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The future of complexity engineering

Review article

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Abstract: *Complexity Engineering* encompasses a set of approaches to engineering systems which are typically composed of various interacting entities often exhibiting self-* behaviours and emergence. The engineer or designer uses methods that benefit from the findings of complexity science and often considerably differ from the classical engineering approach of "divide and conquer".

This article provides an overview on some very interdisciplinary and innovative research areas and projects in the field of Complexity Engineering, including synthetic biology, chemistry, artificial life, self-healing materials and others. It then classifies the presented work according to five types of nature-inspired technology, namely: (1) using technology to understand nature, (2) nature-inspiration for technology, (3) using technology on natural systems, (4) using biotechnology methods in software engineering, and (5) using technology to model nature. Finally, future trends in Complexity Engineering are indicated and related risks are discussed.

Keywords: Complexity Engineering • Self-organisation • Emergence • Artificial life • Bio-inspiration • Self-healing • Smart systems • Collective robotics • Multi-agent systems • Services • Micro / Nano swarms • Synthetic biology • Chem-IT • Self-* properties

1. Introduction

Complexity Engineering is the coming together of various approaches to the engineering and synthesis of all kinds of systems that are complex, adaptive, self-organising, self-adaptive, self-managing, self-healing and may exhibit emergence. Research efforts are being made in many fields, some of which are very distinct from each other, but still share important characteristics. An important percentage of the work being done is application-centered at this stage, and thus quite specific to the topic being studied, but nevertheless there are similarities in the paradigms on which the approaches are based. Many of the systems being studied share a subset of the following features:

- Composed of many often fairly autonomous entities (agents, modules, components, capsules, etc)
- Multiple and multi-lateral interactions between the entities and with the environment
- No central control
- No or limited external control
- Emergence of patterns, behaviours, system-level or global phenomena

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- Self-organisation, self-adaptation, self-management, self-healing, and other self-* properties
- Development and/or evolution at entity, cluster or system level

Systems with such characteristics exist both in nature and technology. They have already been observed for some time in physics, chemistry and biology, but they also increasingly appear in multi-disciplinary research involving computer science/software engineering, robotics, biology, chemistry and others.

When facing systems with such characteristics, traditional or classical engineering often reaches its limits in terms of providing scalability as well as coping with complexity and self-* properties; classical engineering is therefore in such cases no longer the preferential approach. An alternative is inspired by the findings of complexity science, and uses them for a different type of engineering, referred to as *Complexity Engineering*.

In two previous publications, we discussed important concepts for complexity engineering [1] and reviewed advances made in complexity engineering, with a focus on computer science applications [2]. In this article we investigate a step further and discuss complexity engineering in other research areas, including collective robotics, swarms in nano and microtechnology, systems biology, Chem-IT, artificial chemical life, self-healing technologies, and various types of smart systems.

A similar paradigm shift from classical engineering towards a complex systems approach is promoted under the name of *Emergent Engineering* [3]. Moreover, illustrating a growing interest in the field, the Springer Journal of Natural Computing is publishing a special issue on "engineering emergence" including articles about various related topics, such as degeneracy in evolvable assembly systems [4]. In line with the paradigm of complexity engineering, *Systems Aikido* [5] is a suggestion to use a system's intrinsic dynamic behaviour in pursuit of the researcher's goal. Also [6] argued in favour of engineering systems with emergence, and illustrated this with so-called *nanites*, which are nano-scale robots that build micro-scale artefacts, based on local rules. No matter how large or small the system, the underlying idea is mainly to use the mechanisms of *Complex Adaptive Systems* (CAS) in favour of the engineer's objective [7, 8].

CAS are systems which emerge over time into a coherent form, and adapt and organise themselves without any singular entity deliberately managing or controlling it [9]. CAS are many-body systems, composed of numerous elements of varying sophistication, which interact in a multi-directional way to give rise to the systems global behaviour. The system is embedded in a changing environment, with which it exchanges energy and information. Variables mostly change at the same time with others and in a non-linear manner, which is the reason why it is so difficult to characterize the system's dynamical behaviour. CAS often generate 'more of their kind' [10], which means that one CAS may generate another. To characterise them, researchers describe their components, environment, internal interactions and interactions with the environment. It remains open if there are complex systems which are not adaptive. Some researchers agree, as, depending on its definition, adaptivity may require diversity and natural selection, as shown in ecosystems [11]. For further discussion see [1, 2].

Very much in this sense, "challenges beyond evolvability" have been identified [12], namely those listed below. Indeed, one of the most prominent issues – both an advantage and a challenge – is that in collective systems, the causally interacting elements often provide more functionality than if they were simply added to each other. The nature of this 'more' depends on the technology being used, and guiding it into the right frame is the complexity engineer's task. CAS include many different types of systems, among which are those based on bio-inspired and self-organising approaches; those with evolutionary and adaptive control, software and hardware; and systems which are cognitive, cooperative, evolvable, with developmental plasticity and emerging properties. However, cross-domain elements that are not related to a specific technology still need to be investigated; a more exhaustive list of relevant research questions is provided by [12]. The most important challenges concern [13]:

- The controllability of long-term developmental processes and the controllability of self-* systems
- The complexity of "natural chemistry" and its ability to re-write its own operation
- Artificial sociality and the development of tools to understand systems with their emerging complexity
- Controlling emergence in the sense that at least it is assured what systems will avoid doing.

1.1. A guide to the organisation of this article

Complexity engineering is a field of research that has recently started to emerge, and is growing very fast. While it started in computer science, complexity engineering is now expanding in many disciplines and in many directions. Section 2 of this article sheds light on the most important disciplines and projects that contribute to the area of complexity engineering, but it does not claim to make an exhaustive inventory. For instance, also many examples from cognitive science and neuroscience could be added;

however, due to their close relation to medical and psychological fields, they should be surveyed by authors with the relevant expertise. The same argumentation applies to work done in social and economic sciences. Therefore, this article namely focuses on the following: It provides some additional material on multi-agent systems and services (section 2.1), to complement [2].

Section 2.2 gives an impression of the vast field of collective robotics, which is here used as an inclusive term for the many different types of systems which are different from traditional industrial robots.

In section 2.3, swarms in nano and microtechnology are introduced. They are somewhere between macroscopic swarms of robots, and the innovative fields related to chemistry and biotechnology, which follows subsequently:

The first in this set of three unconventional areas is systems biology and synthetic biology (section 2.4), the second is Chem-IT (section 2.5), where computation is implemented on chemical systems, and the third is chemical artificial life (section 2.6), where researchers try to simulate or physically create systems that share sufficient properties with natural living systems to be considered alive as well. This classification into three areas is not carved in stone; it is a mere suggestion, intended to establish some structure among the many fascinating projects currently being investigated.

Living systems exhibit a plentitude of self-* properties, and thus the survey moves on to that area: a choice of self-healing materials and products can be found in section 2.7; for a more complete survey, refer to [14]. Systems with other self-* properties have been discussed in [2, 15–17], for instance, and are not explicitly listed here for the sake of brevity.

However, smart systems of many kinds often also display certain self-* properties due to their need to be as autonomous as possible (section 2.8). Usually, they rely on elaborate software systems, such as multi-agent systems, but the focus is on their concrete application and purpose, as opposed to the systems discussed in section 2.1 and [2], where the focus is on the computational technology.

The second part of the article – from section 3 – makes a synthesis, beginning with the essence of what complexity engineering is. Section 3.1 provides a classification and summary of the work surveyed in section 2 with regards to the nature/technology interface. Section 3.2 sheds light on the relation between 'bio' and 'techno', which is becoming increasingly diffuse. Risks of this development and complexity engineering in general are considered in section 3.3, whereas section 3.4 sketches the potential of complexity engineering and its pluri-disciplinary approach for our future. Finally, section 4 concludes this article.

2. Contributing disciplines and projects

The main research fields which contribute to the body of work being done in complexity engineering are listed in Table 1; looking at the bigger picture, they belong to the six main areas of: engineering (including the many different types, such as mechanics, electronics, etc), computer science and software engineering, social sciences, physics and chemistry, materials sciences, and biology. The complexity engineering approaches being followed are all interdisciplinary and include aspects of two or often more research fields, as indicated by the marks in Table 1. Each of the following subsections includes a short introduction to the area and a brief review of important work. Note that due to space constraints, only a small selection of the most remarkable articles could be included for each area.

2.1. Multi-agent systems and services

A large proportion of the early efforts in complexity engineering have been done in the area of computer science and software engineering, and it is still a very active area of research. The introduction of *Autonomic Computing* [18] triggered a lot of research on systems that are increasingly able to take care of themselves, that are adaptive and fulfill their functions under changing conditions. Many of the approaches to implement autonomic computing use agents and services, as these technologies naturally come with adaptivity, robustness and a fair degree of autonomy. Agents are autonomous units of software that have the ability to act on behalf of themselves or somebody else. They are able to interact with their peers and their environment, they may have a certain knowledge and certain interfaces. Often, they are able to provide services and request services from others. Agents may be pure software, or be associated with a physical body of any kind, in which case they are called *embodied*. Given their nature, multi-agent systems are often an intuitive model for other complex adaptive systems. For more details and a survey please refer to [2]. The following additional projects are also worth considering in this context:

- To ease the engineering of artificial self-organising systems, a catalogue of self-organising mechanisms in terms of modular and reusable design patterns, with a clear distinction of where one mechanism stops and where another one starts, was created [19]. The patterns are organised in different layers: in the bottom layer are the basic mechanisms that can be used individually or in composition with others to form more complex patterns (*e.g.* evaporation or

Table 1. Research areas in complexity engineering (rows) often include aspects from several fields (columns). Two or three marks indicate a strong contribution, whereas a single one stands for a weaker influence. A mark between brackets stands for the application of principles rather than using the actual substrate of the area. In some cases, such as self-healing systems, the contributions of the different fields depend on the individual applications.

	Engineering	Computer science	Social sciences	Physics and chemistry	Materials sciences	Biology (principles)
MAS and services	xx	xxx	x			(x)
Collective robotics	xxx	xx	x			(x)
Micro/Nano swarms		(x)		xx	x	(x)
Synthetic biology	x			xx		xxx
Chem-IT		xx		xxx	x	x
Artificial chemical life	x	x		xxx	xx	xx
Self-healing systems	x	x		x	x	x
Smart systems	xx	xxx	x			(x)

spreading); in the middle layer are the mechanisms formed by combinations of the bottom layer mechanisms (*e.g.* digital pheromone or gradients); and the top layer contains higher-level patterns that provide different ways to exploit the basic and composed mechanisms proposed in the bottom and middle layers (*e.g.* chemotaxis or ant foraging). The different patterns are fully described, from the problem they address, and the solution they provide, to implementation details including flow and sequence diagrams, as well as related cases of usage.

- BIO-CORE [20] is an execution model that provides core bio-inspired services, i.e. low-level services providing basic bio-inspired mechanisms, such as evaporation, aggregation or spreading, which are shared by higher-level services or applications. To ease the design and implementation of self-organising applications (or high-level services), by supporting reuse of code and algorithms, BIO-CORE proposes these low-level services at the heart of any middleware or infrastructure supporting such applications, under the form of core built-in services around which all other services are built.

- *Shifters* [21] are software agents that are similar to stem cells: in the beginning, they are neutral elements and then evolve towards having a specific function. This emergent adaptation is based on the needs of the system as well as adaptation pattern [22] and caused by the agent's interactions with its peers. This approach is particularly interesting because it models a biological process that produces great diversity and robustness based on a set of simple rules and environmental influences.

- Taking inspiration from chemical reactions, the MYRIADS project [23] designs and implements systems and environments for autonomous service and resource management in distributed virtualised infrastructures. The focus is on creating dependable applications and efficiently managing resources in the future *Internet of Services*. Computations happen according to a set of rules, similar to how chemical reactions happen between molecules in a solution. The computational 'molecules' are stored in a multiset, and their reactions occur in parallel and in an autonomous way. A similar approach is followed in the context of the *Internet of Services (IoS)*, where services are composed to fulfil tasks that are specified as workflows [24].

- The SAPERE project [25] targets the development of a highly-innovative theoretical and practical framework for the decentralised deployment, execution, and management, of self-aware and adaptive pervasive services in future and emerging network scenarios. It takes inspiration from chemical reactions for designing and developing pervasive ecosystems of services by combining situation-awareness techniques, with self-composition, self-organisation and self-management.

Complex computing systems have become ubiquitous, and most people could not live without them any more; the Internet is only one such example. A trend which we observe tends towards embodied computing, which means that the software is intimately linked to some kind of physical device. These devices then collaborate with each other in opportunistic ways, just as the user may require them to do, but without explicitly specifying that. In some cases, the computation does not happen in silicon any more, but rather in biological substrates, as explained in section 2.5. Although this kind of technology is still in its infancy, we expect that progress will be made quickly, and a large variety of applications will emerge.

2.2. Collective robotics

Many different approaches come together in collective, mobile, and modular robotics, some of which are rather centralised, top-down or use hard-coded robot behaviours. Although certainly also worthy, those approaches are not of interest here. Our focus is on systems that are distributed, decentralised, bottom-up and that use behaviours which are flexible, adaptive, evolvable and emergent. This is not an exhaustive list – any number of approaches or projects could be added – but it illustrates the kind of work that would qualify as complexity engineering because it is unconventional; also the evolution of a neural controller for a robotic system or other applications of neural computing [26] could be included.

It is difficult to find an all-inclusive term for the kind of robotic systems considered here; there is a variety of terms which sometimes refer to similar concepts, but depending on the individual researcher's interest, refer to different ideas. E.g., robotic swarms may be composed of collaborative or competitive individuals; self-reconfigurable robotic systems may have a certain degree of centralised planning, or may consist of completely autonomous entities. To make space for all, the term 'collective robotics' was chosen as a title for this section, although it may sometimes also refer to a very specific case. The meaning here concerns systems that are composed of a set of robotic entities or modules which together exhibit a certain behaviour.

The 'Handbook of Collective Robotics' [13] provides insight into mechatronic, chemical, bacteriological, biological, and hybrid systems, using cooperative, networked, swarm, self-organising, evolutionary and bio-inspired design principles and targeting a variety of applications.

Collective robotic systems are often controlled by multi-agent systems or something similar, as they also naturally model distributed adaptive systems. They almost always show some kind of emergent behaviour, and are ideal substrates for experimenting with complexity engineering principles. Most collective robotic systems are at the scale of a few millimeters, which makes them easy to handle, observe and control. The danger of harmful behaviour is close to zero.

- Many different types of *swarm robots* exist; most of them move on wheels, but a few of them fly [27] or swim [28]. An example of wheeled robots are *Swarm-bots*, composed of small mobile *s-bots* which have grippers to connect with peers; they can move individually or in clusters. Recent advances showed that they are able to transport broken peers to a repair zone [29]. If necessary – because a cluster of robots has broken down – the robots autonomously trigger self-assembly to form a collaborating cluster with as many members as needed. Through local communication using different LED colour codes, they efficiently allocate resources and can overcome deadlock situations.

  The social interactions of mobile robots depend on the availability of local memory [30]. When memory is available, robots can learn, and learning by imitation leads to the emergence of certain behaviours, even in the absence of verbal communication between the robots. Also swarming behaviour relies on local interactions, without the need for direct communication. While most natural swarms are composed of relatively homogeneous individuals, swarms of flocking robots do not require a homogeneous group of participating robots; swarming behaviour also emerges in the presence of non-aligning robots [31].

  Another example of how module properties and their interaction with physical principles can be exploited to achieve emergent behaviours is the following: Floating robot modules on a water surface have been observed to segregate depending on their individual characteristics [32]. Active modules vibrate, while passive modules do not, but they are otherwise identical. A system starting with randomly distributed active and passive modules tends towards a dynamic equilibrium where the active modules tend to gather in one area, and the passive ones free up as much space as possible for the active ones by assembling in another area of the water surface.

- In *evolutionary robotics* [33], robots are considered as autonomous artificial organisms that co-evolve their body and control system, depending on the environment, and without human interaction. This area of research originates from Braitenberg's thought experiments on neurally driven vehicles [34], which was about the idea that control systems could be evolved. The Evobody project[1] also relates to this insight about the co-evolution of the body and the brain; more about Evobody in section 2.6.

- All around the world, there are about a dozen research groups working on their own type of *self-reconfigurable robots* [35]. Their research is manifold and includes on-line and on-board evolutionary experiments with collectively morphogenetic robots such as, for instance, ATRONs [26]. These robotic systems are composed of a set of autonomous modules that collaborate to form a bigger body; typical

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[1] `http://www.evobody.eu`

numbers are a few, a few dozens, and – in simulation – a few thousand modules. Platforms such as the one developed for the Symbrion and Replicator projects [36] provide a distributed computational system, able to run learning and evolutionary algorithms. Such robotic systems can run autonomously or with human influence.

A "reality gap" mostly exists between system simulations and physical reality, which makes the development of the various aspects of robotic systems difficult. A mixed system, combining simulation and physical controllers, may help engineers overcome the reality gap [36]. It provides the possibility to approximate the global system state using local sensors, to use information provided by robot-to-robot interactions, and the robots' internal states. The difficulty is in interpreting the sensors in the right way to make sense of their measurements and being able to use the information for decision making. An artificial immune system [37] as well as approaches for computational systems to gain spatial or generally contextual awareness [38] may be used for this purpose.

- So-called *soft robots* [39] are able to significantly deform themselves and alter their shape, at a much higher level of detail than discrete modular robots. Ideally, their body – which contains no rigid parts at all – should be co-evolved with their gait [40] for the material properties and the locomotion mechanisms to be in sync. As soft and deformable bodies can possess near-infinite degrees of freedom, their control is way beyond usual controllability. Biological inspiration may come from worms or amoebae. Soft robots are thus a classical example of complexity engineering; no traditional approach to engineering or controlling robots would be suitable here, and innovative, cross-disciplinary ideas are necessary.

- Inspired by the information-processing of simple micro-organisms executing phototaxis or chemotaxis, robots may be controlled by *artificial hormone systems* [41]. A roughly abstracted model of inter-cellular signal emission and signal processing is used to make the robot move at little computational cost and with only simple sensors. Again, this is an example of how biology, computation and robotics lead to an innovative solution for an engineering problem that could not otherwise be solved with comparable results.

- Taking the idea of building a fully autonomous robot to its ultimate conclusion, the artificial creatures must be able to feed from their environment. The *EcoBot* [42] is a robot that transforms organic material, ideally waste but currently trapped flies, into energy. Once they have reached a useful degree of efficiency, the "stomach" of the robot – microbial fuel cells – could be used for any type of energy-autonomous system that has access to organic material and water. Furthermore, this invention brings the engineering of artificial life a step forward.

The above examples illustrate how collective robotics are a melting pot for a variety of disciplines and approaches to solving problems. They are optimal experimentation platforms and will certainly help the principles of complexity engineering become more explicit, tangible and performable.

2.3. Swarms in micro- and nanotechnology

The selection of work reviewed in this section focuses on engineering at a very small scale; it is about how to create and control tiny robots and swarms composed of them. Classical engineering techniques are often at a loss here, as the forces which govern nanometric systems are very different from those acting at the macroscale, and additionally, the means for the human to interact with nanometric systems are often very limited. As a consequence, the approaches to control or steer systems must be different as well. Principles like self-assembly and self-organisation become important, and one of the challenges is how to guide them towards the desired outcome. E.g., if the goal is to make component A connect with component B, the experiment will not be executed with just one or a few of each components, but rather with a few hundred or thousand, and the engineer will work on how to provide the system with the right conditions and the right dynamics for the intended system behaviour to occur.

- Material components of diverse nature have been found to self-assemble under certain conditions. While static self-assembly happens in systems that are at local and global equilibria and do not dissipate energy, systems with dynamic self-assembly tend to be out of equilibrium while building structural and functional complexity [43].

  An example are magnetic particles swimming between two immiscible liquids which are exposed to alternating magnetic fields. The *self-assembling structures* are magnetic asters (in reference to the flower of that name) composed of micro and nanoparticles [43]. If the top-liquid is replaced by air, particle snakes are observed instead of asters. The structures move, interact with each other, and seem to be 'almost alive'. Dipole-dipole interactions govern their behaviour. Asters generate 'larger-scale three-dimensional toroidal flows' with their magnetic moments pointing inwards – to the aster center – or outwards. Asters can move in a controlled way, and neighbouring asters may exchange particles and even absorb each other. Thanks to the possibility to open up asters, they can be used to enclose other particles (for instance, glass beads) and transport them to a desired place. This work provides insight into the engineering of smart materials and *soft robotics* (mentioned in section 2.2), using self-assembled micro-grippers made of swimming nano-particles.

- *Carbon nanotubes* and other nano-metric geometries exhibit self-assembly and growth, either random or according to DNA origami templates [44]. Where the common serial lithography is too slow, this technology allows scientists to fabricate a large amount of nano-devices in parallel. This in turn enables the nano-structures to be used for applications such as three-dimensional memory. Self-assembled carbon nano-structures have also been observed to grow on a gold substrate under specific conditions including an elevated temperature and a helium atmosphere [45]. Understanding how such structures grow, and how their growth can be influenced, is fundamental for a diversity of future applications in nanotechnology.

- *Swarm chemistry* [46] is an artificial chemistry framework that uses artificial swarm populations as chemical reactants. The simulated reactions emerge from spatiotemporal patterns of collective behavior through the kinetic interaction between multiple chemical species. When active particles, which are moving and kinetically interacting, collide with passive particles, which remain still and inactive, the passive ones are transformed into active ones, and thus also participate in the simulated swarming behaviour [47]. Potential applications could for instance be in personalised medicine, where substances become active under certain conditions, and take very directed and specific actions.

- Similarly, research foresees swarms of nano-robots to be used in medical applications, for instance swimming in patient's blood vessels [48]. The sensors carried by the robots would allow them to act on various chemical or physical parameters such as temperature, pressure and the local concentration of substances in the blood. Such robots could identify targets for the administration of medication, deliver drugs, establish connections to certain nanometric structures of the body, or help early diagnosis. Actuators of suitable scale may be electromagnetic, piezoelectric, electrostatic or electrothermal. Usable energy may be provided through temperature gradients, electric or magnetic fields, or kinetic energy.

Microtechnology and nanotechnology have huge potential for a large variety of applications. They are at the same time very inspiring as well as scary. A lot of research is still necessary before any conclusion can be drawn concerning their safety, which is mainly due to their very small scale. Nano-particules are able to effortlessly penetrate mammalian body tissue, which, again, can be both a chance and a threat. Slightly bigger structures are big enough to be contained in a blood vessel, for instance, but small enough to swim around without bothering the blood stream. Other applications of nanotechnology are purely technological, as illustrated by the example of the carbon nanotubes which repair broken electronic connections on circuits. To conclude, there is a lot of potential for innovative technology at the very small scale, but researchers must be responsible and careful.

2.4. Systems biology and synthetic biology

Systems biology is the analysis of the interactions between the components of biological systems over time; it also includes an iterative cycle in which biology problems lead to the development of new technologies and computational tools [49]. The importance of systems biology for complexity engineering is based on the rich pool of inspiration, which complex biological systems provide, and the engineering applications which result from using biology-based mechanisms and phenomena in technology.

- As an example, *innate immunity* is discussed under the aspects of emergence, robustness, modularity and suitable systems level analyses. Systems biology and technology compose a cycle, where systems biology drives technology, and technology in turn revolutionises systems biology by opening frontiers and generating new fields of inquiry. The roles, which systems biology plays with innate immunity [49] include: filling the gaps to create an integrated picture, enhancing the rate at which discoveries are made, clarifying how emergent properties arise from bio-molecular networks, and predicting effects of genetic or environmental perturbations.

- Another area of systems biology is *personalised medicine* [50]: every person will have a slightly different reaction to the treatments of a specific disease with a specific medication, and it would therefore be very beneficial to customise medicine. In cancer treatment, this need is particularly prominent because every tumor is unique and specific to its carrier. Incorporating the *molecular fingerprint* of the patient, and the associated growth kinetics of the tumor, when fine-tuning the treatment regimen, would be very helpful.

In *synthetic biology*, researchers add engineering to biology and create new organisms, both organic and *in silico*. Besides the potential for evolving innovative engineering solutions, these efforts may also lead to a better understanding of how original biological organisms function. *In silico* examples include *morphogenetic* or *embryomorphic engineering* [51, 52], where simulated cells reproduce and grow by self-assembly according to simple local rules, progressively building an artificial organisms in a similar way as a natural organism grows. The cells proliferate, migrate and self-pattern into differentiated domains. Each cell's behaviour is controlled by an internal gene regulatory network [53]. Examples of physical experiments based on the same principles are done in morphogenetic or *epigenetic robotics* [149–151], where the morphology and control system of robots are evolved to fit a certain environment and then physically built. These works explore the causal and programmable link from genotype to phenotype as well as the co-development of body and (natural or artificial) brain.

Other experiments demonstrate, as proof-of-concept, that dividing the development of organisms in various stages enables the self-assembly of more complex morphologies not otherwise possible [54]. Not only biological systems, but also the assembly process of engineered systems may benefit from the a development in stages.

Synthetic biology indisputably carries certain risks. The Synbiosafe project[2] investigates 'potential and perceived risks due to deliberate or accidental damage'. This concerns [55]:

- Biosafety: avoiding unintended consequences
- Biosecurity: coping with harmful misuse
- Dealing with the ethical, religious and philosophical implications of creating unnatural life forms
- Intellectual property: can modified life forms be patented?

The situation in systems biology and synthetic biology is similar to the one in nanotechnology: all of them are research fields that have recently emerged, and are increasingly attracting the interest or researchers and industry because they open up a whole new world of possibilities. It remains, however, to be investigated how the safety of such technologies can be assured.

2.5. Chem-IT

The term *Chem-IT* refers to computation executed in chemical instead of silicon-based systems. The area – discussed for instance at the Bio-Chemi-IT Workshop of the ECAL'11 Conference[3], includes biological and chemical information technologies, molecular and chemical computing, molecular robots, the integration of information processing with (bio-)chemical production, nano-bio-info interfaces, cellular engineering, artificial neurons, and programmable information chemistry as well as unconventional computing substrates. Molecular computing or (bio)chemical computing is a promising approach for cases where the structure of the problem being explored parallels the structure of the (bio)chemical system, or in environments where electronics cannot be deployed. [56, 57].

The basis of this research is the observation that molecular materials have suitable properties for high density integration of computing systems [58]. Currently used molecules range from organic semiconductor materials for low-cost circuits to genetically modified proteins for commercial imaging equipment. Suitable architectures and less rigid computing paradigms are being developed under the names of *reaction-diffusion computing, self-assembly computing*, and *conformation-based computing*. Molecular computing is best considered not as a competitor for conventional computing, but as an opportunity for new applications, in particular in micro-robotics and bio-immersive computing [58]. Self-assembly, self-organisation, self-healing and emergence are only examples of phenomena that are observed and investigated in Chem-IT.

Examples of current projects in the area of chemical computing are:

- NEUNEU[4] – Artificial Wet Neuronal Networks from Compartmentalised Excitable Chemical Media – which explores the development of mass-producible chemical information processing components and their interconnection into functional architectures. Mass production is often both a challenge and a chance for alternative technologies, and advances in one area may very well cross-fertilise others.

- BACTOCOM[5], where the idea is to achieve computation in bacteria DNA. Microbes are considered

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[2] *Safe synthetic biology, see* http://www.synbiosafe.eu

[3] http://www.ecal11.org/workshops/#biochemit

[4] http://www.neu-n.eu

[5] http://www.bactocom.eu

as 'micro-machines' that process information about their own state and their environment, and that are able to exchange DNA material with peers. This capability is being exploited for computational operations. While very interesting, this interdisciplinary research may create associations with horror scenarios as discussed in section 3.3.

- MATCH-IT[6] – MATrix for CHemical IT – investigating programmable chemical systems. An addressable chemical container (*chemtainer*) production system is added and interfaced with electronic computers via MEMS technology with regulatory feedback loops. Similar to the biological sub-cellular matrix, the chemical containers at the micro and nanoscales will self-assemble and self-repair and be replicable.

- *DNA Computing* is a sub-field of molecular computing that uses molecules and bio-molecular operations to solve problems and perform computations. It is a novel approach for solving complex problems that cannot be solved using standards computers (such as NP-complete problems). The main idea consists in representing data structures as DNA (data is stored using strings of DNA alphabet), highly parallel operations then occur at the molecular level on these strings [59].

As a general tendency, Chem-IT is a recently emerged research area that is growing and becoming more diverse. It represents an alternative to silicon-based computing, which has been very well established over the last few decades, and where besides the continuous efforts to optimise and improve, the potential for innovation is limited. In Chem-IT, however, there is no boundary to people's creativity.

2.6. Artificial chemical life

Artificial life researchers are investigating how life may have started by attempting to create artificial life forms based on various types of artificial cells. A related question is how life might be, if it was based on a different or simpler chemistry. Natural and artificial life are prime examples of systems exhibiting emergent phenomena and self-* properties, and thus their investigation represents a very important part of complexity engineering.

- *Protocells* [60] represent the body of research in chemistry and bottom-up synthetic biology [61] that intends to investigate how life could have emerged. Chemical compositions have been found that exhibit life-like characteristics including "cells" (or rather, blobs or bubbles) separating, merging, interacting, pulsating and moving through chemotaxis. A potential application for protocells is the "Future Venice" project[7]: the idea is that protocells use substances available in the water or air to self-assemble and build "living" structures that dynamically reinforce the existing old ones, such as walls and piles.
  During the origin of life, genomes and membranes began to collaborate through physiochemical mechanisms that led to the emergence of cellular behaviours [62] including growth, genome replication, membrane transfer between adjacent cells and cell division. It appears that cell fitness is closely linked to both membrane fitness and genome fitness. The exploration of minimal chemical cell systems – *chells* – promises to lead to insights into the origins of biological complexity.
  Some controversy exists around the question whether there is a difference between protocells and chells. Protocells generally reference the origins of life. Protocells can be called as such without possessing all of the functions of living cells; they may be able to move towards nutrients, but not replicate themselves. 'Proto-' itself means 'earliest form of' and protocells may be seen as a prototype of a cell.
  Chells are more associated with artificial life. Chells can be composed of components that are less biological with more inorganic structures, catalysts, and information systems. While protocells are typically composed of *amphiphiles* [63] (substances which have both *hydrophilic* (water-loving) and *lipophilic* (fat-loving) properties) that are found in small quantities in human bodies, chells can be made out of inorganic materials that form membranes as well, but are not found in modern life.
  A third term also carrying subtle nuances is *artificial cell*. While this can be used interchangeably with protocell and chell, it is also used to describe synthetic organisms, where all of the components are synthesised from scratch. This may also have a broader meaning to imply only fully functioning living cells. Oddly, this is also used for more abstract contexts like a computer-based system mimicking living functions.

- The so-called *Venter cells* [64] – not undisputedly claimed to be the first viable synthetic cells – are biological cells with artificial genomes. The phe-

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[6] http://fp7-matchit.eu

[7] http://www.futurevenice.org

notype of these cells is fully determined by the artificial genotype, and the properties of the original biological bacteria cells, of which only the cell body remains, are lost. The synthetic cells are capable of continuous self-replication. Venter cells are a proof of principle [65]: genomes can be produced by the computer, chemically made in the laboratory, without the use of any natural DNA, and then transplanted into a recipient cell to produce a new viable type of cells.

- While the synthesis of a complete cell is still a challenge, the bottom-up construction of an *artificial organelle*, which is capable of generating the bioenergy, is experimentally feasible [66]. Also, similar to components from a toolbox [67], DNA string modules can be used to create life-like behaviours *in vitro*; it enables the construction of arbitrary chemical networks, including autocatalytic ones (that is, where the reaction product itself is the catalyst for that reaction). Such systems carry high potential for the engineering of self-sustaining biotechnical applications.

- Besides *in vitro* research, also *in silico* experiments provide researchers with insights: EvoGrid [68] is a computer simulation framework for research in distributed artificial chemistry, investigating the origins of life. EcoSim [69] allows researchers to study the evolutionary process and the emergence of species in an individual-based evolving predator-prey ecosystem simulation, where individual behaviors affect evolution and speciation.

- One of the challenges with creating artificial life is when it can actually be considered 'alive'. This question is closely related to the definition of 'life' itself, which again, is very controversial. There has been some agreement on life needing a *container*, that is, some semi-permeable active boundary or membrane, a *metabolism* to generate and channel energy, as well as an *information system* such as genes, which works with high fidelity but is able to cope with imperfections and mutations [70].
  In artificial intelligence, a similar challenge was – or is – to define when a machine or a computer can be considered as being intelligent or exhibiting intelligent behaviour (which is not always the same). In the early phases of research in artificial intelligence, when intelligence was perceived as being about information processing, the Turing test [71] was suggested as a suitable measure: it investigates whether a machine can imitate the act of thinking in such a way that a human interrogator cannot perceive the difference between a human or artificial interlocutor. Although the quest for finding such machines has not been generally satisfied yet, and the meaning of 'intelligence' has changed [72], the Turing test has contributed to a better understanding of what intelligence and artificial intelligence are (not). Similarly, a Turing test for artificial life was suggested [70] : instead of a human interrogator interacting with a human or a computer, a natural cell would interact with another natural cell or a chemical cell. However, the nature of this interaction, the language to be used, as well as the necessary life support systems represent major problems, and the idea has been abandoned by most researchers.

- Finally, the Evobody project (discussed in section 2.2) brings computing, mechatronics and synthetic biology together in the attempt to create living, evolving systems of any embodied nature. It investigates the principles governing such systems as well as their future impact on science, society and technology. This project may strive towards the ultimate goal of bringing it all together, but it also carries a high risk of creating systems that might get out of control, as discussed in section 3.3.

While the study of how life emerges is very important and may provide us with great insights, the risk of creating living systems that might get out of control represents a non-neglectable risk. The only comfort is that researchers are still quite far away from actually creating artificial life, and progress happens in very small steps. There is hope that by the time research comes close to a breakthrough, also the understanding of how to control artificial life and how to set effective boundaries will have advanced accordingly.

2.7. Self-healing materials and products

Human and animal skin is a perfect example of a self-healing tissue which is able to cope with quite serious injuries and most often re-establish a fully functional state. Also many plants are able to self-repair when they are damaged. Engineers and material scientists have in many cases successfully applied this inspiration to artificial substances and tools.

- Probably one of the earliest examples of *modern self-repairing technology* are car tires invented around 1934: the first tires that could temporarily self-repair in case of damage had been invented for military purposes – to resist gun shots – and were then also used on commuter trains and trolleys [73]. Since then, various versions of the idea have appeared and been sold to customers who are ready to pay the higher price. The most common principle for self-healing tires is that a liquid sealing agent is inside the tire and instantaneously closes any hole. Another principle uses the heat caused by a gunshot penetrating a tire to locally melt the material; re-sealing happens then automatically between the separated surfaces through re-bonding of the polymer chains.

- In the agricultural industry, *self-sharpening ploughshares* were developed because the traditional ploughshares would become dull after a few hours' work. The principle was patented in 1785 by Robert Ransome from Ipswich, UK [74]. The principle was that the lower surface would be cooled more than the upper one. With iron being harder at lower temperatures, the lower surface would thus be harder, and abrasion would be slower than on the upper side. This simple mechanism assured that the cutting edge would always be sharp, and it still works the same way nowadays. Certainly, the calculations of abrasion laws have become preciser, and the materials more sophisticated, *e.g.* multi-layered [75]. But self-sharpening ploughshares are still observed to perform considerably better than traditional ones [76].

  Self-sharpening knives work with the same principle, but the increased hardness of one surface is due to Hardide^{TM}, which consists of Tungsten Carbide nano-particles dispersed in a metal Tungsten matrix. Nano-structured materials show unique toughness, crack and impact-resistance. Thus coating only one side of tools for cutting paper and plastics, while leaving the other side uncoated and therefore more vulnerable to abrasion, leads to self-sharpening effects [77]. Indeed, the thin hard coating on one side of the blade will serve as the sharp cutting surface, while the softer metal which carries the coating will get abraded and never let the blade become blunt.

- While usually not referred to as self-healing or self-repairing, also shape memory alloys or *smart metals* are capable of re-establishing an initial cold-forged state after deformation. Shape memory materials [78] are used in numerous applications across many fields, including aircraft, the automotive industry and medical engineering, to name but a few. For instance, pipes can be connected more easily when the connecting sleeve is being cooled and mechanically expanded for the pipes to be inserted; the sleeve will form a tight fit when returning to its original shape at ambient temperature. Parts made of shape memory alloys are also being used as actuators, where a temperature change will make them move. Eyeglass frames made of such material are more robust because they can temporarily deform under a mechanical load and return to their original shape when released.

- The *single molecule car* engineering project [79, 80] builds a four-wheel drive "car" from carbon atoms. The tiny car is then powered by electrons pulses fueled to the car by a specific tunneling technique. The molecule car can run across a conductive surface and is able to transport another single molecule. This novel technology is a step towards developing other molecule-size machinery traveling in the human body.

- *Chemical self-sharpening* effects have been observed in ion-exchange membranes [81]. In this context, the term "self-sharpening" refers to the purity of a separation of two liquids, and the higher the charge density of the membrane, the purer (sharper) becomes the separation of the liquids.

- *Self-repairing coatings* or paint have hit the headlines several times over the last few years and created great expectations among car owners [82], but they are still waiting for this paint to become commercially available. An "early stage" company called *Autonomic Materials* have started to market self-healing coatings from Champaign, Illinois, USA, under an exclusive license.

  The polymer coatings contain *micro-capsules* filled with repairing agents as well as catalysts which are set free when the coating is damaged. The healing polymerisation process takes energy from ultra-violet light, and re-creates an even surface. By treating micro-cracks in their early phases, bigger cracks are prevented from spreading [83, 84]. It remains, however, open if larger-scale damage caused by mechanical influences can be healed as well.

- In *self-healing bearings*, one of the usual steel balls is replaced by a ceramic ball, which will constantly polish the raceways and maintain them in a super-finished condition. This considerably increases the bearing's wear resistance, while reducing noise and vibration [85].

  Alternatively, the same principle as in self-healing paint can also be used for bearing surface coatings: lubricant capsules will burst when surface wear starts to appear, and can – at least for as long as the additional lubrication lasts – prevent further damage [86].

- *Self-healing concrete* – as used in construction – contains micro-capsules with a sodium silicate solution [87]. Corrosion is effectively inhibited, and cracks are healed. Also structures built of traditional lime mortar are known to exhibit such self-healing properties through natural recristallisation when exposed to air, but concrete has many other properties which are needed by today's construction industry.

- In *polymers and composites*, three types of self-healing have been observed so far: capsule-based healing systems, vascular healing systems (inspired by the caoutchouc tree), and intrinsic healing polymers [88]. Capsule-based mechanisms are one-off healing mechanisms, whereas vascular healing systems may work time and again, as the healing agent can be replenished. Systems with intrinsic healing properties do not need a healing agent, as their molecules naturally rebuild ruptured connections. The self-healing mechanisms may occur with or without human intervention and may or may not require an external source of energy or pressure.
  Self-healing not only helps fight against corrosion and mechanical damage but also thermic damage, and besides the previously cited approaches to self-healing, also nano-beam healing elements, passive self-healing, autonomic self-healing and ballistic self-repair are being explored [89].

- To make *electronic circuits* self-heal, carbon nanotubes have been encapsulated inside polymer spheres. Carbon nanotubes have a high electrical conductivity and their elongated shape is ideal for lining up to bridge gaps [90]. When the electronic circuits experience a mechanical impact – for instance because a phone falls down – tiny gaps may appear in the structure and impair the functionality. The carbon nanotubes may then repair the circuit and reestablish its function. Alternatively, the same effect is reached through the inclusion of microcapsules that are filled with a liquid metal (gallium-indium) [91, 92]. A combination of bigger and smaller microcapsules may optimise both reliability and conductivity after repair.

- Another approach to self-repairing electronic hardware is inspired by *eucaryotes and procaryotes* [93]: Memory cells contain the equivalent of DNA fragments which describe the cell's characteristics and functionalities. Faulty genes can then be extracted from neighbouring cells and using correlation mechanisms, allow the damaged cell to self-repair and establish its original state. The system is hierarchical, with the logical block corresponding to a biological molecule, up to an electronic array representing a biofilm formed of bacteria, and a bus standing for a cytoskeleton.

- The concept of logical self-assembly or self-configuration is also found in irregular Cellular Automata (CA) where cells, driven by rules that govern not only their next state mapping but also which neighbouring cells are used to determine the next state, arrange themselves into complex shapes [94]. The desired global pattern is partitioned into sub-regions, each denoted by different neighbourhood functions. Self-assembly originates from the origin cell and new cells attach themselves to existing cells that broadcast their cell state. By further arranging for the CA rules to cause deterministic convergent behaviour, self-assembly is regulated by convergence i.e., once the CA has reached convergent state, assembly is complete. The presence of convergent rules also makes the system self-repairing; the pattern will automatically reconfigure to the convergent state in the event of an external disturbance. The method is extensible to 3D patterns and complex designs.

- A self-healing house – currently being investigated in a project named *Intelligent Safe and Secure Buildings*[8] – includes nano polymer particles which convert into liquid when under pressure, flow into cracks, and solidify. Sensors in the walls and building structures collect data about vibrations and stress, and allow the inhabitants to be warned early in case of danger.

- On-the-fly repairs (in the literal sense) occur in *self-healing aircraft*: the hollow parts of composite-based plane are filled with a hardening epoxy resin, which "bleeds" out of any hole or crack that forms during a flight and patches it up. This assures a safe continuation of the journey, until the aircraft can be properly repaired on the ground. An eye-catching colouring of the healing resin assures that ground crews would spot the defective areas immediately. The idea is that the healing liquid might be flowing through a vascular system in a composite sandwich panel of which the outer shell of the aircraft is made, similar to the way blood circulates in our body [95, 96].

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[8] `http://cordis.europa.eu/fetch?CALLER=EN_NEWS&ACTION=D&SESSION=&RCN=27445`

On a different level, the solar-powered *Odysseus* [97] also executes self-healing on-the-fly: the aircraft will be able to autonomously modify its body by excluding failing modules. Odysseus is a project in the scope of the DARPA Vulture programme, aiming at aircraft which can remain airborne over a duration of five years.

Self-healing and self-repairing technologies of all kinds offer promising perspectives for the future, and their engineering needs to be fostered. The EPSRC Centre for Innovative Manufacturing in Through-life Engineering at Cranfield University, UK, is making efforts to structure and organise the self-healing/self-repair research community.

2.8. Smart systems

An important part of complexity engineering is about virtual and real things merging to become a new whole. These larger systems often rely on principles of self-awareness, self-adaptation, self-management, self-organisation, self-diagnosis and in some cases also self-repair of some kind. Many different examples illustrate this development, some of which are mentioned in this section.

- A variety of *Telecare* technologies [98] allow elderly people and/or people with handicaps and chronic illnesses to live at home while being monitored and assisted constantly or when required. Besides giving people more independence and freedom, Telecare also has the potential to reduce cost for the health care system by automating certain monitoring functions. Services, which Telecare can provide, include the surveillance of cardiovascular functions, blood glucose levels, asthma symptoms, location of people with dementia, and mobility of the elderly, including the detection of falls. Current research investigates the use of assistance robots of various types. Apart from the technological questions and the importance of the robots being easy to use for the elderly, also social aspects must be investigated. Telecare systems are examples of systems where humans collaborate with a variety of technologies and compose various types of socio-technical systems.

- In *opportunistic sensor networks*, applications that could be running anywhere send tasks to the network, and sensors which happen to be able to provide the necessary sensor readings, submit their data. As an example, a navigation application may ask for live travel updates, and the network would then collect data from sensors all over the relevant area. Such mobile sensors could either be carried by people or be mounted on cars and other devices. The sensor network must then manage the tasking and uploading opportunities and use mobility informed scheduling at the sensor access points [99]. The latter may enlarge their sphere of interaction by increasing transmission power or building multi-hop interaction spheres, but there is a trade-off between increased transmission and higher energy consumption.
  Autonomous sensors are increasingly coupled with agent technologies [100, 101] and local energy harvesting solutions. In some situations, the devices include information processing capabilities. This will allow the sensors to make more informed decisions about their own behaviour and lead to sensor networks that exhibit more flexibility, robustness, and autonomy. These are desired characteristics for most complexity engineering systems.

- Similarly, *self-guided bullets* are able to adjust their own trajectory [102]. An optical sensor at the nose of the bullet senses a laser beam that guides it to its target, which may be two kilometers away. The information is passed to an eight-bit processor which controls an electromagnetic actuator that steers the tiny fins, altering the ammunition's path.

- *Smart phones* carry a set of sensors – camera, microphone, GPS, accelerometer, and sometimes others – which can be used for various purposes, including some which were not planned initially, when users happen to be at the right place at the right time. For users to develop their own applications, easy-to-use programming platforms are necessary, such as PRISM [103]. The focus is on generality, security, scalability, as well as situation recognition and context-awareness. Again, this is an important aspect to develop for general use in complexity engineering.

- *Intelligent transportation systems (ITS)* aim to reduce road congestion, increase safety and mobility, as well as to enhance the productivity and effectiveness of private and public fleets [104]. At the vehicle level, ITS include concepts for cars to be equipped with proximity and acceleration sensors to assist the driver in avoiding collisions with pedestrians, other vehicles and obstacles in general [105]. Using communication between vehicles and sensor-equipped infrastructure in proximity, collective intelligence can be used to reduce traffic congestion and avoid critical situations. Algorithms have been proposed for optimising performance, safety, reliability and stability. They take advantage of learning techniques such as pattern matching and context recognition. At an organisational level, the focus was originally on private and public transportation, but has recently shifted to include commercial organisations, governmental agencies, institutions, highway operators, equipment manufacturers, system vendors and others. Freight ITS encompasses concepts for improved commercial vehicle operations, advanced fleet management, city logistics and electronic business [104]. Among the technologies used are electronic vehicle and cargo identification, location and tracking, pre-clearance and in-motion verifications. Various simulation and optimisation techniques rely on distributed computing. They are classical example of complex adaptive systems in technology.

- The *AutoNomos* project [106] uses methods from the field of *Organic Computing* [107], to develop a distributed, self-organising traffic management system. It consequently applies local rules and local decentralized data processing, which assures robustness and scalability. This project develops the concept of Hovering Data Clouds for collecting and disseminating data related to traffic conditions over a VANET (vehicular ad hoc network).

- The tendency towards *digital economies* [108] is fundamentally changing the way people and companies work. Traditional constraints in terms of geography, transaction costs, coordination, identity through jobs, and knowledge scarcity are fading. The new paradigm is that the right individual – customer or employee – can connect to the right situation – product or job – at the right time. This requires an architecture of participation, protocols of collaboration, and new notions of how work can be achieved. Key concepts are *responsible autonomy* and *peer-production*.

  In classical companies and according to a rule of thumb, 80% of the sales are generated by 20% of the efforts – thus the wish to eliminate the 20% of sales which require 80% of the efforts. ICT-based companies such as Amazon, however, are able to use the same coordination system for all of their sales, with no additional effort even for products that are rarely sold. Cumulated, these rare sales compose important numbers. This “aggregate value of the many” is also called peer-production. Also Wikipedia and Linux were created in this way – having a few employees build the infrastructure, and letting the big crowd make a high number of small contributions, leading to a complete system. For the best results, a balance between hierarchical coordination and bottom-up peer-production must be sought [108].

  Digital economies enable their members to interact and self-organise, driven by intrinsic motivations. The emerging collective productivity and intelligence is typically greater than the sum of the individual contributions. A shift will be observed from “knowledge is power” towards “the ability to generate knowledge and to learn is power” [108].

- *Ambient intelligence* [109] is a further development of *ubiquitous computing* [110], which introduced the idea of electronic devices being embedded parts of a finely granular distributed network, and *pervasive computing* [111], which additionally emphasised the importance of interoperability and seamless interconnectivity. Ambient intelligence is unobtrusive and supportive from the end-user’s perspective; it is sensitive and responsive to the presence of humans [109]. It uses information and intelligence that is hidden in the network. Contributing devices and services include wireless sensor networks, lightning, sound, vision, domestic appliances, personal health care devices, wearable electronics, smart phones, computers and many others [112].

  Perspectives which particularly need further investigation [109] include a standardised open platform for ambient control which provides access to physical objects; tangible interfaces which bridge the real/physical world and the virtual/digital world; customer-friendly end-user programming for customisation; sensory experiences to gauge the emotional state of the user and adapt the system accordingly (*affective computing* [113]); social presence of other persons; trustful persuasion of the user; *e-inclusion* (the accessibility of ICT for all persons), the possibility of the integration of electronics in the human body, privacy and ethics in general.

2.8.1. Collaborative networks

Companies, organisations and individuals often collaborate on project basis or to fulfil a specific task. For these temporary purposes, they form *virtual organisations* and *collaborative networks* [114].

Digital ecosystems (DES) as well as virtual enterprises and collaborative networks [115] are suitable models for all kinds of networked systems, especially those in an open, flexible, demand-driven interactive environment [116]. DES models can also be built on top of social software and swarm intelligence systems. According to its definition, a DES is a loosely-coupled, demand-driven, domain clustered, agent-based collaborative environment where each species is proactive and responsive for its own benefit or profit. It is a self-organising digital infrastructure for networked organisations or agents that support cooperation, knowledge sharing and development of open and adaptive technologies and evolutionary domain knowledge-rich environments [116]. Collaborative networks, can take many different forms, including cognitive networks, networks for innovation management, knowledge sharing or resource sharing. Important *human aspects* of collaborative networks include trust issues, knowledge sharing, coordination and planning activities as well as incentives, communication and mutual understanding and their influence on the business processes and the corresponding supporting IT tools [115].

Collaborative networks are also formed to answer emergencies. Such rescue networks could become more adaptive if they were based on self-organisation [117]. *Self-organizing security (SOS)* networks are suggested as an architectural foundation for deploying dynamic, short lived emergency response organisations. Simulations enable decision-makers to anticipate the evolution of emerging crises and evaluate the effectiveness of different collaborations between the involved services, including police, ambulance, fire fighters, and others.

2.8.2. Smart houses

Intelligent houses [118] are at the service of their users. Such houses get minimal input from their inhabitants and adapt to fulfil their wishes, with the help of sensors distributed in the house. An increasing number of devices in the house contain electronic components; adding computing and communication capabilities is a relatively small step, which allows them to process data locally and to integrate into a network, accessible from diverse points such as a handheld, a laptop, a TV, or other user interfaces. One of the first applications is the automatic regulation of the house climate. Windows, window blinds, ventilation, air conditioning and heating can be operated automatically and according to the individual inhabitants wishes, depending on the current weather situation and the temperature difference between inside and outside the house as well as time of day.

Every inhabitant has their own user profile, where his or her preferences are stored. The system can locate and possibly identify persons in the house, due to a carried RFID chip or thanks to the person's typical habits. The system can then adapt and offer diverse services, such as providing the preferred water temperature in the shower. Illumination can be personalized as well as entertainment such as music, TV or information from the internet about the cinema program, stock market or general news, displayed on screens or projected to walls. Different modes may be selected, according to opportunities like romantic dinner, early morning wake up, family lunch, or cosy Sunday at home. More advanced functionalities like brewing coffee at the right moment or other kitchen/cleaning services are for now left to the reader's imagination.

Home security is also an issue. Intruders can be detected and alerts sent to the absent house owner and to the police, eventually including pictures of the person in question. Doors can lock themselves and alarm systems can switch on and off depending on the presence of the inhabitants and their preferences. Mechanical keys become redundant in normal mode – but they could be used as the second solution in case of software problems or electricity cuts. The mechanisms for such incidences have to be prepared, ranging from the presence of a standby set to the possibility of operating all devices manually. Safety issues are important; intelligent houses are possibly less threatened by ordinary burglars, but 'network pirates' which try to attack the house software may be a serious danger. Separating house systems from the internet helps, but further measures have to be taken, eventually combined with advanced identification technologies such as reading fingerprints or iris patterns to exclude unauthorised persons from the access to the house.

Considerable research is being done on intelligent houses which self-regulate for energy efficiency [119] and improved safety (mentioned in section 2.7). Progress is achieved both in academia[9] and industry[10].

2.8.3. Smart energy grid

The purpose of *smart energy grids* is to make the current energy network more efficient and eco-friendly [120]. Besides electricity conduction, the grid needs to include an IT-layer which enables two-way communication between producers and consumers. This communication layer will support large volumes of data to be exchanged between a multitude of participants in a heterogeneous *ad-hoc* network; both energy providers and consumers may join or leave the network at any time. The existing *semantic web* technologies could be used for this purpose. The requirements include a decentralised architecture integrating heterogeneous and continuously changing producers and consumers, structured and machine-interpretable data models, support for the participants to make decisions autonomously, as well as security and privacy.

Wireless technologies may also be a key enabler for the smart grid as they allow for large numbers of participants to simultaneously join or leave the network seamlessly [121]. Additional advantages include application awareness, high service coverage, and prioritised routing of data. Smart grids will rely on a variety of supporting technologies, all

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[9] e.g. ICOST `http://www.icost2011.org`

[10] e.g. Smart Homes `http://smarthomes2011.com`

of which need to be joined in a unifying framework. Smart meters will monitor the power consumptions of devices, and intelligent energy management strategies will preferentially make them run when electricity is abundant and cheap.

Ten steps for energy providers to advance towards a smarter grid were identified in [122]. The vision of the smart grid includes reduced overall energy consumption, reducing carbon emissions by optimising the load management and thus reducing peak generation, and reducing traditional energy production by renewable sources. Furthermore, a smarter grid will have self-healing properties and resist attacks, will motivate customers to get involved and optimise their usage, and accommodates all energy generation and storage options. To this purpose, the smart grid will require distributed intelligence, digital communications for real-time data exchange, and decision and control software which is able to organise and analyse immense amounts of data and act accordingly. Also, extremely large numbers of control points will need to be managed [122].

The development of the smart energy grid is one of the main projects of the *European Institute of Innovation and Technology (EIT)*[11], with many industrial and academic partners joining forces to create a sustainable future. Siemens [123] is one of the international players contributing with consumer-side solutions for smart energy usage, including smart meters which are able to indicate the instantaneous consumption for electric domestic appliances as well as to distribute the energy according to priority rules. For instance, a fridge would use energy when it is abundant and cheap, but stay idle at peak times.

2.8.4. File and information sharing

Over the last few years, several types of information and file sharing platforms have emerged and developed their own dynamics. As a common characteristic, on these platforms, the information providers or producers are at the same time also the consumers, which is sometimes entitled a *prosumer*.

Typical of the culture of Wikipedia is collaboration in good faith [124], and similarly, most people's information disclosure on Facebook [125] is proof of either a lot of faith in each others good will, or proof of people's lack of consideration or knowledge of safety-related issues. Social interactions decide about a person's popularity on Facebook, and on Youtube [126] they determine which videos become successes.

Another recent example of the ubiquitous use of mobile communication and information sharing is how the London riots in 2011 were organised on Twitter and Facebook. Logically, it is necessary for police and governments to keep up-to-date and adapt their approaches. For instance, UK police have started to communicate with the public on Twitter.

The idea that computer virus technology could be used for beneficial purposes has appeared several times, but so far not proven to be viable, as reports show[12]. As it appears, virus technology does not offer enough benefits for justifying their malicious characteristics, and the latter seem not to be necessary for tackling any problems.

While some developments of these collaborative platforms simply emerge, others require new technology to grow and improve. For instance, P2P file sharing based on a bees algorithm [127] offers an optimised search algorithm involving more selective node tracing as well as a more efficient and robust sharing mechanism. In usual *Mobile Ad Hoc Networks (MANETs)* , file requests may take a long time while being passed through the network, which may be flooded with control messages, thus leading to signal traffic congestion. The bees algorithm is an alternative to the popular ant colony optimisation algorithm, used in a variety of problems, and also for improving efficiency of P2P files indexing and retrieval as [128], or in the Self-Chord framework [129] – a self-organising version of the Chord framework. On a side note, the ant colony optimisation algorithm has been applied to a variety of problems, including industrial assembly lines [130] and shop floor scheduling [131].

2.8.5. Trends in smart systems

The above research and development projects are mere examples of a variety of smart systems. There is almost no limit as to where sensors, actuators and communication devices might be integrated or added, today and in the future. The opportunistic collaboration and competition between entities in open systems both creates and requires a diversity of self-* properties. Smart systems are thus intrinsically robust and resilient, adaptable and flexible.

Research in complexity engineering benefits from the advances in smart systems because the underlying mechanisms and principles are increasingly well understood and demonstrated. At the same time, advances in complexity engineering allow system designers to rely on well-investigated methods and to assure that the systems have the desired characteristics, no matter what happens.

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[11] `http://eit.ictlabs.eu/ict-labs/thematic-action-lines/smart-energy-systems`

[12] `http://www.cknow.com/cms/vtutor/are-there-good-viruses.html`

3. Synthesis

Complexity engineering is the creation of systems while benefiting from the findings of complexity science. The question is not so much in which ways complexity engineering would be better than classical engineering, but rather, in which situations classical engineering comes to its limits, and complexity engineering can help. This is mostly the case with complex systems which are composed of many interacting components, where the interactions are multiple and changing in time; open systems; systems which have to function in a dynamic environment and strongly interact with it [1]. Complex systems use adaptation, anticipation and robustness to cope with their often unpredictable environment [132], and complexity engineering therefore requires tools which take these issues into account.

Such systems, said to have emergent functionality [133], are useful in cases where there is a lot of dependence on the environment and it is difficult or impossible to foresee all possible circumstances in advance. Traditional systems are therefore unlikely to be able to cope with such conditions. Systems with emergent functionality can be seen as a contrast to reducible systems and usually hierarchical functionality; the latter means that a function is not achieved directly by a component or a hierarchical system of components, but indirectly by the interaction of lower-level components among themselves and with the world. Careful design at micro-level leads to behaviours at macro-level which are within the desired range.

Typically, no single entity within the system knows how to solve the entire problem. The knowledge for solving local problems is distributed across the system [132], and together, the entities achieve an emerging global solution. The right interactions need to be carefully engineered into the system, so that the systems self-organising capabilities serve our purpose, i.e. they do satisfy and support the requirements [134].

Complexity engineering will not lead to systems which are unpredictable, non-deterministic or uncontrolled. The output (i.e. certain aspects) may be predicted and controlled – it is how the system arrived to that output that can not be known, complex or not computationally reproducible [134]. However, it remains an open question if the latter is acceptable for all application domains. The system's development cannot be completely separated from the system's operation in the case of a complex system [135].

3.1. Classification with regards to nature/technology interface

As mentioned previously, a considerable amount of complexity engineering is inspired by systems found in nature, including physics, chemistry, biology and social systems of various types. Taking into account existing work and recent innovative approaches, a set of different ways of how nature-inspiration can interact with technology and engineering has been identified and is presented in the following subsection. Afterwards, the previously introduced work is classified according to the different types of nature-inspiration.

The classification suggested in this section is open for debate, but it provides a basis for discussion and helps widen the exposure of complex systems exhibiting self-* properties and emergence to the engineering community.

Inspiration for novelty in technology can take various forms. Each of them has particular goals and strategies, and researchers should be aware of them. The items 1, 2a and 2b on the following list correspond to the three research phases of inspiration by nature described in [136]. The last three items are additional [15]. Table 2 gives an overview of inspirations and applications.

(1) **Using technology to understand natural systems:** Biologists, chemists and physicists have for a long time been using technological tools to help them investigate natural systems and to verify the established models. The palette of such tools includes oscilloscopes, gyroscopes as well as compound pendulums. More recently, computers allowed researchers to run large-scale simulations with thousands of iterations. Even more sophisticated, nowadays researchers use robots to emulate natural systems, and they even succeed in incorporating robotic 'cockroaches' into real cockroach swarms [137, 138].

(2a) **Using ideas from natural systems to experiment and find usable mechanisms:** This refers to the experimental phase of *bionics*. Researchers understood long ago that they can learn from nature and use mechanisms discovered in natural systems to solve engineering problems. However, most mechanisms need to be adapted in order to be usable, and this can only happen through an experimentation phase in the lab. Different versions are often discovered by changing the initial mechanisms, and the researchers can let their creativity play. Examples include robotics swarms such as Swarm-bots [139] and Swarmanoids [140, 141].

(2b) **Using ideas from natural systems to build usable technology:** The final goal of most bionic or biomimetic developments is using them in real-world applications. This means that they have to comply with industrial standards. It has been achieved for many technologies, such as velcro adhesives, ultrasound, radar and sonar systems, dolphin-shaped boats, ultra-hydrophobic and self-cleaning surfaces based on the Lotus effect, and cat-eye reflectors. Researchers now increasingly approach distributed and autonomous adaptive systems, which are more difficult to build than other bionic applications. Theory and practice of biomimetics are discussed in [142], and the benefits of bionics in [143].

Table 2. Engineering and natural systems.

Phase	Inspiration/assisting tools	Application/goal
(1)	Technological tools	Understanding natural systems
(2)	Natural systems	(Industrial) engineering
(3)	Engineering methods	Biotechnology on living substrates
(4)	Biotechnological methods	Software engineering (agents)
(5)	Software engineering methods	Building artificial models to understand natural systems

Table 3. Classification of complexity engineering work according to the 5 types of nature-inspiration. MAS stands for 'multi-agent systems'.

	(1) Using technology to understand nature	(2) Nature-inspiration for technology	(3) Using technology on natural systems	(4) Using biotech. in SW eng.	(5) Using technology to model nature
MAS and services	x	x		x	x
Collective robotics		x			x
Micro/Nano swarms		x	x		
Systems biology	x		x		x
Synthetic biology	x	x			x
Chem-IT			x		
Artificial chemical life	x	x	x		x
Self-healing products		x			
Smart systems		x	x	x	

(3) **Using the 'engineering toolbox' on natural systems:** Denominated *biotechnology, bio-medical engineering, genetic engineering, synthetic biology* or similar, these disciplines use engineering technology on natural substrates such as living cells, bacteria and sometimes higher animals. Researchers grow virus cells in high-tech tanks [144] to produce vaccines, they try reproducing epidermic tissue, inner organs, or genetically modified animals. Many different technologies are being used to diverse purposes. As a specific example, when a certain gene is implanted and then inherited by future generations, cancerigenous cells can become fluorescent, which facilitates their identification under the microscope [145].

(4) **Using biotechnology methods for software engineering:** Researchers in computer science now often take inspiration from methods used in biotechnology, in particular in cell engineering. Methods which work for living cells supposedly also work for software agents. In the Evobody project[13], such methods and principles are applied to embodied evolving systems which are "electro-mechanic, bio-organic, hybrid of these, or whatever else" and can interact, reproduce and die.

(5) **Using ideas from engineering to build new models for understanding natural systems:** Probably the most recently initiated discipline considers architectures and mechanisms used by engineers to create technological systems which have nothing to do with natural systems. Natural scientists then use such ideas to build new models for understanding natural systems [146], in the sense that if engineers have come up with ideas, maybe nature has invented them long ago. For instance, robotic cockroaches [138] and shepherd robots [147] have been successfully integrated in animal societies.

Table 3 indicates how complexity engineering approaches and projects can be classified according to the five types of nature-inspiration. In some cases, opinions may differ, and we encourage discussion.

3.2. Relation between bio and techno

Traditionally, there was a strict separation between what was nature or natural, and artificial (which, indeed, means 'man-made'). It even had some judgmental character, in the sense that natural was or maybe still is considered as being 'better' or healthier than artificial. Most people have recognised that it is not that simple; *e.g.*, cancer is a natural development, although often triggered by man-made factors. On the other hand, some artificial inventions are highly beneficial if applied correctly, like water filtering devices. Without access to clean water, most living being –

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[13] http://www.evobody.eu, see section 2.2

apart from some specialists – will not survive for very long. Indeed, most technology can be used for the good or the evil.

Besides the fading of this good/bad-connotation, also the border between natural and artificial is getting blurred. Many applications use technology on natural systems. Some use natural systems to enhance technology, while others use technology to enhance natural systems. For instance, certain types of crop have only very faint similarity with their natural ancestors, after centuries of breeding and even genetic modifications. The question now is, are they still natural beings?

Besides mixing technological and natural units, some systems now increasingly mix technological and human units, there is a plethora of socio-technical systems ranging from crowdsourcing (*e.g.* using humans for computing tasks in exchange of financial rewards), to social networks of humans exploiting social media as Twitter of Facebook to organise, to advanced medical systems where a patient is monitored by technology-enable services and humans as nurses, doctors or family members. Challenging questions arise from those systems: what is their reliability and dependability, what incentives should be considered, and what about privacy and ethics concerns?

It appears likely that in the future, the boundaries between natural and artificial will completely disappear. So far, a sure way to distinguish between natural and artificial was the fact that only natural systems can be alive, although not all natural systems are alive, indeed. A rather recent development is that the creation of 'artificial living systems' (see section 2.6) becomes conceivable. While this is a fascinating possibility, it also carries risks that are impossible to fathom at the current stage of research.

3.3. Risks

While Terminator[14] scenarios are rather unlikely to become real, nightmares such as described in Prey[15] are indeed not that far from research being done in some laboratories; indeed, there is research being done on nano-swarms, genetically modified and evolving bacteria and viruses, artificial life forms, innovative cameras, distributed systems, biologically implemented computation, and many more. It is only a question of time until researchers combine these technologies, and until something gets into the wrong hands, or otherwise out of control.

Again, all technology can be used for the good or the evil, but what makes biotechnology and related areas particularly dangerous is the combination of technology with the unique property of living systems to evolve and find ways to survive no matter what. As far as we humans can judge, natural living systems seem to have a way of not damaging the world beyond repair. Natural disasters have always happened, and species have always gone extinct, but so far, natural life on Earth has always been able to recover. During the short time of its existence so far, the human race has been lucky enough to survive epidemics and attacks from predators, including other mammals as well as microbes. But will we be strong enough to resist the attack of a technology-enhanced, evolving living system of microbes? The latest viruses which led to outbreaks of global panic allowed us certainly only a very brief glimpse of what is yet to come.

Needless to say, the reader may be confident that most researchers are responsible and careful with both what they create and what they release into the environment. Furthermore, not all technologies cited in this article carry such risks in themselves, but they certainly have the potential to make systems more user-friendly, more robust, resilient and dependable. For instance, a car with self-healing paint would come very handy, and a swarm of robotic fish that collect pollution [28] would save the oceans from a lot of damage. It appears thus that research in complexity engineering is worth taking the associated risks, as long as the researchers are aware of their responsibility.

3.4. The potential of Complexity Engineering

The advantage of non-traditional approaches to engineering are manifold. They include the possibility to create systems which cannot be understood or designed with common methods. Typically, such systems consist of many entities which interact in multi-lateral ways; these interactions and interdependencies are often too complex to analyse with traditional tools. Complexity engineering provides the engineer with an approach that allows for such systems to be designed, observed and guided towards reaching the desired properties.

The pluridisciplinary nature of complexity engineering creates many synergies in terms of the substances, materials and devices that are used, the methods that are applied, and mindsets which researchers from different disciplines bring and share. Often, innovation consists of "thinking out of the box" or applying concepts and methods which function in one area to another, completely unrelated area. This is one of the main assets of complexity engineering, besides the fact that complexity engineers attempt to learn from the greatest expert that has ever existed: Nature itself.

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[14] *1984 science fiction action film directed by James Cameron, starring Arnold Schwarzenegger; several sequels.*

[15] *2002 novel by Michael Crichton*

4. Conclusion

The efforts being made under the umbrella of *Complexity Engineering* are increasing. Not only researchers but also industry are in the process of discovering its amazing potential. However, progress is fragmented and often, researchers are only partially aware of the relevant work done in related areas. Interdisciplinary conferences such as ALIFE[16] and ECAL[17] are necessary for cross-fertilisation and the exchange of ideas between researchers that are investigating similar ideas and/or following similar paradigms although in distinct fields of applications.

As a first general tendency, we identify that systems with self-* properties (that is, systems which are able to take care of themselves, exhibiting self-adaptivity, self-organisation, self-healing etc.) have started to emerge in many different and previously unrelated areas. Researchers are increasingly discovering the advantages of systems that are able to take care of themselves, thus increasing their own robustness, resilience, and life-cycle time. A slightly different flavour of the same tendency may be referred to as *living technology* [148], which describes human-made systems that evolve and modify their characteristics while in use and in accordance with the changing requirements and environment.

The other general tendency is the focus on improved sustainability, which includes the use of renewable resources, recycling, and the intelligent management of resource usage. Opportunistic collaborations and symbioses are becoming more important, with people joining forces to reach shared or related goals.

While researching technical aspects of these systems, ethical and responsible research and industry-lead efforts are required to consider and tackle upfront risks related to this technology, in particular those in relation to systems getting out of control or environment damage.

We observe that the borders between different research areas are getting blurred, and we foresee that this development will further increase. Pluri-disciplinary collaborations and corresponding publication media will grow, and we can only hope that their scientific recognition will improve soon.

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