges as a two dimensional concept. At the lower level it appears as a composite system with some interconnection topology defined on the subsystems, which are now assumed to possess information processing capabilities. It is the latter property that allows these subsystems to act as *agents* and *SoS* to emerge as a *multi-agent system (**MAS**)* [41] composed of multiple interacting *intelligent agents* (the subsystems). This multi-agent systems view allows *SoS* to act as vehicle to solve problems which are difficult for an individual agent. The *multi-agent* dimension of *SoS* may have characteristics such as:

- **Autonomy**: the agents are at least partially autonomous.
- **Local views**: no agent has a full global view of the system, or the system is too complex for an agent to make practical use of such knowledge.
- **Decentralization**: there is no designated single controlling agent, but decision and information gathering is distributed.

It is the above properties that allow *SoS* to develop "self-organization" capabilities. The nature of the specific problems is closely related to the type of the operational rule that is defined. It is these general features of *SoS* that makes them relevant to the study of *M-MTS*. The nature of CoS and SoS is captured as a UML Class in Tables 3 and 4 [40].

Class: ***Composite Systems***	
Attributes:	• An aggregate of interrelated constituents which are components or systems themselves • Constituent components or systems have specialised functions/roles • Some constituent components or systems are critical to functionality and sustainability of the whole • Constituent systems perform sub-functions of the whole
Operations:	• Manifest emergence • Emergence is lost with the loss of critical constituents or disaggregation of the whole • Emergence is weakened when critical constituents are at fault state • Has normal, degraded and failed states of operation • In an operational context, there's an additional emergency state

Table3: The definition of Composite System as a UML Class

Class: ***System of Systems***	
Attributes:	• Constituents are sustainable functioning systems on their own • There's absence or lack of constituent criticality in the sustainability of the whole • Constituent systems may have specialised functions/roles
Operations:	• Manifests emergence • Possesses high degree of resilience and sustainability • Emergence is sustained with the loss of constituents • Emergence is weakened when constituents are at fault state • Has normal, degraded and failed states of operation • In an operational context, there's an additional emergency state

Table 4: The definition of System of Systems as a UML Class

6. Multi-Modal Transportation and Integration of Operations of Transportation Networks

The description of *SoS* demonstrates its relevance for the study of *M-MTS* related problems. Table 5 describes Multi-Modal System as a UML Class. We now focus on a specific problem within *M-MTS* related to transport problems of Mega Cities and specifically on the issues of integration of Operations of Transportation Networks.

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, higher service availability, 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

Table 5: The definition of a Multi-Modal System as a UML Class

A Transportation Network in a large city is a complex system involving a large number of transportation networks (road, rail, underground, etc). Operations deal with the overall system and they are supporting the execution of different transport scenarios. Against the background of a doubling of demand, we intend to test the hypothesis that segregation, or some form of smart cooperation of any of the suburban services of a major city can deliver substantial cost efficiencies and increased capacity from a radically different approach compared to the existing situation.

It must be noted that the physical networks are interconnected, but the operations and business processes should cooperate, but not necessarily be centralised. Growth and increased capacity should be addressed by a strategy that aims for:

(i) Cooperating Segregation, or Disaggregation of operations and business processes;
(ii) Physical growth of the system aiming for increased connectivity of the network itself and integration with the transportation global system;
(iii) Strategies and policies that promote the evolution of Rail Transport to the new state.

The segregation of the system is essentially an attempt to decompose a "System of Systems" into coordinated subsystems that can handle uncertainty, cope with emergencies, deliver increased capacity and support growth in an organised and manageable way. The key problem behind Disaggregation is the development of a coordinated distributed approach leading to a new architectural change to the way operations and business are organised. This is in response to the lack of flexibility available in existing separated and uncoordinated processes, or highly connected, with hierarchical structuring of their operations processes which suffer from inability to support operations with changing conditions and demands for increased capacity. This problem has emerged in other fields such as Discrete Manufacturing, Process Control, Supply Chain Management etc. with names as “Holonic Manufacturing”, “Reconfigurable Process Control”. Our approach will use elements of the so-called Holonic Manufacturing [12],[37], [39], which has been developed in the discrete manufacturing domain to address the limitations of existing hierarchical structures. Future Railway Systems will need to cope with changes in the market, introduction and integration of new technology, frequent system disturbances and changes in production orders. Therefore, their monitoring, management and control will require constant adaptation and high flexibility.

The Holonic systems paradigm is a highly distributed control paradigm for complex systems that has been applied successfully in discrete manufacturing and supply chain management and which promise to handle the above challenges and problems successfully. The overall framework is based on the concept of autonomous cooperating agents, called "holons". The holon taxonomy is based on the physical components of the systems, operational issues, services provided, demand for services, and resources as basic building blocks. They are structured using object-oriented design concepts like aggregation and specialization. Additional holons may be introduced to provide the basic holons with specialized advice. The resulting architecture will follow the general features for holonic manufacturing, where the autonomy of the agents provides the system with the ability to react to disturbances, while the existence of hierarchical control elements provides the system with opportunities for global optimization. The resulting architecture is expected to remain flexible, allowing control strategies ranging from very hierarchical to very heterarchical.

The basic problem addressed here is that of decomposition of the overall complex system. This is essentially a problem of organisation of processes (physical, operational, market related). Note that neither hierarchical nor heterarchical system organisations cope adequately with the multitude of demands introduced by the need to disaggregate the processes of a modern Railway System. Hierarchical systems typically have a rigid structure that impedes them to react to these disturbances in an agile way. Heterarchical systems handle disturbances very well and can continuously adapt themselves to their environment; however, heterarchical control does not guarantee high performance or predictable behaviour. The actual challenge lies in the requirement that future Railway Systems need both performance and reactivity. The answer to this challenge is sought in deploying theories on complex adaptive systems. Looking at living organisms and social organizations, Koestler made the observation that complex system can only arise 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. This has led to the development of the principles of Holonic Manufacturing [39]. The Holonic Manufacturing Paradigm implies a highly distributed organization of the overall system, where intelligence is distributed over the individual entities. These entities are cooperative, intelligent, autonomous modules, called "holons." The new element in the holonic organisation is the fact that the individual entities work together in temporary hierarchies (called "holarchies") to achieve a global goal. The holonic concept combines the best features of hierarchical and heterarchical organization). It preserves the stability of hierarchy while providing the dynamic flexibility of a heterarchy. In this way, a holonic organisation combines high performance with robustness against changes and disturbances.

The aim is to develop a taxonomy of individual holons occurring in a Holonic Railway System (HRS) and define their role in the overall operations, management and future evolutionary process. Such a taxonomy will help the management to better understand the concepts behind holonic operability and, more specifically, to understand the interaction mechanisms in a complex society of holons in a railway system. As a result, it will guide the designer of railway subsystems and processes to define the suitable railway holons. This will lead to a design methodology for a holonic railway control architecture that is adaptable, capable to cope with disturbances, responsible to market needs and capable of integrating technological innovation without disturbing existing smooth operations. The main tasks for the development of the new architecture for Holonic Railway System (HRS) will be the following:

- Definition of autonomous holons to provide robust operation and agility in the face of change and disturbances;
- Development of loose hierarchies to allow global optimization;
- Specification of flexible holarchies to allow reconfiguration upon changing needs, and the evolution with new technology;
- A migration path from current Railway System development to a Holonic architecture.

7. Conclusions and Challenges

The general problem of Multi-Modal Transport has been presented as a problem that can be studied within the framework of the new systems paradigm, namely the *SoS* paradigm. We have developed and proposed new definitions for the key concepts of system, emergence, composite and system of systems as well as the hypothesis that emergence is the key characteristic of a system of any degree of complexity which can be physical or virtual in nature. We have also clarified the distinguishing features between composite systems and system of systems. Most man-made and natural systems are of composite nature and the system of system is characterised by a generalisation of the notion of composition in terms of the notion of *systems play*. The SoS paradigm offers architectural and operational attributes which present a potent alternative in tackling large scale and global problems. There are already many challenges in the understanding, characterisation and assurance of the complexity of Multi-Modal Transport systems given the large integrated body of hardware, software, rules and human agents. The multi-modal transportation provides a typical case of SoS; identifying the structural and behavioural aspects which can render a resilient system of systems is a challenge and fundamental work on *SoS* is needed. The essence of the benefits of SoS paradigm applied to the M-MTS lies in the cooperative independent modes that render much higher availability, utilisation and social value for the same deployed resources. A more specific topic within *M-MTS* is the case of the integrated railway system, where re-engineering may benefit by aiming to introduce autonomous holons which may enable architecting and operating a highly resilient network.

References

[1] Karcanias, N. and Vasileiadou, S., 2007. Systems and their Origins in Ancient Greece. In: *Proceedings of the European Control Conference ECC 07*. Kos, Greece, 2-5 July 2007.

[2] Von Bertalanffy, L., 1968. *General system theory: foundations, development, applications*. New York: George Braziller.

[3] Bowler, D., 1981. *General Systems Thinking*. New York: North Holland.

[4] Karcanias, N., 2008. Structure evolving systems and control in integrated design. *Annual Reviews in Control*, 32, pp. 161–182.

[5] Jamshidi, M., 1983. *Large Scale Systems: Modeling and Control*. New York: North Holland.

[6] Rijnsdorp, J.E., 1991. *Integrated Process Control and Automation*. Amsterdam: Elsevier.

[7] Karcanias, N., 2000. The Integration Problem in Advanced Manufacturing: Systems and Control issues. In: *Proceedings of ASI 2000*. Bordeaux, France, 18-20 September 2000.

[8] Van Brussel, H., Bongaorts, L., Wyns, J., Valckenaers, P. and Van Ginderachter, T., 1999. Trends and Perspectives: A Conceptual Framework for Holonic Manufacturing: Identification of Manufacturing Holons. *Journal of Manufacturing Systems*, 18(1), pp. 35-52.

[9] Koestler, A., 1989. The *ghost in the machine.* London: Arkana Books.

[10] Valckenaers, P., Van Brussel, H., Bongaerts, L. and Wyns, J., 1997). Holonic Manufacturing Systems. *Journal of Integrated Computer-Aided Engineering*, 4(3), pp. 191 201.

[11] Van Brussel, H., 1994. Holonic Manufacturing Systems, the Vision Matching the Problem. In: *Proc. of 1st European Conf. on Holonic Mfg. Systems*, Hannover, Germany, 1 Dec. 1994.

[12] MacFarlane, D. C., 1995. Holonic Manufacturing Systems in Continuous Processing: Concepts and Control Requirements. In: *Proceedings ASI '95*, Portugal.

[13] Iwata, K. and Onosato, M., 1994. Random Manufacturing System: a New Concept of Manufacturing Systems for Production to Order. *Annals of the CIRP,* 43(1), pp. 379-384.

[14] Simon, H. A., 1990. *The Science of the Artificial,* 2nd ed. Cambridge, MA: MIT Press.

[15] Dilts, D. M., Boyd, N. P. and Whorms, H. H., 1991. The Evolution of Control Architectures for Automated Manufacturing Systems. *Journal of Mfg. Systems*, 10(1), pp. 79-93.
[16] MacFarlane, A. G. J., 1993, Information, Knowledge and Control. In: H.I. Trentelman and J.C. Willems, ed. *Essays on Control; Perspectives in Theory and Its Applications*. Berlin: Birkhäuser Basel. pp. 1-28.
[17] Mesarovic, M.D. and Takahara, Y., 1989. Abstract Systems Theory. Lecture Notes in Control and Information Sciences, Vol. 116, Berlin: Springer-Verlag.
[18] Mesarovic, M.D. and Takahara, Y., 1974. *General Systems Theory: Mathematical Foundations.* New York: Academic Press.
[19] Karcanias, N., 2004. *System concepts for general processes: specification of a new framework*. London: Systems and Control Centre, City University London.
[20] Beer, S., 1959. *Cybernetics and Management*. London: University Press.
[21] Laszlo, E., 1972. *Introduction to Systems Philosophy*. Gordon and Breach.
[22] Maier, M. W., 1998. Architecting Principles for System of Systems. *Systems Engineering*, 1(4), pp. 267-284.
[23] Morari, M., Arkun, Y. and Stephanopoulos, G., Studies in the Synthesis of Control Structures for Chemical Processes. *AICHE Journal*, Vol. 26, Vol. 27, (Parts I to V).
[24] Karcanias, N., 1994. Global Process Instrumentation: Issues and Problems of a Systems and Control Theory Framework. *Measurement*, 14, pp. 103-113.
[25] Karcanias, N., 1995. Integrated Process Design: A Generic Control Theory/Design Based Framework. *Computers in Industry*, 26, pp. 291-301.
[26] DeLaurentis D., 2007. *System of Systems Definition and Vocabulary*. West Lafayette, IN: Purdue University.
[27] Jamshidi, M., 2008. *System of Systems Engineering –Innovations for the 21st Century*. Wiley Series in Systems Engineering. New York: John Wiley & Sons, Inc.
[28] Carlock, P. G. and R. E. Fenton, 2001. System of Systems (SoS) Enterprise Systems for Information-Intensive Organizations. *Systems Engineering*, 4(4), pp. 242-261.
[29] Pei, R. S., 2000. Systems of Systems Integration (SoSI) - A Smart Way of Acquiring Army C4I2WS Systems. In: *Proceedings of the Summer Computer Simulation Conference*, pp. 134-139.
[30] Luskasik, S. J., 1998. Systems, Systems of Systems, and the Education of Engineers. *Artificial Intelligence for Engineering Design, Analysis, and Manufacturing*, 12(1), pp. 11-60.
[31] Maier, M. W., 1998. Architecting Principles for System of Systems. *Systems Engineering*, 1(4), pp. 267-284.
[32] Karcanias, N., 1996. Control problems in global process instrumentation: A structural approach. *Computers and Chemical Engineering*, 20, pp. 1101–1106.
[33] Popper, S., Bankes, S., Callaway, R. and DeLaurentis, D., 2004. *System-of-Systems Symposium: Report on a Summer Conversation*. Potomac Inst. Policy Stud, Arlington, VA.
[34] Wooldridge, M., 2002. *An Introduction to MultiAgent Systems.* New York: John Wiley & Sons Ltd.
[35] De Laurentis, D.A. and Callaway, R.K., 2006. A System-of-Systems Perspective for Future Public Policy. *Review of Policy Research*, 21(6), pp. 829-837.
[36] Sage, A. P. and C. D. Cuppan, 2001. On the Systems Engineering and Management of Systems of Systems and Federations of Systems. *Information, Knowledge, Systems Management*, 2(4), pp. 325-334.
[37] Van Brussel, H., Bongaorts, L., Wyns, J., Valckenaers, P., and Van Ginderachter, T., 1999. Trends and Perspectives: A Conceptual Framework for Holonic Manufacturing: Identification of Manufacturing Holons. *Journal of Manufacturing Systems*, 18(1), pp. 35-52.
[38] Leitao, P., 2009. Agent-based distributed manufacturing control: A state-of-the-art survey. *Engineering Applications of Artificial Intelligence*, 22, pp. 979–991.
[39] Giret, A. and Botti, V., 2009. Engineering Holonic Manufacturing Systems. *Computers in Industry*, 60, pp. 428–440.
[40] Karcanias, N. and Hessami, A. G., 2010. Complexity and the notion of System of Systems: Part (i): General Systems and Complexity"; Part (ii): Defining the Notion of System of Systems. In: *Proceedings of 2010 World Automation Congress International Symposium on Intelligent Automation and Control (ISIAC)*, Kobe, Japan, 19 – 23 September.
[41] Alonso, A., Karcanias, N. and Hessami, A. G., 2013. Multi-Agent Systems: A new paradigm for Systems of Systems". In *Proceedings of the Eighth International Conference on Systems (ICONS 2013)*, Seville, Spain, Jan 27 - Feb 1.