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Chapter 8

Emergence of Holonic Enterprises from Multi-Agent Systems: A Fuzzy Evolutionary Approach

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8.1 Introduction

The recent advances in information and networking technologies have enabled global connections unthinkable before. The web is linking our world enabling partnerships otherwise impossible in all areas of our life. From e-Commerce and e-Business to e-Learning and e-Health the economics strategies as well as the routine professional practices have been irreversibly contaminated with the spice of electronic connectivity. Supported by this technological leverage new paradigms have emerged with models that are dynamic, autonomous, self-organizing and proactive, generically coined as 'intelligent'. In particular the novel AI paradigm of distributed intelligence referred to as Multi-Agent Systems (MAS) has challenged the software world and with it the world of information technologies through its ability to enable emulation in Cyberspace of real-world societies with their entities modeled as agents.

The marriage between MAS and the Internet has enabled a parallel world of information to 'live' in the Web Universe emulating our games in all aspects of life, be they economic, financial, business, school or health related, or even just-for-fun in computer games. Paradigm shifts abound in our world, building on the power of distributed intelligence on the web to change the driving forces from competition to cooperation, from individualism to strategic partnering, from power-from-information to authority-from- wisdom, from fear to trust.

Interdisciplinarity is the keyword in the creation of novel paradigms for the connected world. In 2001 Lotfi Zadeh and Masoud Nikravesh have suggested another marriage that has proven successful in the connected world: Fuzzy Logic and the Internet (Nikravesh and Azvine 2001). Endowing the Information Highway with the best tool known so far for handling imprecision is not only a blessing but as well an act of grace in a time when the explosion of unclassified and unsorted information makes it practically unusable. However an extended family has proven more successful in the meantime, as search engines using evolutionary search and neural networks are now learning customer preferences in e-marketing systems (Norvig 2002). History repeats itself again and Fuzzy Logic makes now room to the whole family of computational intelligence on the web: it's *Soft Computing* and the Internet!

Adding reasoning capabilities to search engines (Zadeh 2002) is not the only way the Internet can be helped. If the reasoning is encapsulated in a *software agent* (that is an expert system in its own rights), or better in a society of agents (that is a MAS) who 'live' independently on the web, then the Internet becomes a dynamic environment through which agents move from place to place to deliver their services and eventually to compose them with the ones of other agents, just like people cooperate by exchanging services and/or putting together their competencies in a larger, more complex service.

By suggesting the third marriage, between Soft Computing and Agent Technology, Vincenzo Loia has proven to be a man of vision. Now empowered with the ability of soft

computing, virtual communities of agents that emulate our World in Cyberspace are able to deal with the uncertainty intrinsic in the real-life that they mirror.
This third marriage closes the triad: Multi-Agent Systems-Internet-Soft Computing to enable the Web become a Dynamic Service Environment[1] (DSE) supporting emulation of real-life communities in all aspects of life, from business and commerce to education and health. What a leverage for us when the agents acting on our behalf make the best decisions and turn the world around in our favor without us needing to do more then click on the cell-phone to give the final blessing by 'OK'–ing the deal. Or when they can find the best partners to help our company get that highly demanded product on the market sooner then the competitor can manage. This dream turns day-by-day into reality, with every successful implementation of agent technology, with every new application involving distributed intelligence on the soft-computing-empowered web.
This chapter seals the magic MAS-Internet-Soft Computing triad to create a web-centric model endowing virtual communities/societies (generically coined as 'enterprises') with proactive self-organizing properties in an open environment connected via the dynamic Web.
In Section 8.2 we present the *holonic enterprise* (HE) as a paradigm of paradigms embracing holonics, MAS, web-centric, Virtual Enterprise (VE) and the novel business paradigm of co-opetition to enable harmonious workflow/information management in a virtual organization. Section 8.3 presents the HE as an information ecosystem, underlying the functional patterns that generate its fundamental properties. A fuzzy-evolutionary approach which enables the HE with the property of self-organization and evolution in Cyberspace towards the best structure is presented in Sections 8.4 and 8.5. Section 8.6 illustrates on a numerical toy example that the theoretical concepts work.

8.2 The Holonic Enterprise as a Paradigm of Paradigms

In the Web-Centric Economy the Dynamic Systems Environment information infrastructure supports production, binds organizations together and reflects in all other organizational aspects. Specifically, production processes are information rich and the dynamics of the information infrastructure is the tool for carrying it out both at individual locales and across the global environment. The electronic linking implies that work matter (or critical parts of it) is being transferred across virtual locales via the DSE which supports organizational information which in turn can mirror social organization.
The HE has emerged as a business paradigm from the need for flexible open reconfigurable models able to emulate the market dynamics in the networked economy (McHugh *et al.* 1995) which necessitates that strategies and relationships evolve over time, changing with the dynamic business environment. The HE integrates into a unified, versatile model several paradigms that have emerged as a result of the tremendous shift in the business dynamics on the global market enabled by the Internet and communication network technologies.

8.2.1 The Universes' Self-Organizing Structure: Holonics Paradigm

The main idea of the HE model stems from the work of Arthur Koestler (Koestler 1968). Koestler postulated a set of underlying principles to explain the self-organizing tendencies of social and biological systems. He proposed the term *holon* to describe the elements of these systems. This term is a combination of the Greek word *holos*, meaning "whole", with the suffix *-on* meaning "part", as in prot*on* or neur*on*. This term reflects the tendencies of

[1] www.agentcities.org (The Global Agentcities Task Force has the mandate to bring together forces from all continents in a common effort to develop the dynamic infrastructures of tomorrow's 'alive'-Web.)

holons to act as autonomous entities, yet cooperating to form apparently self-organizing hierarchies of subsystems, such as the cell/tissue/organ/system hierarchy in biology.
Starting from the empirical observation that, from the Solar System to the Atom the Universe is organized into self-replicating structures of nested hierarchies intrinsically embedded in the functionality of natural systems, in his attempt to creating a model for self-organization in biological systems, Koestler has identified structural patterns of self-replicating structures, named holarchies. Holarchies have been envisioned as models for the Universe's self-organizing structure in which holons at several levels of resolution in the nested hierarchy (Koestler 1968), (Figure 1) behave as autonomous wholes and yet as cooperative parts for achieving the goal of the holarchy.

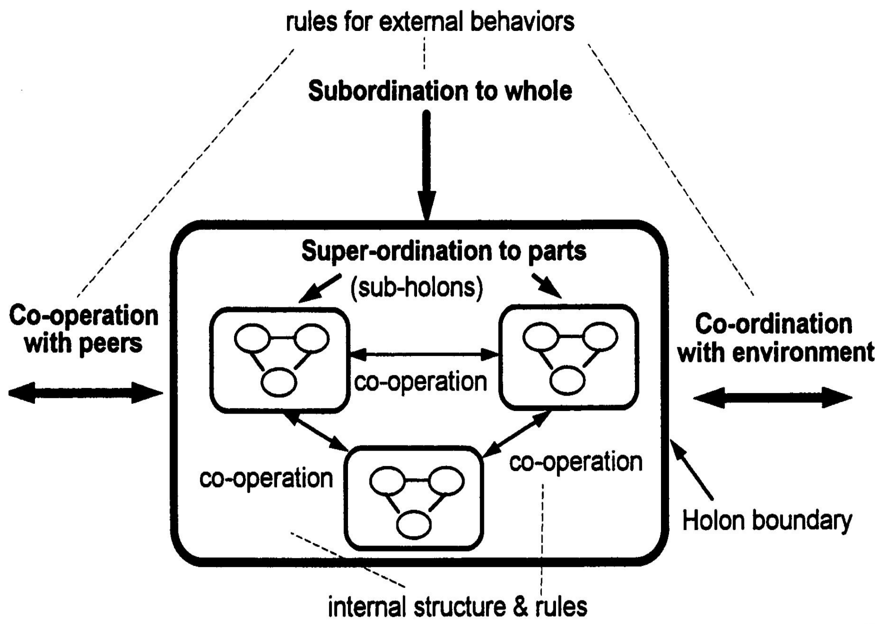


Figure 1. Generic Model of a Holarchy.

In such a nested hierarchy each holon is a sub-system retaining the characteristic attributes of the whole system. What actually defines a holarchy is a purpose around which holons are clustered and subdivided in sub-holons at several levels of resolution according to the organizational dissectibility required. A Confederation is a *political holarchy*, for example having Canada at the highest level of resolution then the provinces at the immediate lower level, and finally the cities at the lowest levels in the hierarchy. Each individual person is regarded as a primitive holon within this social holarchy.
From a software engineering perspective a holon, as a unit of composition retaining characteristic attributes of the whole system (holarchy), can be viewed as a class. Thus the object-oriented paradigm seemed[2] suitable for modeling holarchies as software systems.
Within a holarchy, holons can belong to different clusters simultaneously, displaying *rule-governed behavior*. The rules define a system as a holon with an individuality of its own; they determine its invariant properties, its structural configuration and functional pattern. The greatest challenge faced by holons in a holarchy is 'the whole in the part' dichotomy. As autonomous systems (wholes) holons are animated by autonomy and separation forces while being constraint as parts of the holarchy to work cooperatively with other holons towards the common goal around which the holarchy was formed. The duality autonomy-cooperation as main contradictory forces within a holarchy is balanced by the rules that define the functionality of such a system of semi-autonomous holons (Christensen 1994,

[2] HMS – Strategies, Vol. 1 (Deliverable of WP6, March 1994 – Confidential).

Zhang and Norrie 1999). These rules endow the holons with interdependence, namely the capability of integration as parts within the holarchy. Of crucial importance is that rules ensure coordination with local environment that is with the other holons and sub-holarchies. It has been identified -on a manufacturing holarchy (Shu and Norrie 1999)- that the rules organize the holarchies around patterns of functionality, named generically *patterns of holonic collaboration*, Figure 2, which will be further detailed in the context of the HE.

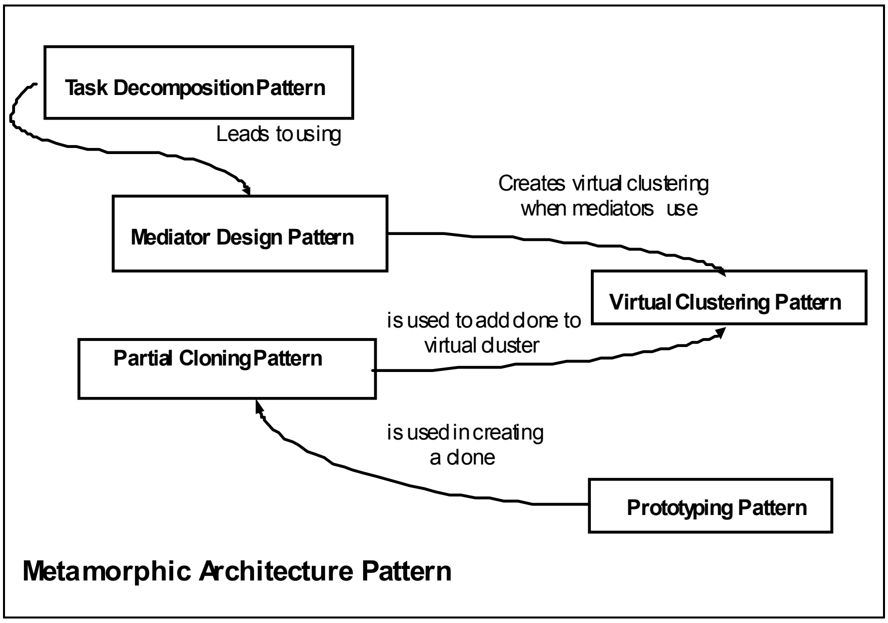


Figure 2. Patterns of Holonic Collaboration

8.2.2 The Universe Encapsulated in Software: Multi-Agent Paradigm

In response to the need for modeling the complexity of interactions in large scale distributed systems, agent technology has emerged (from the AI distributed intelligence task force) as a paradigm for structuring, designing and building software systems that require complex interactions between autonomous distributed (software) components (Woolridge 2001). While the object-oriented paradigm models systems focusing on the structural, static characteristics of their parts which are defined through encapsulation and inheritance, the agent paradigm models systems focusing on the underlining dynamics defined by the *interactions* between their parts. In contrast to the passive way in which objects communicate by invoking methods in one another in a way controlled externally by the user (e.g. from a 'main' program), agents are capable to initiate communication and decide (like a human) when and how to respond to external stimuli (e.g. manifested upon them as requests from other agents). From this perspective the agent paradigm extends the object paradigm in that agents can be regarded as proactive objects (Weiss 1999) that have an internal mechanism which governs their behavior enabling them to initiate action as well as to respond to the outside environment in an autonomous way. With this in mind one can define:

- an intelligent agent as a *software entity* which exhibits, in some significant measure, autonomy, intelligence, and environmental awareness, and which interacts with its environment to achieve internal goals;
- a multi-agent system (MAS) as a software system in which program modules (the individual agents) are given autonomy and intelligence and an underlining coordination mechanism (implementing rules for collaboration, like for holarchies) which enables collaboration between such modules (agents) to attain system objectives

8.2.3 MAS as Software Representations of Holarchies

A software representation of a holarchy thus appears natural as MAS, consisting of autonomous yet cooperative agents. From this perspective a MAS is regarded as a system of agents (software holons) which can cooperate to achieve a goal or objective. The MAS (software holarchy) defines the basic rules for cooperation of the agents (software holons) and thereby limits their autonomy. In this context a**utonomy** is defined as the capability of an entity (agent/holon) to create and control the execution of its own plans and/or strategies while c**ooperation** - as a process whereby a set of entities (agents/holons) develop mutually acceptable plans and execute them.

The debate on clarifying the difference between holons and agents is an ongoing issue in the research communities using these paradigms. Given the essentially different path on which each concept was developed the question itself is inappropriate. Holarchies (Koestler 1968) have been envisioned as models for the Universe's self-organizing structure (Section 8.2.1). On the other side, agents have been envisioned as a software paradigm aiming to expand the limitations of the static object model with proactive capabilities of autonomy and environmental awareness, the emphasis being on the *interaction* between software components rather then on their structure. In the sequel we briefly present the main characteristics of the holonic and MAS paradigms (Woolridge 2001).

Thus, holonics is an *organizational paradigm* (inspired by the self-organizing properties of natural systems) which models organizations as nested clusters (holons) of sub-organizations (sub-holons) driven towards a common purpose by collaborative rules. The rules act as forces that coordinate interactions between sub-holons working together towards to common purpose. MAS is a *software paradigm* which aims to represent dynamical systems in software by focusing on the interactions between their parts (modeled as software agents).

The common denominator between holonics and MAS as paradigms is obviously the focus on the dynamics of the interactions, however in a MAS there is no pre-assigned condition that the interactions should be driven by cooperative forces, while in a holonic system this is a precondition for the existence of the holarchy per se (the glue that binds the holarchy together driving it towards the common goal.) It is this 'team-spirit' that characterizes a holarchy, in that all its component parts at all levels of resolution work together towards achieving the goal in an optimal manner. This 'togetherness' drives the self-organizing power that configures all the sub-holons to optimize the interactions within the holarchy to reach the common goal with maximum efficiency. On the other side in a MAS agents may interact based on competitive rather than cooperative rules (e.g. electronic markets or other competitive/conflicting environments such as military scenarios; competing over resources or societal/political disputes, etc.) – which is excluded as a possibility in a holarchy.

Organizational hoarchies are real-world entities (as we exemplified before Canada as a Confederation being a political holarchy. Other examples are: a global enterprise is a collaborative purpose-driven/market-driven holarchy; a distributed manufacturing system is a production-driven holarchy, the organism is a survival-driven holarchy, The Universe is an evolution-driven holarchy.

As elements of such organizational holarchies, holons per se are by no means software entities. Thus a 'comparison' with agents does not really make sense. In the manufacturing domain (Ulieru *et al.* 2000) however holons have been considered to be software and physical entities alike, in a co-habitation nature-software expressed through the concept of 'partial cloning' of a physical entity (either a human or a manufacturing machine/robot) as software entity which encapsulates those characteristics abstracted from the real entity needed in the particular collaborative context of the holarchy. Thus one distinguishes two ontological levels in a manufacturing holarchy, Figure 3: a physical one (humans and machines cooperating to fulfill the production needs optimally) and a logical (software) one, which emulates the physical one through software entities (objects or agents) to enable the coordination of production through intelligent control procedures (Brennan 2000). The software representation of the manufacturing holarchy enables emulation of production with distribution of the scheduled tasks on the various software agents ‘cloning’ the physical machines and once an optimal configuration solution has been reached the appropriate control law is deployed from the software agent on the appropriate physical machine at the appropriate time[3] (Zhang and Norrie 1999).

An intrinsic issue in manufacturing holarchies is thus co-habitation physical holons – software agents. In such a manufacturing co-habitation context the concepts of holon and agent merge and software agents are regarded as holons (but not vice versa, of course). From this perspective, as a software paradigm MAS appears to be an excellent tool for emulating holarchies. A MAS which emulates a holonic system will consists of agents driven by a coordination mechanism designed according to the rules for cooperation of the respective holarchy. With this in mind it is easy to point that software holarchies are specialized MAS that define the interaction between their agents based on the underlining cooperative holonic model. Such software ‘holons’ appear to be specialized agents that have a particular structure and holonic properties, that is they are decomposable into sub-agents which work cooperatively towards a common goal of the holarchy.

8.2.4 The Web as a Living Organism: Global Enterprises as Holarchies

The tremendous progress of information and communication technologies has transformed our World to an extent to which real-life entities virtually “exist” in a parallel Universe of information. The World Wide Web connects by invisible links these entities through their virtual “clones” forming “societies” in which the virtual entities (mostly modeled as software agents) have their own “life” interacting with an autonomy of their own. Implementing an organizational holarchy (real life system) into software using the MAS paradigm opens the perspective of regarding the Web as a “living organism” consisting of a society of agents that emulates different contexts of the world cloned in software according to the abstractions needed for the specific contextual purpose that determines the holarchy.

In such holarchies enterprises can be partially “cloned” as agents to interact and form global virtual organizations. Two main paradigms have emerged supported by this technological development.

8.2.4.1 The Web-Centric Paradigm: Glue in Virtual Organizations

The use of the World Wide Web in business has radically altered expectations regarding the appropriate infrastructure for enterprise systems. The Web-Centric Enterprise[4] (Hornberger 2001) is a novel business model that provides a foundation on which companies can build processes and procedures to create products for their customers within the context of today's market dynamics in which systems need to be able to accommodate unique customer requirements, both upon initial implementation and over time. Unlike existing point solutions that focus on a single-department or activity product, such as data management or product-design-and-manufacturing, the Web-Centric model addresses product and process life cycle management across the extended enterprise regarded as a global organization. At the core of the Web-Centric Enterprise model is a breakthrough in information technology infrastructure conceptualization, namely the internet-enabled

[3] http://www.holobloc.com/.
[4] http://www.hourgroup.com/e-energy/reg2001.html

software infrastructure acting as a worldwide open DSE (footnote 1). Such an integrated framework enables sharing of information, services and applications among suppliers, employees, partners and customers via:

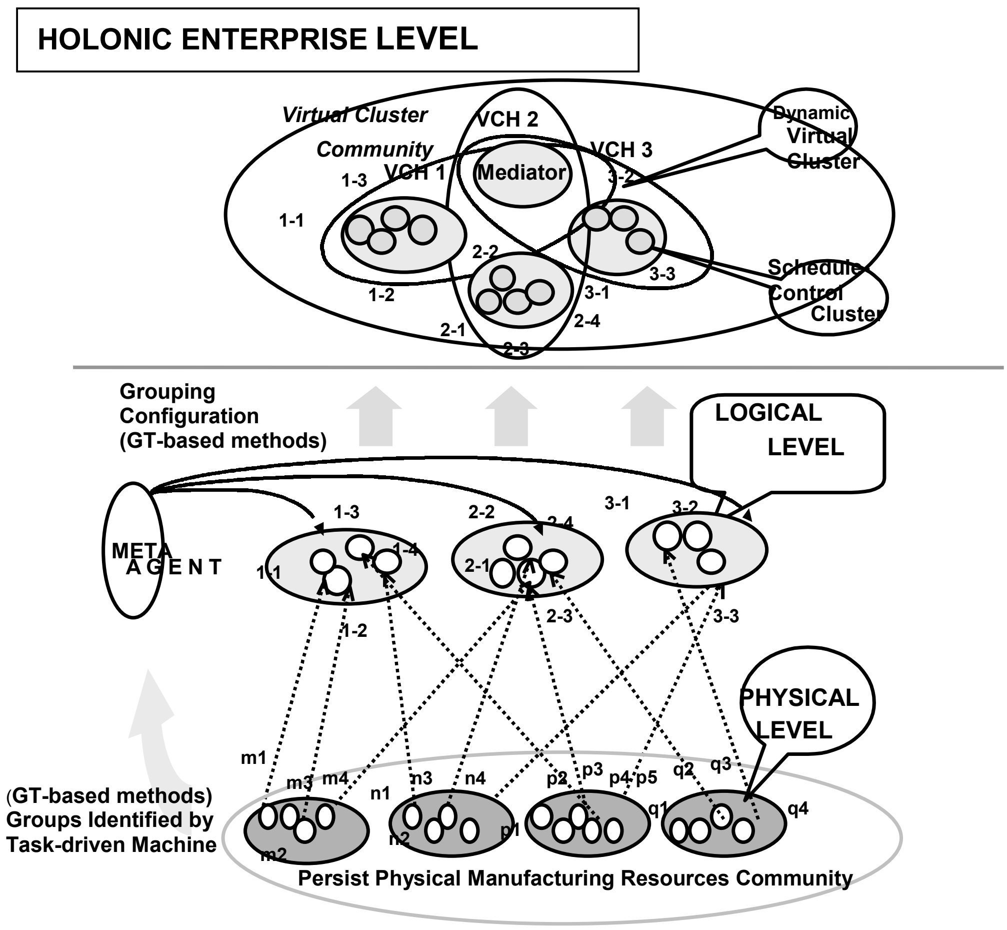


Figure 3. Logical and Physical Level in a Holonic Enterprise

- Deployment of automated, intelligent software services (e.g., internet-enabled negotiations, financial transactions, advertising and bidding; order placement/delivery, automatic order tracking and reporting, etc.)
- Complex interactions between such services (e.g., compliance policies; argumentation and persuasion via complex conversation protocols, bargaining, etc.);
- Dynamic discovery and composition of services to create new compound value added services (e.g., dynamic virtual clustering of synergetic partnerships of collaborative organizations aiming to achieve a common goal, finding and accessing an unknown service that is available on the Web, matching of different templates from different sources to design a product optimally, etc.).

Such a dynamic Web synergistically glues different dispersed organizations/resources into an added value holarchy capable to accomplish more then the sum of each individual organization/resource could.

8.2.4.2 Bringing The World Together: The Virtual Enterprise (VE) Paradigm

A virtual organization or company is one whose members are geographically apart, usually working by electronic linking via computers while appearing to others to be a single, unified organization with a real physical location. Within a virtual organization work cannot be completed without support of an information technology infrastructure in linking the parts.

The VE (VE) paradigm differs from the Web-centric paradigm in that a VE is a distinct organizational form, not just a property of any organization. Thus, Web-centric organizations that can use communications extensively, but not in a way critical in fulfilling the goal of the organization (e.g., a multinational corporation with dispersed parts being on the same satellite network whose use, however, is not critical for completing the production process) are not VE. In today's global economy in which enterprises put together their competitive advantage to leverage a higher purpose otherwise impossible to achieve the VE is an appropriate model for strategic partnerships. Such a strategic partnership model calls for new perspectives on competition in the global open internet-enabled economy.

8.2.5 Balancing Autonomy and Cooperation in the Networked Economy: The Co-opetition Paradigm

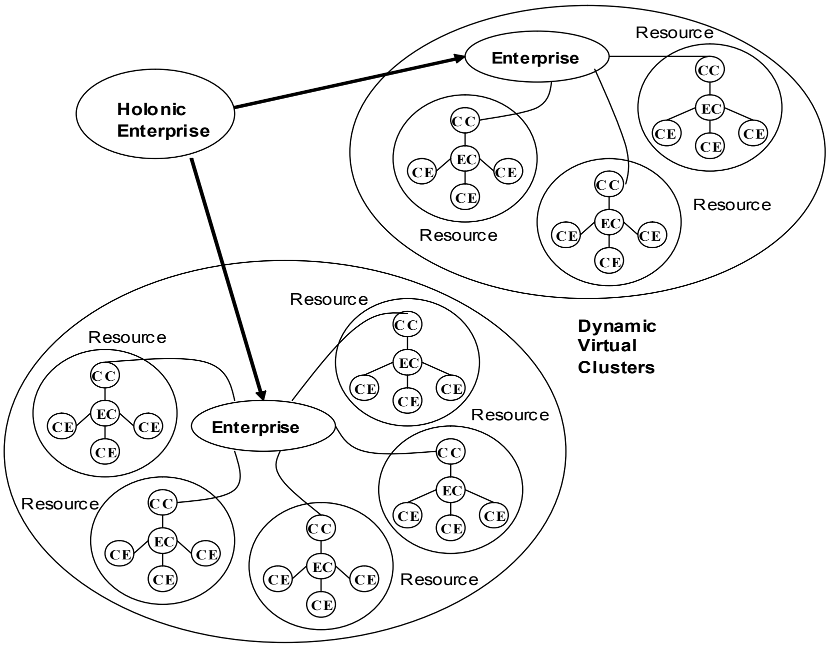
The new economy mandates the shift from industrial age, "brick and mortar" strategic thinking to an emphasis on new alliances and a rethinking of traditional partnerships. Alliances and partnerships can be formed in ways that increase value for all players. The concept of co-opetition (Brandenburger and Nalebuff 1996) builds on the duality inherent in all relationships with respect to win-win and win-lose interactions. The success of most businesses is dependent on the success of others, yet they must compete to capture value created in the market and protect their own interests. The main issues to be addressed when developing a business strategy based on co-opetition are:

- Who are the players in the network and how can they collaborate to maximize value?
- Which relationships are complementary in nature (which companies can add value to what they provide)?
- Which players are competitors, and are there mutually beneficial ways to create value?
- What should they do to leverage relationships with customers and suppliers?
- What can they do to sustain their competitive advantage over time?

From this perspective we can regard the global enterprise as a holarchy whose holons interact according to co-opetition rules implemented as strategies for negotiation, collaboration, cooperation and other coordination mechanisms defining the patterns of holonic collaboration according to which the holarchy functions.

8.3 The Holonic Enterprise as an Information Ecosystem

Considering VEs as holarchies of web-glued enterprises, which are modeled as MAS - naturally leads to the concept of HE, Figure 4. Thus a HE is a holarchy of collaborative enterprises, where each enterprise is regarded as a holon and is modeled by a software agent with *holonic* properties, so that the software agent may be composed of other agents that behave in a similar way but perform different functions at lower levels of resolution. There are three levels of resolution within the HE holarchy (Ulieru *et al.* 2002):



Dynamic Virtual Clustering Pattern in a Holonic Enterprise

Figure 4. Holonic Enterprise as an Information-Ecosystem

8.3.1 Inter-enterprise, global collaboration level

At this level several holon-enterprises cluster into a collaborative holarchy to produce a product or service. The clustering criteria support maximal synergy and efficiency. Traditionally this level was regarded as a mostly static chain of customers and suppliers through which the workflow and information was moving from the end customer that required the product to the end supplier that delivered it. In the HE the *supply chain* paradigm is replaced by the *collaborative holarchy* paradigm. With each collaborative partner modeled as an agent that encapsulates those abstractions relevant to the particular cooperation, a dynamic virtual cluster emerges that can be configured on-line according to the collaborative goals.

8.3.2 Intra-enterprise level

Once each enterprise has undertaken responsibility for the assigned part of the work, it has to organize in turn its own internal resources to deliver on time according to the coordination requirements of the collaborative cluster. Planning and dynamic scheduling of resources at this level enable functional reconfiguration and flexibility via (re)selecting functional units, (re)assigning their locations, and (re)defining their interconnections (e.g., rerouting around a broken machine, changing the functions of a multi-functional machine). This is achieved through a replication of the dynamic virtual clustering mechanism having now each resource within the enterprise cloned as an agent that abstracts those functional characteristics relevant to the specific task assigned by the collaborative holarchy to the partner.

8.3.3 Basic resource level

To enable the resource management through the DSE each resource (machine; human; information entity) is cloned as an agent that abstracts those parameters needed for the

configuration of the holonic production system.
Thus the HE paradigm links the three levels of a global collaborative organization to build a web-centric ecosystem partnering in which the workflow is harmoniously managed through the dynamic information infrastructure (the logical level in Figure 3) that links the resources of all involved organizations (the physical level in Figure 3).

8.3.4 Patterns of Holonic Collaboration

The coordination backbone for a HE is based on the patterns of holonic collaboration (Figure 2). They follow the design patterns for adaptive MAS identified in (Shu and Norrie 1999). The overall architecture of the HE builds on the Metamorphic Architecture Pattern (Maturana and Norrie 1996) that replicates at all levels. This pattern works by synergetic integration of two other patterns

- **Dynamic Virtual Clustering** This pattern is facilitated by the general layered architecture of the HE. The dynamic virtual clustering pattern plays a crucial role in that it embeds the self-organizing properties of a HE. The main responsibility of this pattern is to configure the enterprise to minimize cost enabling for flexible, re-configurable structures. At all levels of the HE, task propagation occurs by a process of virtual cluster (or holarchy) formation. It is debatable if this pattern should be implemented by mutual adjustment mechanisms (in a totally decentralized manner which would leave room for maximum autonomy in the holarchy) or via a mediator - Figure 3 (Maturana and Norrie 1996). This implementation (which is suitable for manufacturing holarchies) places the control of the holarchy into a mediator agent and by this reduces the degree of autonomy of the individual holons in the HE.
- **Mediator Agent Pattern** supporting the decision-making process that creates and (re)-configures the dynamic virtual clusters of collaborative entities, eventually by adding/removing entities to/from the holarchy.
- **Partial Cloning Pattern.** This pattern defines which of the enterprise's characteristics (attributes and functionality) we need to abstract into agents at each level when modeling the HE as a collaborative multi-agent system.
- **Task Decomposition-Distribution Pattern.** This pattern is enhanced with capability to distribute harmoniously among the participants, the overall task assigned to the collaborative holon, at each level. The main mechanisms by which this pattern works are:
  - ***task distribution among the cluster's entities*** (outside-in view from the mediator "down" into each collaborative partner at that level) and
  - ***task deployment within each entity*** (inside-out view – from the entity, regarded as a holon with distributed resources available to it for accomplishing the assigned task, to the mediator).
- **Ontology Pattern.** This consists of two kind of ontologies:
  - for **'peer-to-peer'** communication within each level (that is **'inter-agent' communication among entities that form a cluster);**
  - for **'inter-level' communication** that enables deployment of tasks assigned at higher levels (by the mediator) on lower level clusters of resources as well as reporting (from the lower level to the higher) of emergency situations for which rescheduling/re-planning reconfiguration are required.

For more details on the flow of information among the three levels of the HE as well as on the interaction between the physical and logical level please see (Ulieru *et al.* 2002).
In the sequel we propose a fuzzy-evolutionary approach that implemented within the mediator - Figure 3 (Maturana and Norrie 1996) - stabilizes the HE in an optimal structure by first configuring it through optimal clustering of the existing resources via fuzzy entropy

minimization (Section 8.4) then by expanding the search on the dynamic Web for even better resources to iteratively replace the old ones (Section 8.5).

8.4 Emergence of Holonic Enterprises from Virtual Enterprises: The Natural Order is Holonic

The first part of this approach is an implementation of the dynamic virtual clustering pattern that optimizes the information and resource management across the HE to fulfill in the most efficient way the holarchy goal. The main idea is to minimize the entropy in the information spread across the VE (modeled as a multi-agent system) – such that each holon maximizes its knowledge of the task it is assigned, in order to best accomplish it. This naturally leads to the (self)organization of the VE in a holarchy (which defines a HE).

We consider the holarchy having its resources predefined and represented as software agents at the logical level of the HE. At this level the holarchy is regarded as a MAS. Our purpose is to organize the HE such that it can accomplish the goal (say manufacturing of a certain product) with minimal cost. This calls for all the resources to be loaded at optimal capacity through a harmonized flow of information and material across the HE. Given that we aim to attain and preserve this perfect order in the holarchy it seems natural to attempt this by minimizing the entropy measuring the degree of order in the information spread across the holarchy's resources.

To enable a mathematical formalism that can support this purpose we regard a MAS as a dynamical system in which agents exchange information and organize it through reasoning into knowledge about the assigned goal (Ulieru and Ramakhrishnan 1999). Optimal knowledge at the holarchy's highest level of resolution (inter-enterprise level) corresponds to an optimal level of information organization and distribution among the agents within all levels of the holarchy. We consider the entropy as a measure of the degree of order in the information spread across the multi-agent system modeling the holarchy. One can envision the agents in the MAS as being under the influence of an information "field" which drives the agent interactions towards achieving "equilibrium" with other agents with respect to this entropy[5].

This information is usually uncertain, requiring several ways of modeling to cope with the different aspects of the uncertainty. Fuzzy set theory offers an adequate framework for dealing with this uncertainty (Klir and Folger 1988). Therefore we will use the generalized fuzzy entropy (Zimmermann 1991) to measure the degree of order in the information spread across the holarchy. The generalized fuzzy entropy is the measure of the "potential" of this information field and *equilibrium* for the agents under this influence corresponds to an optimal organization of the information across the MAS with respect to the assigned goal's achievement (Ulieru and Ramakhrishnan 1999). When the circumstances change across the holarchy (due to unexpected events, such as need to change a partner that went out of business, machine break-down, raw materials unavailable, etc.) the equilibrium point changes as well inducing a new re-distribution of information among the agents with new emerging agent interactions.

We start with the assumption that only the set of resources available for the holarchy formation is given (that is we know the enterprises that will collaborate to accomplish the pre-set goal) and we aim to organize these enterprises such that their resources are optimally used to accomplish the goal most efficiently (minimal cost and time). In short we have a VE with several distributed partners linked via the dynamic Web and we want to

[5] The information 'field' acts upon the agents much in the same manner as the gravitational and electromagnetic fields act upon physical and electrical entities respectively.

organize it such that it accomplishes a certain goal optimally. In the sequel we will prove mathematically that the optimal organizational structure of the distributed partners' resources is a holarchy, so a HE enterprise emerges from the VE.

8.4.1 A Framework for Capturing Uncertainty in MAS

Denote by $\mathbb{A}_N = \{a_n\}_{n\in\overline{1,N}}$ the set of $N \geq 1$ agents that belong to the MAS modeling a VE. Based only on the initial uncertain information, one can build a family $\mathbb{P} = \{\mathbb{P}_k\}_{k\in\overline{1,K}}$, containing $K \geq 1$ collections of clustering configurations, for a preset global goal (Figure 3). Each $\mathbb{P}_k$ ($k \in \overline{1,K}$) can be referred to as a *source-plan* in the sense that it can be a source of partitions for a MAS plan. Thus, a source-plan is expressed as a collection of $M_k \geq 1$ different clustering configurations in which the agents team-up to accomplish the enterprise goal: $\mathbb{P}_k = \{P_{k,m}\}_{m\in\overline{1,M_k}}$. The only available information about $\mathbb{P}_k$ is the *degree of occurrence* associated to each of its clustering configurations (Figure 3), $P_{k,m}$, which can be assigned as a possibility measure (Dubois and Prade 1988), $\alpha_{k,m} \in [0,1]$. Thus, the corresponding degrees of occurrence are members of a two-dimension family $\{\alpha_{k,m}\}_{k\in\overline{1,K};m\in\overline{1,M_k}}$, which quantifies all the available information about the MAS modeling the VE.

We aim to construct a measure of uncertainty, V (from "vagueness") (Klir and Folger 1988), fuzzy-type, real-valued, defined on the set of all source-plans of $\mathbb{A}_N$ and optimize it in order to select the *least vague* source-plan from the family $\mathbb{P} = \{\mathbb{P}_k\}_{k\in\overline{1,K}}$:

$$\mathbb{P}_{k_0} = \underset{k\in\overline{1,K}}{\arg\operatorname{opt}} V(\mathbb{P}_k), \text{ where } k_o \in \overline{1,K} \tag{1}$$

The cost function V required in problem (1) will be constructed by using a *measure of fuzziness* (Klir and Folger 1988). We present hereafter the steps of this construction.

8.4.2 Modeling Agent Interactions via Fuzzy Relations

We model agent interactions through fuzzy relations considering that two agents are in relation if they exchange information. As two agents exchanging information are as well in the same cluster one can describe the clustering configurations by means of these fuzzy relations. The family of fuzzy relations, $\{\mathbb{R}_k\}_{k\in\overline{1,K}}$, modeling the clustering possibility over the MAS agents($\mathbb{A}_N$) is built using the possibility measures $\{\alpha_{k,m}\}_{k\in\overline{1,K};m\in\overline{1,M_k}}$ and the family of source-plans $\{\mathbb{P}_k\}_{k\in\overline{1,K}}$. Consider $k \in \overline{1,K}$ and $m \in \overline{1,M_k}$ arbitrarily fixed.

In construction of the fuzzy relation $\mathbb{R}_k$, one starts from the observation that associating agents in clusters is very similar to grouping them into *compatibility* or *equivalence classes*, given a (binary) crisp relation between them. The compatibility properties of reflexivity and symmetry are fulfilled for covers (overlapped clusters), whereas the equivalence conditions of compatibility and transitivity stand for partitions. The corresponding crisp relation denoted by $R_{k,m}$, can be described by the statement: *two agents are related if they belong to the same cluster*. The facts that a and b are, respectively *are not* in the relation $R_{k,m}$ (where $a,b \in \mathbb{A}_N$) are expressed by "$aR_{k,m}b$" and "$a \neg R_{k,m} b$" respectively. The relation $R_{k,m}$ is a $N \times N$ matrix $H_{k,m} \in \Re^{N \times N}$ - the *characteristic matrix* which completely specifies the configuration $P_{k,m}$. Consequently, we can construct an elementary fuzzy (binary) relation $\mathrm{R}_{k,m}$ whose membership matrix is expressed as the product between the characteristic matrix $H_{k,m}$, and the degree of occurrence $\alpha_{k,m}$, that is: $\alpha_{k,m} H_{k,m}$. This fuzzy relation of $\mathbb{A}_N \times \mathbb{A}_N$ is also uniquely associated to $P_{k,m}$. If $k \in \overline{1,K}$ is kept fixed, but m varies in the range $\overline{1,M_k}$, then a family of fuzzy elementary relations is generated: $\{\mathrm{R}_{k,m}\}_{m \in \overline{1,M_k}}$. Naturally, R_k is then defined as the fuzzy union. Thus a bijective map associating a family of source plans $\mathrm{P} = \{\mathrm{P}_k\}_{k \in \overline{1,K}}$ to a fuzzy relation measuring their possibility of occurrence $\mathrm{R} = \{\mathrm{R}_k\}_{k \in \overline{1,K}}$, can be built:

$$T(\mathrm{P}_k) = \mathrm{R}_k \;, \; \forall k \in \overline{1,K} \tag{2}$$

8.4.3 Fuzzy Entropy as a Measure of Order in MAS

A measure that evaluates "the fuzziness" of a fuzzy set by taking into consideration both the set and its (fuzzy) complement is the *Shannon measure*, derived from the generalized Shannon's function:

$$\begin{bmatrix} S : [0,1]^M \quad \to \Re_+ \\ (x_1,\ldots,x_M) \mapsto S(x) \overset{def}{=} -\sum_{m=1}^{M} \left[x_m \log_2 x_m + (1-x_m)\log_2(1-x_m) \right] \end{bmatrix} \tag{3}$$

If the argument of this function is a probability distribution, it is referred to as *Shannon entropy*. If the argument is a membership function defining a fuzzy set, it is refereed to as *(Shannon) fuzzy entropy* (Zimmermann 1991). Denote the fuzzy entropy by S_μ. Then, according to equation (3), S_μ is expressed for all $k \in \overline{1,K}$ by:

$$S_\mu(\mathrm{R}_k) = -\sum_{i=1}^{N}\sum_{j=1}^{N} \mathrm{M}_k[i,j] \log_2 \mathrm{M}_k[i,j] - \sum_{i=1}^{N}\sum_{j=1}^{N} [1-\mathrm{M}_k[i,j]] \log_2 [1-\mathrm{M}_k[i,j]]. \tag{4}$$

Although a unique maximum of Shannon fuzzy entropy (4) exists, we are searching for one of its minima that corresponds to a most efficient resource clustering in the VE. The required measure of uncertainty, V, is obtained by composing S_μ in (4) with T in (2), that is: $V = S_\mu \circ T$. Since T is a bijection, the optimization problem (1) is equivalent with:

$$\mathrm{P}_{k_0} = T^{-1}(\arg\min_{k\in\overline{1,K}} S_\mu(\mathrm{P}_k)) \text{ , where } k_o \in \overline{1,K} . \qquad (5)$$

8.4.4 Building the Optimal Configuration of the Multi-Agent System modeling the VE

P_{k_0} is the least fuzzy (minimally fuzzy), i.e. the least uncertain source-plan. The fuzzy relation encoding the agent clustering to fulfill the VE goal according to this optimal plan, R_{k_0} is useful in the reverse construction of a *least uncertain plan*, as follows. Once one pair ($\mathrm{P}_{k_0}, \mathrm{R}_{k_0}$) has been selected by solving the problem (5), a corresponding source-plan should be identified.
The α-cuts of R_{k_0} are the crisp relations $R_{k_0,\alpha}$, for degrees of membership $\alpha \in [0,1]$. The characteristic matrix elements of $R_{k_0,\alpha}$ are defined by:

$$H_{k_0,\alpha}[i,j] \overset{def}{=} \begin{cases} 1 \text{ , if } M_{k_0}[i,j] \geq \alpha \\ 0 \text{ , otherwise} \end{cases} , \forall i,j \in \overline{1,N} \qquad (6)$$

Each matrix $H_{k_0,\alpha}$ in (6) describes a unique clustering configuration of agents over A_N. Thus, two categories of source-plans emerge: *equivalence* or *holonic source-plans* (when R_{k_0} is a similarity relation) and *compatibility source-plans* (when R_{k_0} is only a proximity relation).

- When R_{k_0} is a *similarity relation*, then clusters are associated in order to form new clusters, and a nested hierarchy emerges that organizes the MAS modeling the VE into a holarchy (that is a HE emerges from the VE[6]).
- When R_{k_0} is only a *proximity* relation, tolerance (compatibility) classes can be constructed as collections of eventually overlapping clusters (covers). This time, the fact that clusters could be overlapping (i.e. one or more agents can belong to different clusters simultaneously) reveals the capacity of some agents to play multiple roles by being involved in several tasks at the same time while the holonic properties of the organization are still preserved.

This proves that the optimal organizational structure in a virtual organization is a holarchy.

8.4.5 Virtual Clustering Mechanism

The procedure by which the virtual clustering pattern can be designed to ensure an optimal clustering of resources for most efficient goal accomplishment by the virtual organization is:

[6] a (unique) similarity relation can be constructed starting from the proximity relation R_{k_0}, by computing its *transitive closure*. Thus, the potential holonic structure of MAS can be revealed, even when it seems to evolve in a non-holonic manner.

START

- Initial data: the number of agents: N; the collection of K source-plans: $\mathtt{P} = \{\mathtt{P}_k\}_{k \in \overline{1,K}}$; the occurrence degrees (possibility measures): $\{\alpha_{k,m}\}_{k \in \overline{1,K}; m \in \overline{1,M_k}}$.

- For $k \in \overline{1,K}$:
  - For $m \in \overline{1,M_k}$:

    a. Construct the characteristic matrix $H_{k,m}$ associated to configuration $P_{k,m}$ (Section 8.4.2).

    b. Multiply $H_{k,m}$ by $\alpha_{k,m}$ ($H_{k,m} \leftarrow \alpha_{k,m} H_{k,m}$).
  - Construct the membership matrix of fuzzy relation $\mathtt{R}_k$ by: $\mathtt{M}_k = \underset{m \in \overline{1,M_k}}{\max \bullet} \{H_{k,m}\}$.

[where "$\max\bullet$" acts on matrix elements and not globally, on matrices.]

  - Compute the vagueness of $\mathtt{R}_k$ (by using the symmetry, Section 8.4.3):

$$S_\mu(\mathtt{R}_k) = -2\sum_{i=1}^{N}\sum_{j=i+1}^{N} \mathtt{M}_k[i,j] \log_2 \mathtt{M}_k[i,j] - 2\sum_{i=1}^{N}\sum_{j=i+1}^{N} [1 - \mathtt{M}_k[i,j]] \log_2 [1 - \mathtt{M}_k[i,j]].$$

- Solve the problem: $\mathtt{R}_{k_0} = \arg \min_{k \in \overline{1,K}} S_\mu(\mathtt{R}_k)$.

- List the Solution: The least vague source-plan is $\mathtt{P}_{k_0}$.
- Other alternatives desired?

Yes

  - Construct $\mathtt{Q}_{k_0}$ - the transitive closure of $\mathtt{R}_{k_0}$:

    c. Set $\mathtt{M}_{k_0}^{\mathtt{R}} = \mathtt{M}_{k_0}$.

    d. Compute: $\mathtt{M}_{k_0}^{\mathtt{Q}} = \max\bullet \left\{\mathtt{M}_{k_0}^{\mathtt{R}}, \left(\mathtt{M}_{k_0}^{\mathtt{R}} \circ \mathtt{M}_{k_0}^{\mathtt{R}}\right)\right\}$.

    e. If $\mathtt{M}_{k_0}^{\mathtt{R}} \neq \mathtt{M}_{k_0}^{\mathtt{Q}}$,

    Then: replace the matrix $\mathtt{M}_{k_0}^{\mathtt{R}}$ by $\mathtt{M}_{k_0}^{\mathtt{Q}}$ ($\mathtt{M}_{k_0}^{\mathtt{R}} \leftarrow \mathtt{M}_{k_0}^{\mathtt{Q}}$) and jump to step d.

    Else: $\mathtt{M}_{k_0}^{\mathtt{Q}}$ is the membership matrix of the transitive closure $\mathtt{Q}_{k_0}$.

  - If $\mathtt{M}_{k_0} \neq \mathtt{M}_{k_0}^{\mathtt{Q}}$

Then: $\mathtt{R}_{k_0}$ is just a proximity relation and a compatibility source-plan $\mathtt{P}_{k_0}^{C}$ is obtained by computing its α-cuts.

Else: Q_{k_0} is a similarity relation and a holonic source-plan $P_{k_0}^H$ is obtained by computing the corresponding α-cuts.

No

STOP

Designing the virtual clustering pattern by this procedure endows the VE with self-organizing properties that ensure emergence of the optimal holonic structure once the resources are known (that is once the distributed partners have committed to the common goal and allocated the resources they want to put in to accomplish it.) Thus the above procedure ensures emergence of an optimal HE from any predefined virtual organization.

However one more step is required to cope with the high dynamics of today's Web-centric economy, namely capability to include new partners in the virtual organization. The next section addresses this issue.

8.5 Evolution of the HE in Cyberspace Towards the Best Structure

In the open environment created by the dynamic Web opportunities for improvement of an existing virtual organization arise continuously. New partners and customers alike come into the virtual game bidding their capabilities and money to get the best deal. Staying competitive in this high dynamics requires openness and ability to accommodate chance rapidly through a flexible strategy enabling re-configuration of the organization to be able to respond to new market demands as well as to opportunities (e.g. in playing with a better partner when needed.) In response to this need we have designed an evolutionary search strategy that enables the virtual organization to continuously find better partners fitting the dynamics of its goals as they change according to the market dynamics.

8.5.1 An Evolutionary Search Model for New Agents that Fit Better the HE Objective

We regard 'the living Web' (Subsection 8.2.5) as a genetic evolutionary system. The selection of the agents (partners) that best fit the holarchy's objective is done in a similar way to the natural selection by 'survival of the fittest' through which the agents/partners that best suit the HE with respect to the goal accomplishment are chosen from the offers available on the Web. In this search model the mutation and crossover operators (p_m and p_c) represent probabilities of finding 'keywords' (describing the attributes required from the new partners searched for) inside the search domain considered. Our construction is based on the observation that the search process on an agent domain[7] (Ulieru *et al.* 2001) containing information about a set of agents that "live" on the Web - e.g. a directory "look-up"-like table of "yellow page" agents describing the services that the possible partners offer (Ulieru *et al.* 2000) - is analogous to the genetic selection of the most suitable ones in a population of agents meant to "fit" the virtual organizations' goals.

[7] See the FIPA architecture standard at www.fipa.org

The main idea is to express the fitness function (measuring how well the new agent fits the holarchy's goal) in terms of the fuzzy entropy (4):

$$F = S_\mu \tag{7}$$

With this, minimizing the entropy across the extended MAS (which includes the agents from the search domain) according to HE goal-reach optimization equates optimizing the fitness function which naturally selects the best agents fitting the optimal organizational structure of the HE. In the sequel we present the mathematical formalism for this evolutionary search.

8.5.2 A Fuzzy Measure for Search Relevance Evaluation

The first step in our construction is to define a measure of relevancy for the search of new agents, based on which partners that better fit the HE goal-reach optimum can be found on the Web to replace the existing ones that are less suitable. That is:

$$S_\mu' < S_\mu \tag{8}$$

where S_μ' is the entropy for the HE with the new partners and S_μ - for the initial HE. According to (7), (8) collapses into

$$F' < F \tag{9}$$

(where F' is the fitness function for the HE with new partners) meaning that the new partners better fit the system's goal-reach.

In the previous Section we have proven that minimizing S_μ leads to a fuzzy relation that encodes the best clustering configuration for the HE. This fuzzy relation being either a proximity or a similarity measure it is intuitive to consider it as a good measure for the relevancy of the new agents to the HE goal-reach. Defining for example the fuzzy relation R_k in (2) as a preference relation encoding, e.g. the desire of agents to work cooperatively, gives a relevancy measure that perfectly fits the purpose of the search for better partners. That is – when agents are found for which the preference is higher then for the existing ones, they should replace the old ones. This increases the membership values of the preference relationship, which indicates that the relevance relative to our search is higher. So defining R_k as a preference relationship, leads to the following definition of the relevancy measure **R**:

$$\mathbf{R} = \mathrm{R}_{k_0} = \arg\min_{k \in \overline{1,K}} S_\mu(\mathrm{R}_k) \tag{10}$$

From (10) it results that the higher the preference, the smaller the entropy (and accordingly the fitness (7) of the new agents into the holarchy).

8.5.3 The Dynamic Web Regarded as an Evolutionary System

With this we are ready to present the algorithm that searches for better partners in Cyberspace. We initialize the search process as follows:

(a) The initial population (*phenotype*) consists of the existing agents in the HE before the search.

(b) Calculate **R** for the phenotype
(c) Rank the preferences and determine the optimal source plan (5) by computing the corresponding α-cuts.
(d) The preferences for the optimal source plan represented as binary strings constitute the *genotype*. They encode all the relevant information needed to evolve the HE towards a better structure by selecting better agents while searching on an expanded domain.
(e) The phenotype evolves by reproduction according to how the probabilities of mutation and crossover (p_m and p_c) affect the genotype (Fogel 1998). Each chromosome of the population (in the genotype) will be randomly affected.

We define p_m and p_c to be the probabilities of finding agents in Cyberspace that better fit the HE context. Such agents will have higher preferences (10) then the ones in the phenotype. Michalenicz (Michalenicz 1992) has proven experimentally that e.g. choosing $p_m \leq 1\%$, $p_c = 20 \div 30\%$ leads to convergence of the genetic algorithm. With this the evolutionary search, Figure 5, is done as follows:

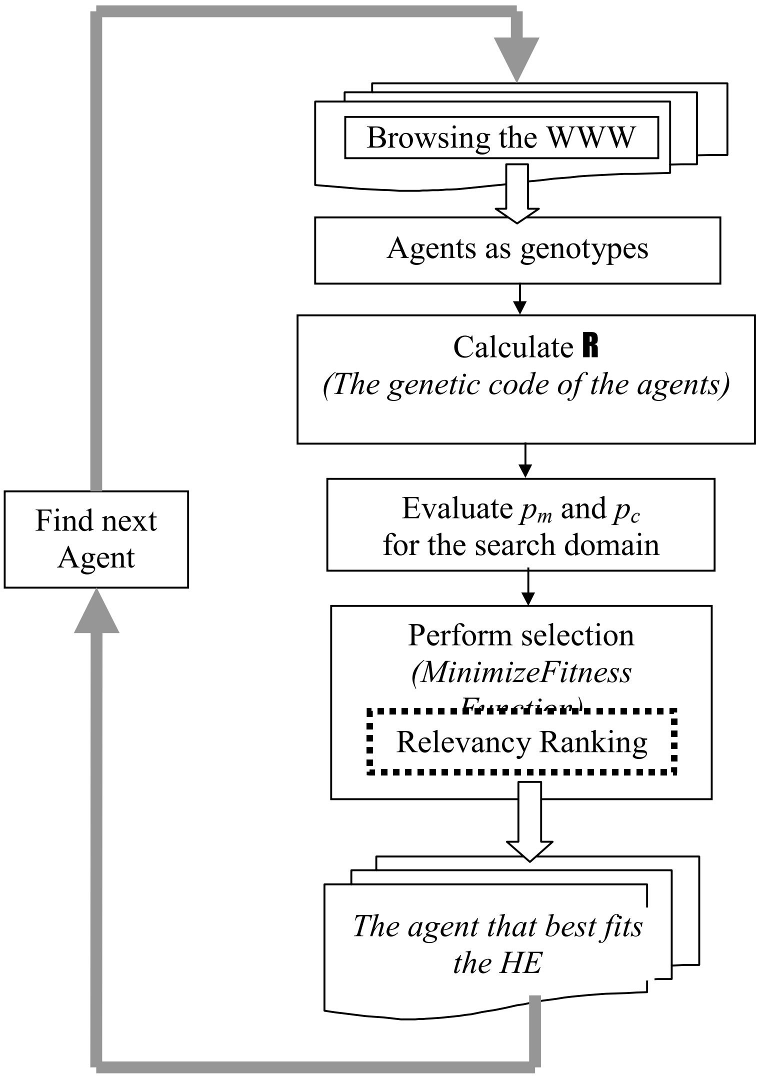


Figure 5. The dynamic search in Cyberspace

(f) Define the goal of the search as maximizing **R** that is: select those agents for which preferences are higher then the highest existing ones, and replace by them the agents with lowest preferences.

(g) Define the search domain, e.g. a standard FIPA agent domain (see footnote 7)[8].
(h) The search process on the chosen agent domain is done by genetic selection of the agents that have highest preferences -using to any classical genetic algorithm (Fogel 1998).
(i) Once the agent domain has been entirely explored a new search is carried on for the next agent domain recommended by the yellow page agent.

The essence of this evolutionary search process stems from the recursive modification of the chromosomes in the genotype in each generation while monitoring the fitness function (7). At each iteration (that is whenever a new agent domain s searched) all members of the current generation (that is the existing agents in the holarchy and the new ones searched for) are compared with each other in terms of the preference measures. The ones with highest preferences are placed at the top and the worst are replaced with the new agents. The subsequent iteration resumes this process on the partially renewed population. In this way the openness to new opportunities for continuous improvement in the HE constituency is achieved and with this the emergence of an optimal structure for the holarchy. Embedding this strategy in the mediator (Figure 3) endows the HE with the capability to continuously evolve towards a better and better structure by bringing to the table better and better partners as they are found.

In the sequel we illustrate on a numerical example how the proposed fuzzy-evolutionary approach works.

8.6 Simulation Results

8.6.1 Emergence of HE structure from MAS

Consider a MAS consisting of $N = 7$ agents for which the following roles have emerged after the vagueness minimization procedure (Subsection 8.4.5) was run: (a_4) – manager of the overall assigned task, (a_2 and a_3) – workers accomplishing the tasks operations by using four resource agents (a_1, a_5, a_6 and a_7), Figure 6. Starting with very parsimonious information about clusters created by couples of agents, each preference is assigned to a pair of agents. Although this information is extremely vague, we will be able to construct compatibility and holonic plans.

The MAS is considered initially as a system about which we do not know anything. We can stimulate it by setting some goals and letting it reach them. When the goals have been inputted, the observed output is the succession of agent clusters that occur each time the MAS transitions from the initial state to the final one (when the optimal holonic structure emerges). In order to get the best response from the MAS (in terms of having it go through as many states as possible), we have stimulated it with a set of goals equivalent to the "white noise" in systems identification (Söderström and Stoica 1989) - i.e. a class of goals, as large as possible, that might be set for the system. By inputting these goals one by one (or in a mixed manner - if this is possible), we can count the number of occurrences for each cluster. By normalizing the numbers (i.e. dividing them by their sum) one obtains the occurrence degrees of each cluster, i.e. the numbers $\{\alpha_{k,m}\}_{k\in\overline{1,K};m\in\overline{1,M_k}}$ that are, in fact, occurrence frequencies of clusters. For these simulation experiments, quasi-random (Gauss type) numbers were generated as occurrence degrees. After ~200 simulations (we used MATLAB), the final holonic clustering patterns emerged. Moreover, some information about the nature of the agents - i.e. whether they are knowledge agents, or yellow-page

[8] The agent domain can be chosen by a yellow page agent [11].

agents or interface agents, etc. (Ulieru *et al.* 2000) - were revealed without any a priori knowledge about the agent's type.

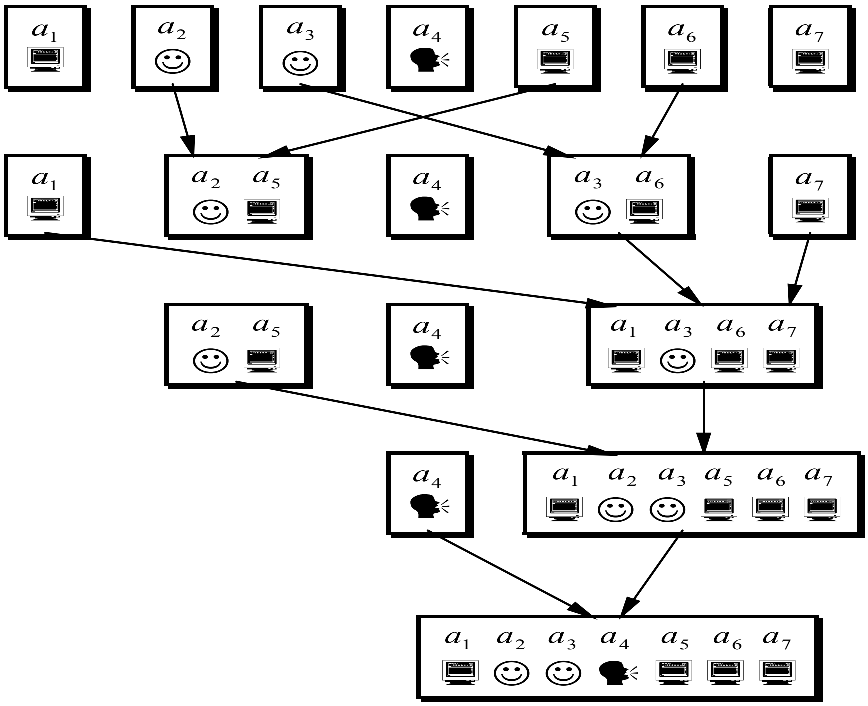


Figure 6. The emerged Holonic Enterprise

Every degree of occurrence is associated with only one pair of agents. Although this information is extremely vague, compatibility and holonic plans are built.
Since $N = 7$, there are maximum $C_7^2 = 21$ possible couples between agents. Each couple of agents has a certain degree of occurrence, but, in general, it is not necessary that all 21 couples appear during the MAS evolution. A null degree of occurrence will be assigned to every impossible couple. However, in this example, all 21 couples were graded by non-null values, in order to avoid triviality.
Starting from this vague information, one constructs first the corresponding fuzzy relation R between the 7 agents. None of the occurrence degrees has disappeared in R.

M_R :

1.0000	**0.5402**	**0.6343**	**0.1877**	**0.3424**	**0.2001**	**0.4863**
0.5402	**1.0000**	**0.3561**	**0.4797**	**0.7651**	**0.2092**	**0.2794**
0.6343	**0.3561**	**1.0000**	**0.4780**	**0.1389**	**0.6858**	**0.6414**
0.1877	**0.4797**	**0.4780**	**1.0000**	**0.3191**	**0.4888**	**0.3347**
0.3424	**0.7651**	**0.1389**	**0.3191**	**1.0000**	**0.2784**	**0.4291**
0.2001	**0.2092**	**0.6858**	**0.4888**	**0.2784**	**1.0000**	**0.1666**
0.4863	**0.2794**	**0.6414**	**0.3347**	**0.4291**	**0.1666**	**1.0000**

Since this relation is only a proximity one, we generate its transitive cover Q :

1.0000 0.5402 0.6343 0.4888 0.5402 0.6343 0.6343

	0.5402	**1.0000**	**0.5402**	**0.4888**	**0.7651**	**0.5402**	**0.5402**
	0.6343	**0.5402**	**1.0000**	**0.4888**	**0.5402**	**0.6858**	**0.6414**
M_Q :	**0.4888**	**0.4888**	**0.4888**	**1.0000**	**0.4888**	**0.4888**	**0.4888**
	0.5402	**0.7651**	**0.5402**	**0.4888**	**1.0000**	**0.5402**	**0.5402**
	0.6343	**0.5402**	**0.6858**	**0.4888**	**0.5402**	**1.0000**	**0.6414**
	0.6343	**0.5402**	**0.6414**	**0.4888**	**0.5402**	**0.6414**	**1.0000**

Q is a similarity relation between agents. In the membership matrix M_Q only 6 non-unitary largest occurrence degrees remain (as the smallest 15 are eliminated by the procedure).
Two types of source-plans result: one emerging from R and including (tolerance) covers (with overlapped clusters) and another – from Q, including partitions (with disjoint clusters), as follows.

First 5 tolerance covers generated by the proximity relation R :

Characteristic matrix

(α = 1.0000)	Clusters:
1 0 0 0 0 0 0	{a1}
0 1 0 0 0 0 0	{a2}
0 0 1 0 0 0 0	{a3}
0 0 0 1 0 0 0	{a4}
0 0 0 0 1 0 0	{a5}
0 0 0 0 0 1 0	{a6}
0 0 0 0 0 0 1	{a7}

Characteristic matrix

(α = 0.7651)	Clusters:
1 0 0 0 0 0 0	{a1}
0 1 0 0 1 0 0	{a2,a5}
0 0 1 0 0 0 0	{a3}
0 0 0 1 0 0 0	{a4}
0 1 0 0 1 0 0	
0 0 0 0 0 1 0	{a6}
0 0 0 0 0 0 1	{a7}

Characteristic matrix

(α = 0.6858)	Clusters:
1 0 0 0 0 0 0	{a1}
0 1 0 0 1 0 0	{a2,a5}
0 0 1 0 0 1 0	{a3,a6}

0 0 0 1 0 0 0	{a4}
0 1 0 0 1 0 0	
0 0 1 0 0 1 0	
0 0 0 0 0 0 1	{a7}

Characteristic matrix

($\alpha = 0.6414$)	Clusters:
1 0 0 0 0 0 0	{a1}
0 1 0 0 1 0 0	{a2,a5}
0 0 1 0 0 1 1	{a3,a6,a7}
0 0 0 1 0 0 0	{a4}
0 1 0 0 1 0 0	
0 0 1 0 0 1 0	{a3,a6}
0 0 1 0 0 0 1	{a3,a7}

Characteristic matrix

($\alpha = 0.6343$)	Clusters:
1 0 1 0 0 0 0	{a1,a3}
0 1 0 0 1 0 0	{a2,a5}
1 0 1 0 0 1 1	{a1,a3,a6,a7}
0 0 0 1 0 0 0	{a4}
0 1 0 0 1 0 0	
0 0 1 0 0 1 0	{a3,a6}
0 0 1 0 0 0 1	{a3,a7}

Partitions generated by the similarity relation Q :

Characteristic matrix

($\alpha = 1.0000$)	Clusters:
1 0 0 0 0 0 0	{a1}
0 1 0 0 0 0 0	{a2}
0 0 1 0 0 0 0	{a3}
0 0 0 1 0 0 0	{a4}
0 0 0 0 1 0 0	{a5}
0 0 0 0 0 1 0	{a6}
0 0 0 0 0 0 1	{a7}

Characteristic matrix

($\alpha = 0.7651$)	Clusters:
1 0 0 0 0 0 0	{a1}
0 1 0 0 1 0 0	{a2,a5}

0 0 1 0 0 0 0	{a3}
0 0 0 1 0 0 0	{a4}
0 1 0 0 1 0 0	
0 0 0 0 0 1 0	{a6}
0 0 0 0 0 0 1	{a7}

Characteristic matrix

($\alpha = 0.6858$)	Clusters:
1 0 0 0 0 0 0	{a1}
0 1 0 0 1 0 0	{a2,a5}
0 0 1 0 0 1 0	{a3,a6}
0 0 0 1 0 0 0	{a4}
0 1 0 0 1 0 0	
0 0 1 0 0 1 0	
0 0 0 0 0 0 1	{a7}

Characteristic matrix

($\alpha = 0.6414$)	Clusters:
1 0 0 0 0 0 0	{a1}
0 1 0 0 1 0 0	{a2,a5}
0 0 1 0 0 1 1	{a3,a6,a7}
0 0 0 1 0 0 0	{a4}
0 1 0 0 1 0 0	
0 0 1 0 0 1 1	
0 0 1 0 0 1 1	

Characteristic matrix

($\alpha = 0.6343$)	Clusters:
1 0 1 0 0 1 1	{a1,a3,a6,a7}
0 1 0 0 1 0 0	{a2,a5}
1 0 1 0 0 1 1	
0 0 0 1 0 0 0	{a4}
0 1 0 0 1 0 0	
1 0 1 0 0 1 1	
1 0 1 0 0 1 1	

Characteristic matrix

($\alpha = 0.5402$)	Clusters:
1 1 1 0 1 1 1	{a1,a2,a3,a5,a6,a7}
1 1 1 0 1 1 1	
1 1 1 0 1 1 1	
0 0 0 1 0 0 0	{a4}
1 1 1 0 1 1 1	
1 1 1 0 1 1 1	
1 1 1 0 1 1 1	

Characteristic matrix

($\alpha = 0.4888$)	Clusters:
1 1 1 1 1 1 1	{a1,a2,a3,a4,a5,a6,a7}
1 1 1 1 1 1 1	

1 1 1 1 1 1 1
1 1 1 1 1 1 1
1 1 1 1 1 1 1
1 1 1 1 1 1 1
1 1 1 1 1 1 1

The MAS evolution starts from the highest degree of occurrence (which is of course 1) and completes when the smallest degree is reached. Assuming that R is optimal, two source-plans (different from the initial one) could be generated: one emerging from R and including (tolerance) covers (with overlapped clusters) and another from Q, including partitions (with disjoint clusters). By ordering in decreasing order of their 6 occurrence degrees the configurations derived from Q, a real plan can be derived, Figure 6. (The Shannon fuzzy entropy of the fuzzy relation R has the value $S_{\mu}(R) = 36.6784$).

The following holonic behavior can be observed for the equivalence source-plan: clusters associate together in order to form larger clusters and, finally, the whole agents set is grouped in one single cluster. Analyzing the preferences in M_R we observe that the manager is tempted to work in association with the executive a_2 (**0.4797**) rather than with a_3 (**0.4780**), but also is oriented to solve problems by himself using the resource a_6 (**0.4888**).

A possible scenario unfolds like this. First, the manager states a goal. Immediately, the executives a_2 and a_3 reach for resources a_5, and, respectively, a_6 that they prefer to work with mostly (this information is as well encoded in M_R). The executive a_3 realizes that he needs more resources and he starts to use both a_1 and a_7 (therefore, maybe, the manager prefers a_2). The next step shows that the two executives associate together (including their resources) in order to reach the goal. The manager joins them only in the final phase, when the goal is reached – to give the final approval.

Our experiments have proven that the method works even in the most general case when we have the most parsimonious knowledge about the system. If enough is known about the agents to build the preference relation from the start, the method will obviously work better.

8.6.2 Evolution towards optimal structure in Cyberspace

We consider for the search an agent domain of 100 agents. The search goal is to optimize the constituency of the HE emerged in the previous Subsection.

For the evolutionary search we use mutation and crossover as follows:

- Mutation - the genetic operator that alters one ore more gene values in a chromosome from its initial state, which can result in entirely new gene values being added to the gene pool. There are different mutation mechanisms but we use the procedure that that simply inverts value of the uniform random chosen gene between the user-specified upper and the lower bounds for that gene.
- Crossover - the genetic operator that combines (mates) two chromosomes (parents) to produce a new chromosome (offspring) can as well be implemented through various mechanisms. We use here the procedure that randomly selects a crossover break point within a chromosome then interchanges the two parent chromosomes at this point to produce two new offspring.
- After binary encoding of the relevancy measures (10) (illustrated in Figure 7 before the encoding) we have evaluated the probabilities of mutation and crossover over the entire agent search domain. Table 1 illustrates the genetic alterations for ten agents

(that is the initial 7 and the first 3 found relevant in the search domain of 100 agents. "Agent#1: mutation – gene#1 -> Agent#2" means: "if a mutation is yelling on the first gene of the preference genotype of Agent #2 then this is replaced by Agent#1".

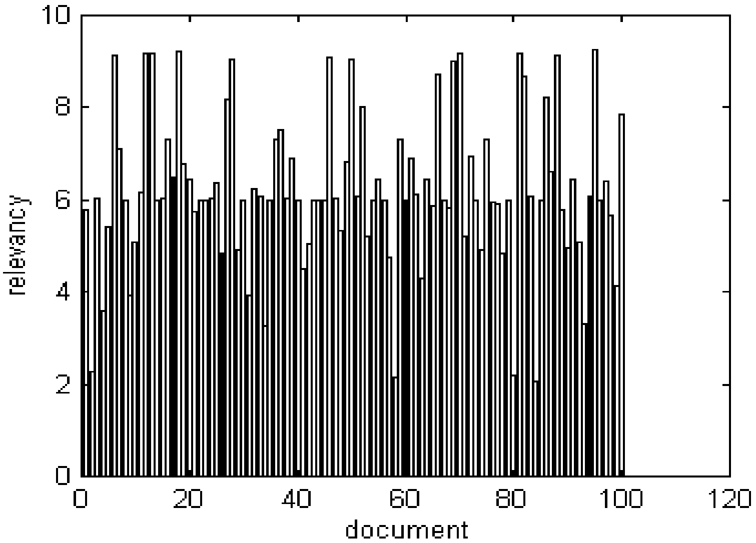


Figure 7. Relevancy measures for the 100 agents in the search domain

Table 1. The observed genetic alteration for mating 3 agents in the search domain with the 7 agents in the HE

Agent#2: mutation - gene#1 → Agent#1
Agent#3: mutation - gene#4 → Agent#4
Agent#5: mutation - gene#1 → Agent#7
Agent#2: mutation - gene#3 → Agent#10
Agent#1, Agent#8: crossover– gene#2 → Agent#4, New
Agent#4, Agent#9: crossover– gene#2 → Agent#1, New
Agent#4, Agent#9: crossover– gene#4 → New, New
Agent#6, Agent#10: crossover– gene#3 → Agent#7, New
Agent#1, Agent#2: crossover– gene#1 → Agent#1, Agent#2
Agent#5, Agent#10: crossover – gene#4 → Agent#7, New
Agent#8, Agent#9: crossover – gene#1 → New, New
Agent#8, Agent#9: crossover – gene#4 → New, New
Agent#3, Agent#4: crossover– anyone → Agent#3, Agent#4
Agent#9, Agent#10: crossover– gene#3 → Agent#1, New
Note: the crossovers between all chromosomes from gene#5 and gene#6 as break points lead to reproduce themselves. Their number is $45 \times (21 + 7) = 1260$

We ran this model by adapting a more general program for automatic location problems (Ionita 1997).
The total possible crossovers:

$$C_m^n = \frac{m!}{n! \times (m-n)!}$$

- the number of possible couples for the 10 agents in Table 1 is:

$$C_{10}^{2} = \frac{10!}{2! \times (10-2)!} = 45$$

- the possible number of crossovers between two chromosomes of 7 genes each:

$$\sum_{p=1}^{5} C_7^p = C_7^1 + C_7^2 + C_7^3 + C_7^4 + C_7^5 =$$

$$= \frac{7!}{1! \times 6!} + \frac{7!}{2! \times 5!} + \frac{7!}{3! \times 4!} + \frac{7!}{4! \times 3!} + \frac{7!}{5! \times 2!} =$$

$$= 7 + 21 + 35 + 35 + 21 = 119$$

The total possible crossovers is thus 45 x 119 = 5355. Based on estimation from Table 1 the probability to meet part of them in our population of ten agents is given by

$$p_c = \frac{1267}{5355} = 0.2366 \qquad (23.66\%)$$

Each chromosome has 7 genes. Thus:

$$no.\ of\ mutations = 7\ genes \times 10\ cromosomes = 70$$

From among them, only four occur in a population of ten agents (Table 1), so we can estimate a probability of mutation:

$$p_m = \frac{4}{70} = 0.0571 \qquad (5.71\%)$$

Applying a genetic search with these probabilities over three different agent domains (each of 100 agents) has converged towards the optimum in about 200 generations, Figure 8 (here expressed in a normalized manner, considering the mean values of the fitness function for each search.)

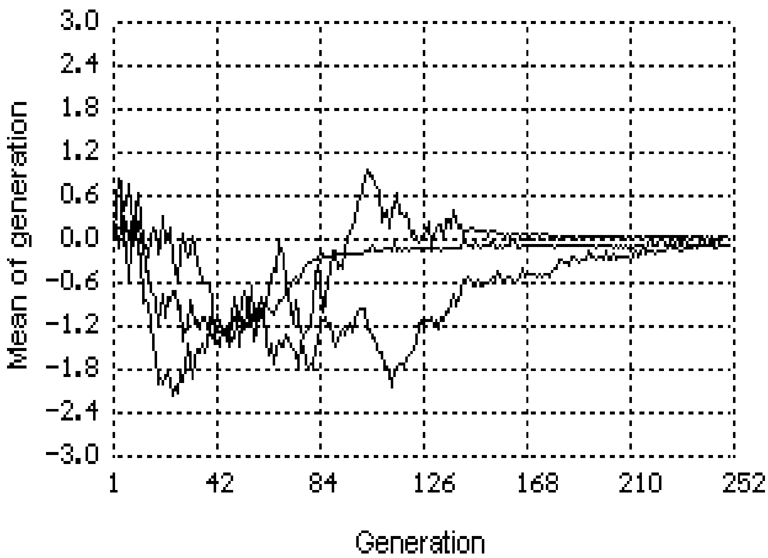


Figure 8. Convergence of the HE structure towards optimum

Embedding this dynamic evolutionary search strategy in the design of the Mediator Pattern enables the HE to continuously evolve in Cyberspace by improving its constituency through addition of better and better partners as they are found to better fit the achievement of its dynamic goals. Once the HE has changed its constituency (through either addition of new partners and/or exclusion of old ones) it will self-organize via the fuzzy entropy minimization by which the dynamic virtual clustering mechanism works, to reach again the optimal holarchic structure that best suits the goal-achievement.

8.7 Conclusion: Towards the Evolutionary, Self-Organizing Cyberspace

As result of the process of evolution driven by the law of synergy, emergence endows the dynamics of composite systems with properties unidentifiable in their individual parts. The phenomenon of emergence involves on one side *self-organization* of the dynamical systems such that the synergetic effects can occur and on the other side interaction with other systems from which the synergetic properties can *evolve* in a new context.
The fuzzy-evolutionary approach introduced in this chapter mimics emergence in natural systems as follows. On one side it induces self-organizing properties by minimizing the entropy measuring the information spread across the dynamical system such that equilibrium is reached in an optimal interaction between the system's parts to reach the system's objectives most efficiently. On the other side it enables system's evolution into a better one by enabling interaction with external systems found via genetic search strategies (mimicking mating with most fit partners in natural evolution) such that the new system's optimal organizational structure (reached by minimizing the entropy) is better then the one before evolution.
MAS enable cloning of real-life systems into autonomous software entities with a 'life' of their own in the dynamic information environment offered by today's Cyberspace. Applying the proposed fuzzy-evolutionary approach to the virtual societies "living" on the dynamic Web endows them with behavioral properties characteristic to natural systems. The HE paradigm provides a framework for information and resource management in global virtual organizations by modeling enterprise entities as software agents linked through the internet (Ulieru *et al.* 2002). In this parallel universe of information, enterprises enabled with the proposed emergence mechanism can evolve towards better and better structures while at the same time self-organizing their resources to optimally accomplish the desired objectives.
Encapsulating the dynamic evolutionary search strategy in the mediator and designing the virtual clustering mechanism by the fuzzy entropy minimization strategy proposed here empowers the HE with self-adapting properties and moreover enables it to evolve like a social organism in Cyberspace, by mating its components with new partners as they are discovered in a continuous incremental improvement search process.
Our current work focuses on the application of this strategy to the design of internet-enabled soft computing holarchies for telemedicine - e-Health, telehealth and telematics (Ulieru 2002a).

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References

Brandenburger, A. M. and Nalebuff, B. J., (1996), *Co-opetition*, Doubleday NY.

Brennan, R. (2000), "Performance comparison and analysis of reactive and planning-based control architectures for manufacturing", *Robotics and Computer Integrated Manufacturing 16(2-3),* pp. 191-200.

Christensen, J.H. (1994), "Holonic Manufacturing Systems: Initial Architecture and Standards Directions", *Proceedings of the First European conference on Holonic Manufacturing systems*, European HMS Consortium, Hanover, Germany.

Dubois, D. and Prade, H. (1988), *Possibility Theory*, Plenum Press NY, ISBN 0-306-42520-3.

Fogel, D. (1998) *Evolutionary Computation*: The Fossil Record, IEEE Press, May 1998, ISBN: 0780334817.

Hornberger, R. (2001), "Adapting to the Net Economy", Presentation at the *Energy E-Business Reality Workshop*, Calgary, Alberta.

Ionita, S. (1997), *Genetic Algorithms for Control Engineering Applications* (in Romanian), ECIT-97, Pitesti, Romania, 21-22 Nov. 1997, p. 77-84.

Klir, G. and Folger, T. (1988), *Fuzzy sets, Uncertainty, and Information*, Prentice Hall.

Koestler, A. (1968), *The Ghost in the Machine*, MacMillan.

Maturana, F. and Norrie D.H. (1996), "Multi-agent Mediator Architecture for Distributed Manufacturing", *Journal of Intelligent Manufacturing*, 7, pp.257-270.

McHugh, P., Merli, G. and Wheeler W.A. (1995), *Beyond Business Process Reengineering: Towards the HE*, John Wiley 1995, ISBN 0-471-95087-4.

Michalenicz, Z. (1992), *Genetic Algorithms + Data Structures = Evolution Programs*, Springer Verlag.

Nikravesh, M and Azvine, B. (Eds.) (2001) *New Directions in Enhancing the Power of the Internet*, UC Berkeley Electronics Research Laboratory, Memorandum No. UCB/ERL M01/28, August 2001.

Norvig, P. (2002), "Building a Better Search Engine", *Distinguished Lecture Series, University of California at Berkeley*, Jan 31, 2002. (http://buffy.eecs.berkeley.edu/ Seminars/2002/Jan/020131.norvig.html).

Shu, S. and Norrie, D.H. (1999), "Patterns for Adaptive Multi-Agent Systems in Intelligent Manufacturing", *Proceedings of the 2nd International Workshop on Intelligent Manufacturing Systems* (IMS'99), Leuven, Belgium, September 22-24, pp. 67-74.

Söderström, T. and Stoica, P. (1989), *System Identification,* Prentice Hall, London.

Ulieru, M. and Ramakhrishnan S. (1999), "An Approach to the Modeling of Multi-Agent Systems as Fuzzy Dynamical Systems", *Advances in Artificial Intelligence and Engineering Cybernetics, Vol. V: Multi-Agent Systems/Space-Time Logic/Neural Networks* (George Lasker, Ed.), IIAS-68-99, ISBN 0921836619.

Ulieru, M., Norrie, D.H., Kremer, R. and Shen, W. (2000), "A Multi-Resolution Collaborative Architecture for web-Centric Global Manufacturing", *Information Science*, volume 127, Journal no. 7669, ISSN # 0020-0255.

Ulieru, M, Cobzaru, M. and Norrie, D. (2001), "A FIPA-OS Based Multi-Agent Architecture for Global Supply-Chain Applications", *Proceedings of IPMM 2001 International Conference on Intelligent Processing and Manufacturing of Materials*, July 29-August 3, 2001, Vancouver, BC.

Ulieru, M., Walker, S. and Brennan, R. (2002), "The Holonic Enterprise, A Model for Internet-Enabled Global Supply Chain and Workflow Management", *Journal of Integrated Manufacturing Systems – Special Issue on Enabling Supply Chain Integration using Internet Technologies* (McIvor Editor).

Ulieru, M. (2002a), "Internet-Enabled Soft Computing Holarchies for e-Health Applications", Invited Chapter in *Fuzzy Logic and the Internet* (Zadeh, L.A. and M. Nikravesh, Eds.), Physica Verlag.

Weiss, G. (Editor) (1999), *Multiagent Systems, a Modern Approach to Distributed Artificial Intelligence*, The MIT Press, Cambridge, Massachusetts.

Woolridge, M. (Editor) (2001), "Foreword" to the *Proceedings of the Workshop on Agent-Oriented Software Engineering, International Conference Autonomous Agents 2001*, Montreal, Canada.

Zadeh, L.A. (2002), "A Prototype-Centered Approach to Adding Deduction Capability to Search Engines - The Concept of Protoform", Key Note Address at the 3rd World Congress on Computational Intelligence (WCCI 2002), Honolulu, Hawaii, May 12-17, 2002.

Zhang, H., and Norrie, D.H. (1999), "Holonic Control at the Production and Controller Levels", *Proceedings of the 2nd International Workshop on Intelligent Manufacturing Systems*, Leuven, Belgium, pp. 215-224.

Zimmermann, H-J (1991), – *Fuzzy Set Theory And Its Applications*, Kluwer Academic.