Engineering Industrial Ecosystems in a Networked World

Mihaela Ulieru[1], *Senior Member, IEEE* and Stefan Grobbelaar[2], *Student Member, IEEE*

Adaptive Risk Management Laboratory, University of New Brunswick, Canada

***Abstract*—We underline the co-evolutionary progress from collaborative automation to the extended and integrated global enterprise through which Industrial Informatics evolved mirroring the paradigm shifts in networking and communications under five years of tumultuous technological transformations. Latest trends that support the dynamic interplay of distributed intelligent technologies and services in today's complex and converging interdependent ecosystem of a networked world are revealed. Our efforts in setting up a solid foundation for prototyping and experimentation with the tomorrow's industrial ecosystems in preparation to meet the upcoming challenges inherent in these future developments, are detailed.**

***Keywords*.** Industrial ecosystem, industrial informatics, complexity science, eNetworks, holonic enterprise, networked manufacturing.

I. INTRODUCTION: FIVE YEARS OF INDUSTRIAL INFORMATICS

The development of industrial informatics along the five years since the 1st INDIN Conference [46] was marked by most tumultuous transformations in the information and communication technologies (ICT) domain, which are radically and rapidly changing our world. The initial vision [39] has materialized in that, on the informatics side, eNetworks are today the pervasive infrastructures supporting industrial development in the 'global village' of our networked world. In 2004 we were wondering if the industry is prepared for a new paradigm with strong information processing content (the 'informatics' ingredient in the INDIN recipe). Today we witness how eNetworks connect global enterprises in *holistic digital ecosystems* of networked manufacturing (eManufacturing) in which autonomous eServices cohabitate harmoniously within the synchronous production workflow [40] managed via eLogistics. Along these five years Industrial Informatics co-evolved in synch with the ICT developments as progressively marked by the annual conferences of this growing community, with each INDIN Conference adding a new dimension to the industrial informatics picture. In 2003 under the Theme 'eLogistics for a Fail-Safe World' we positioned Industrial Informatics at the lead of and endowed it with the responsibility for designing resilient and robust products and processes, using the novel distributed intelligence paradigms emerging at the time on the foundation of breakthrough Internet-enabled linkages. We aimed at the development of processing technologies with ability to respond quickly to changes in the market as well as in society, to find the best ways to cope with the dynamics of our fast paced world, including the unfortunate threats that mutated the societal and economic course with unprecedented disruptions at the beginning of the new Millennium. Thus, security and safety were positioned at the forefront of Industrial Informatics, mirroring their emphasis in the ICT domain. The dynamic creation of response-oriented and short-living network-enabled hybrid organizational structures demanded by a 'fail-safe World' as aimed by the 1st INDIN, inspired the Theme of INDIN 2004 which proposed the vision of "intelligent industrial environments". Emerging from the holonic manufacturing paradigm [14] materialized today in the emergence of digital manufacturing ecosystems in which collaborative automation is the only way to thrive and progress in the global knowledge economy, the OOONEIDA concept supports the creation of intelligent, flexible manufacturing environments [42] as a living example and clear proof of success in a networked world. The business dimension has been added by INDIN 2005 – underlining the crucial aspect of ICT in successfully running the industrial process, thus pushing the frontier of the industrial ecosystem at the confluence of technological breakthrough driven by market demand. And the fourth dimension – integrating services into the manufacturing ecosystems - was added by INDIN 2006. Thus INDIN 2007 takes over a *holistic industrial ecosystem* emerging in a networked world – integrating the four dimensions of industry, ICT (informatics), business and services - aiming to face the new challenges arising from its more and more dynamic, heterogeneous, distributed and complex nature. This calls for new paradigms to enable the seamless creation of manufacturing ecosystems that evolve and adapt in tune with the market dynamics to enable the controlled sharing and management of information over the Internet and industrial networks critical to the effective planning, coordination and execution of activities and the movement of materials/services through the value chain to address the various stages of today's product or service life cycle [28].

The future of industrial informatics will continue to be driven by progress in the ICT dimension as such it is there where we shall focus our explorations in the quest to develop the cutting edge technologies of tomorrow. With the premise that progress in industrial informatics will mirror the paradigm shifts in networking and

[1] Canada Research Chair (http://www.cs.unb.ca/~ulieru/)
[2] Formerly with the Institut Fur Computertechnik at TU Vienna

communications, in the sequel we will dare to anticipate the major trends in the dynamic interplay of distributed intelligent technologies and services driving tomorrow's complex and converging interdependent ecosystem of a networked world while pointing to how and where will it take the industry.

II. Where the Future Lies: The Radical Shift

THE Future Internet is envisioned to leap towards a radical transformation from how we know it today (a mere communication highway) into a vast *hybrid network* seamlessly integrating physical (mobile or static) systems to power, control or operate virtually any device, appliance or system/infrastructure. Manipulation of the physical world occurs locally but control and observability are enabled safely and securely across a (virtual) network. It is this emerging 'hybrid network' that we refer to as an 'eNetwork'. An eNetwork integrates computing, communication and storage capabilities with the monitoring and/or control of entities in the physical world, and must do so dependably, safely, securely, efficiently and in real-time. eNetworks enable the spontaneous creation of collaborative societies of artifacts, referred to as "cyber-physical ecosystems" [1]. In such "opportunistic ecosystems", single devices become part of a larger and more *complex* infrastructure in which the individual properties or attributes of single entities are dynamically combined to achieve an emergent desired behavior of the ecosystem. Such a large scale system has to be able to continuously adapt to unforeseen situations and to evolve in an autonomic way, without requiring the need of human intervention. To turn this vision into reality, a set of new paradigms is needed that enable eNetworks to grow (in scale and supported features), adapt and evolve. This entails the need of considering *evolve-ability* as a fundamental and constituent property of such eNetworked cyber-physical ecosystems in which devices are expected to spontaneously cooperate in order to accomplish desired tasks. This represents a major turn, if compared to traditional end-to-end paradigms, for which a *safe* backend connection is assumed to be always present, when needed. *Collaborative systems* will be the rule, rather than the exception, and will drive the way systems will adapt to each other in order to orchestrate complex behaviors, as programmed by end-users. The vision of a collaborative networked society of artifacts relies on the expectation of a distributed execution environment, which will be orchestrating the service components and the devices in the network. This is mostly due to the need of integrating different technologies and software components in order to achieve the desired "system behavior", rather than a device single behavior. The single device becomes part of a larger, and more complex, infrastructure, in which the complementarities of the single elements are exploited in order to achieve an emergent complex behavior. This brings about the need to embed *change* as a constituent property in eNetworks for designing the building blocks of an ***autonomic digital ecosystem*** as model for the future production systems, which will build on the notion of autonomic self-management by embedding control features within modules such that their properties can be exploited in a variety of application-specific ways thus enabling dynamic adaptation to user needs and environmental conditions. Industrial ecosystems will also consider unreliable conditions, noise, and device heterogeneity in order to evaluate the adaptation and organization capacities of the implemented software modules. Services will be built on-the-fly in a totally autonomic way. Particular attention will be taken in the implementation of the end-user interfaces in order to mask internal system complexity to ensure users are able to understand and easily control the systems within their operational environment.

A task as ambitious as development of the eNetworks which will animate the future industrial ecosystems cannot be accomplished in isolation. A vital part of this effort concerns fostering collaboration and consensus-building among researchers working on future global network architectures, who share like-minded visions. Major new long term initiatives in Europe (EU-FET Future Internet Research and Experimentation – FIRE) [43] and the US (NSF NETS research program on Future Internet Network Design – FIND) [44] foster participation of international researchers from academia and industry based on the premise that only in collaboration and via consensus-building can this critical mission be accomplished. CANARIE Inc. - Canada's advanced Internet development organization recently underlined the urgency to look beyond current state-of-the-art models [29]. Researchers participating in such international initiatives can bring priceless expertise and insights into the strategic future directions of industrial informatics. To be a part of these developments the INDIN community must team up with those who drive the development of tomorrow's ICT world. To be able to keep up with and exploit breakthrough findings enabling industrial informatics to sustain and support mankind in facing the future challenges, we are committed to highest quality work dedicated to the design and development of methodologies for engineering industrial ecosystems, as it will be detailed in the sequel.

III. A Platform for Design and Evaluation of Industrial Ecosystems

THE Adaptive Risk Management Laboratory (ARM lab) [1] is concerned with the development of universal models for integrating industrial systems/infrastructures (and the environments to which they are applied) with an overlay control network, i.e. the e-Network [2]. We have identified three functional objectives of the models, namely: network self-organization to increase/preserve resilience, risk mitigation, and the impact of interdependencies. In view of achieving these objectives, we are setting up a platform for the design and evaluation of Cyber-Physical ecosystems, and provide a methodology for design of the platform. The methodology includes:

1) the gathering of industry-specific resource data,
2) a study of the theoretical foundations [3] of Complex Systems [4], Complex Adaptive Systems [5] and Complex Networks [6], and
3) integration of the industry-specific resource data and theoretical foundations into a laboratory test bed for developing e-Network models.

1. *Industry-specific Resource Data*

As illustrated in Figure 1, we deal with two categories of industry data: geography related data (geographic capacity) and partnership resource data (intellectual capacity). The focus application areas of our research are classified according to these categories, as follows:

A. Geographic Capacity

a. *Opportunistic Communications:*

Network-centric computing initiatives [7] envision a decentralized communication system consisting of Wireless Mesh Networks [8] that operate on node-based architectures with emergent management capabilities. The management capabilities may refer to the capabilities of the physical nodes of a network, as well as the user requirements associated with devices connected to the nodes. In [7] a number of use cases of network-centric computing are described. Of these, we focus on *self-managing enterprise operations* that leverage mobile nodes for increased operational scalability. In part A of figure 1, which illustrates a particular application, the nodes of the network are associated with physical devices that manage a set of mobile assets e.g. harvesting vehicles operating in a forestry environment. The physical devices gather vehicle data used to support production, utilization, and inventory interactions between harvesting operations. In such a Wireless Mesh Network, the nodes are comprised of mesh routers and clients (attached to the vehicles) who all operate as both hosts and clients. Their locations depend on the changing geographical locations of the vehicles, where nodes forward data on behalf of other nodes that may not be within the direct wireless transmission range of their destinations [8]. Thus, the vehicles act as mobile routers that collect and deliver data between the nodes of the location-based mesh network and a central operations server. Inter-vehicular communication over a changing topological landscape is described in [9] as *knowledge-based opportunistic forwarding.* The concept is motivated by similar projects [10] within the demand-response research area. In this application example, the gathering of device data is emulated by the Opportunistic Communications Module of our test bed, shown in part C of figure 1.

B. Intellectual Capacity

a. *Holistic Security Ecosystems:*

From a Complex Adaptive Systems perspective [5], organizations and their partner organizations may be described as species within a social ecosystem who are specialized to achieve both their own goals and those of the greater organization (as in the case of a natural ecosystem such as the Little Rock Lake food web [11]). The organization is subject to either gradual or abrupt change. Gradual change is characterized by a steady progression in organizational change, whereas abrupt change is characterized by unpredictable actions and consequences [12]. In the case of an attack, periods of abrupt change increase in frequency, duration and magnitude, however, [13] argues that human actions are able to reduce the effects of abrupt change on ecosystems.

Holonic organizations [14] model organizational change and structure by placing the intellectual capacities of organizations (e.g. resources, people, departments, enterprises) within a nested hierarchy, referred to as a holarchy. The holonic organization includes a specialized Support Holarchy [15] that deals with organizational security in case of attack. The Support Holarchy aims to protect the organization through a mixture of static and mobile agents. The entities of intellectual capacity (referred to as holons in part B of Fig. 1) represent the inputs into our test bed, and are processed by the Modeling and Simulations Module of the test bed (part D of figure 1). For details please refer to [41].

b. *Control of Complex Critical Infrastructures:*

The security of power systems is measured by their ability to provide uninterrupted service to users during failures caused by natural phenomena, human error and intentional disruptive attacks [16]. Regulating agencies have encouraged power companies to achieve security at the expense of efficiency by passing costs on to users. In a future deregulated electricity market, suppliers are likely to compete for users with increased concerns of power quality. As the services associated with increased power quality are unbundled, monitoring and controlling power quality becomes a pricing issue and provides an opportunity for market segment exploitation. Electricity suppliers have developed mathematical models of their control areas [17] that include the continuous gathering of data used for updating the models. Implementing these models, electricity suppliers gain price advantages by

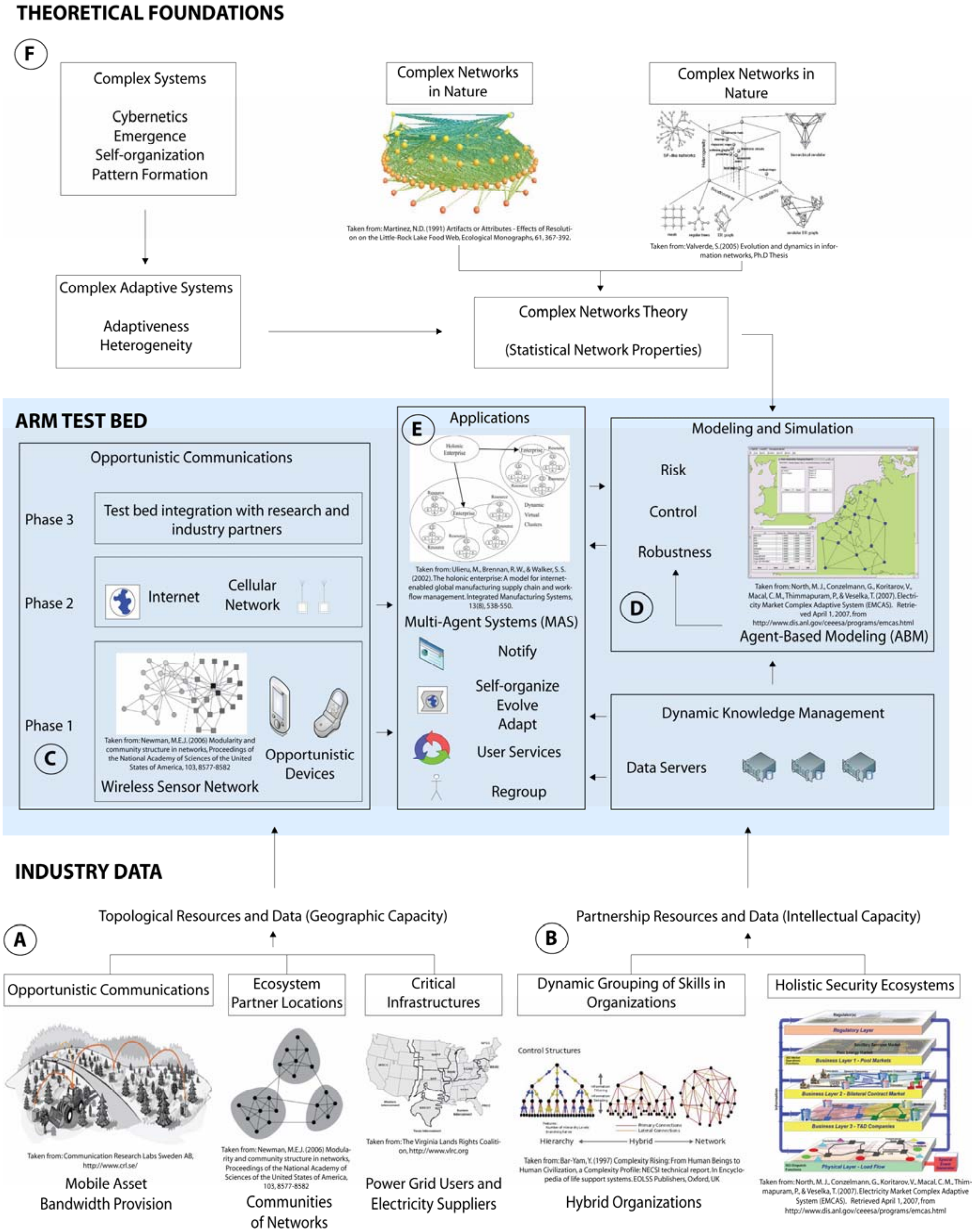

Fig. 1. A platform for design and evaluation of Industrial Ecosystems.

accepting some risk of failure and balancing the risks against cost of recovery and performance penalties in their negotiated contracts. According to part B of figure 1, these models provide an example of possible inputs to the test bed from industry partners.

The data related to each of the application focus areas described above are gathered from physical devices (e.g. Wireless Sensor Network) and industry partners to serve as input into the test bed. The test bed integrates the data into unified models that include each of the application focus areas at a higher level of communications monitoring and control.

2. *Adaptive Risk Management Test Bed*

The shaded area of figure 1 shows the test bed. It is divided into three functional modules:

C. Opportunistic Communications Module

In a broad sense, the Opportunistic Communications Module (marked with C. in Fig. 1) provides a platform for the design and testing of eNetworks as foundation for the Future Internet [18]. Whereas the current Internet provides a means of communication, the Future Internet provides both a means of communication and an interface for seamless connection to our physical environments. Wireless technology is identified in [19] as a main driving force for realizing the Future Internet. In order to achieve these objectives, module C comprises three development phases:

Phase 1 horizontally integrates a Wireless Sensor Network with opportunistic communication devices, e.g. smart phones and PDA's.

Phase 2 vertically integrates the architectures of *phase 1* with the existing Internet and cellular networks.

Phase 3 integrates the combined architectures of *phases 1* and *2* with external industrial and academic research platforms of a Future Internet.

In a narrower sense, the Wireless Sensor Network component of *Phase 1* emulates the gathering of location-based device data as described in section 1. The Wireless Sensor Network component of our test bed represents a subset of Wireless Mesh Networks [20]. It adds to a regular mesh network the ability to sense specific location-based data based on the collaborative effort of a large number of sensor nodes.

D. Modeling and Simulations Module

The Modeling and Simulations Module (marked D in Fig. 1) of the test bed is based on an agent-based modeling (ABM) paradigm [21]. Agent-based models are comprised of multiple, interacting agents situated within a model or simulation environment. Given the lack of a universal agreement on the precise definition of the term "agent", our view abides to the list of common agent features given by [22]. The list features an extension of the work of [21] by [23], [24], and [25].

Agent-based models specify relationships between agents that are supported by an operating environment. Agents can be defined in a variety of ways, from simply reactive (i.e. only perform actions when triggered to do so by some external stimulus), to goal-directed. Environments define the space in which the agents operate, and take two forms for the purpose of this module [22]:

- In a spatially explicit environment, the agents have a location in geometric space, e.g. the location of devices within a critical infrastructure.
- In a spatially implicit environment, the location of agents in the environment is irrelevant, e.g. the nodes of the overlay network for monitoring and controlling the critical infrastructure.

The ability to simulate individual actions of diverse agents and measure the resulting system behavior provides us with a useful tool for studying the effects on processes that operate on multiple operational scales and organizational levels [26]. We distinguish between an agent-based modeling component (ABM) and a Multi Agent Systems (MAS) component of the test bed (parts D and E of figure 1). Although the terms agent-based modeling and Multi Agent Systems are often used interchangeably to describe agent-based models,

- MAS are characterized by the study of societies of artificial autonomous agents, and are mostly applied outside the social sciences and in relation to agent-oriented software development. Their purpose is the implementation of tasks as distributed computational units interacting with each other and the environment.
- ABM is characterized by the study of artificial societies of autonomous agents [27], and is not limited to the design and understanding of artificial agents.

- A software approach refers to the development and programming of agent-based models from the ground up, using a low-level programming language. The disadvantages of this approach are explained in [22].
- Toolkits provide a conceptual framework for organizing and designing agent-based models and include software libraries that have predefined routines and functions specifically designed for agent-based modeling. They provide templates for the design, implementation and visualization of models with a focus on research rather than tool development [30]. Of the many available toolkits (see [31] and [32] for

complete listings), we focus on using the Recursive Porous Agent Simulation [33] and the NetLogo [34] toolkits:

NetLogo is specifically designed for the deployment of models over the Internet and facilitates the development of spatial models by providing a means of importing image files (agent environments). NetLogo is used extensively to develop applications in disciplines varying from biology and physics to the social sciences.

The Recursive Porous Agent Simulation toolkit (Repast) is maintained by the Argonne National Laboratory and managed by the Repast Organization for Architecture and Development (ROAD). Repast caters to the implementation of models in Java (RepastJ) and Microsoft.Net (Repast.Net), and provides the test bed with a suitable environment for more advanced and larger-scale modeling. Examples of spatially explicit models created using Repast include the Electricity Market Complex Adaptive System (EMCAS) [35]

E. Applications Module

Multi-Agent Systems form the basis of our applications module (part E of figure 1). They serve as implementations of our agent-based models and provide a platform for the development of various industrial ecosystems. The Foundation for Intelligent Physical Agents (FIPA) [36] proposes a set of standards and infrastructures to support the deployment, integration and operation of Multi-Agent Systems. We focus on the Java Agent Development Environment (JADE) [37], based on its performance, robustness and number of existing applications [37]. These include CoMMA [38], a JADE implementation for managing organizations by facilitating the creation, transmission and reuse of knowledge in the organization intranet. JADE is written in the Java Language and gives our applications the ready-made pieces of functionality and abstract interfaces for application-dependent tasks. It is particularly geared towards object-oriented programming in distributed, heterogeneous environments that constitute communities of devices or communities of knowledge bases within Holistic Security Ecosystems [41].

3. Theoretical Foundations

Part F of figure 1 shows the theoretical foundations that support the design of our models. The design principles based on Complex Systems as a Control Paradigm for Complex Networks are detailed exposed in [3].

IV. CONCLUSIONS

In the search for paradigms and models that will help us to best exploit the enormous potential unleashed by eNetworks in the industrial world we may have forgotten to look in the mirror – to ourselves as source of inspiration. Is the brain as a dynamic network of networks on which the mind's foundation emerged, too obvious to be noticeable in this race? Not for everyone! And here is the Foresight 'spice' which the INDIN 2007 organizers bring to the picture through their daring attempt to look into the mysteries of human mind for novel engineering and industrial paradigms. While the Neuroscience community [45] looks at the brain's functionality to extrapolate models for intelligent systems ENF [46] undertook the challenge of a holistic approach to emulating the mind by integrating feelings and emotions into a much larger picture, more comprehensive and more attuned to the highest form of intelligence known to us humans. With excitement and delight we will continue to liaise among these two communities in anticipation of the next breakthrough. For now we look forward to INDIN 2008 which aiming to harmonize computers, machines and people, already brings the 'human' dimension into the industrial ecosystem (as anticipated in [39]), thus inviting the ENF paradigm shift to take industrial informatics to new heights in the future!

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